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Interim Report **IR-04-057**

Burden-sharing Rules for Stabilizing Greenhouse-gas Concentrations and Their Equity Implications

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Contents

Abstract

This paper focuses on the equity aspects of international burden sharing for global CO_2 emission stabilization. It first summarizes and classifies five equity principles that may play a role in allocating emission entitlements to countries. These principles are then used to examine ten burden-sharing rules – proposed in the published literature of the field – by analyzing the degree to which each rule incorporates the five equity principles.

The burden-sharing rules surveyed are not readily comparable because they do not use a common global emission (reduction) goal. For that reason, our paper carries out a detailed examination of three sets of quantitative emission entitlements, which are based on three typical burden-sharing rules – the *equal emissions per capita* approach, the *carbon intensity* approach, and the *Triptych* approach – with the idea of comparing their implications for carbon emission entitlements for 67 countries and 9 world regions. To make the three rules comparable, we used a global carbon emission target that leads asymptotically to an atmospheric CO_2 concentration of 550 ppmv.

Reducing carbon emissions to meet this concentration target requires significant global efforts. No burden-sharing scheme aiming at this target can therefore be expected to lead to a negligible burden on all countries. Depending on the equity principle chosen, a scheme can allocate more of the global burden to developing countries or to industrialized countries. Developing countries receive relatively higher entitlements under the *equal emissions per capita* approach whereas industrialized countries are relatively better off under the *carbon intensity* approach. The *Triptych* approach leads to in-between allocations for most countries. Only countries with high carbon intensity in 1990 (for example China, Russia, and Poland) receive the highest entitlements under this burden-sharing rule.

In some countries and regions, emission entitlements as calculated by any of the three burden-sharing rules are so tight that it appears unrealistic to assume that domestic measures alone can be successful in limiting their actual emissions to the emission entitlements assigned to them. It would therefore seem natural to assume that the calculated entitlements determine the initial allocation of tradable emission allowances of countries or regions. Although we make this assumption, we considered any numerical determination of carbon trade flows to be outside the scope of our paper.

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Burden-sharing rules for stabilizing greenhouse-gas concentrations and their equity implications

1 Introduction

Equity and fairness play an important role in international negotiations and agreements. This is particularly the case with the 1992 United Nations Framework Convention on Climate Change (UNFCCC) in which the equity issue is explicitly addressed. In the *Principles* (Article 3) it is stated that, "on the basis of equity and in accordance with their common but differentiated responsibilities and respective capabilities", parties should act to protect the climate system. This formulation was the basis for exempting developing countries in the Kyoto Protocol from the obligation to reduce emissions. However, the eventual success of the UNFCCC will also depend on the active participation of developing countries whose representatives have already made it clear that equity will become a key issue in any such negotiations.

The Kyoto Protocol adopted the so-called *target and time table* approach, which sets specific goals in terms of emission targets at given points in time. At the core of this approach are so-called burden-sharing rules, which can be used to determine the allocation of the emission entitlements of the Parties to the UNFCCC.

In this paper we focus on the relation between equity principles, burden-sharing rules, and emission entitlements. The paper sets out to analyze how different equity concepts presented by different authors can relate to burden-sharing rules proposed in the relevant literature. We carry out this analysis first in a qualitative way by assessing ten popular burden-sharing rules from the perspective of five equity principles that have been argued to be relevant for the task.

We then examine three particularly typical and popular representatives of the ten burden-sharing rules (the *equal emissions per capita* approach, the *carbon intensity* approach, and a modified *Triptych* approach) in a unified frame. In other words, we use these rules to calculate emission entitlements for 67 selected countries (and the "Rest of the World") that add up to a global trajectory leading to an asymptotic atmospheric carbon dioxide concentration of 550 parts per million in volume (ppmv). We then assess the equity aspects of these three rules in terms of three representative indicators, one reflecting equal rights to emit, and two reflecting equal efforts to mitigate. Note that the actual carbon emissions may be different from the allocated emission entitlements if international carbon-emission trading or other kinds of flexibility, such as joint implementation and the clean-development mechanism, are allowed. We assess the equitability of the burden-sharing rules in terms of the allocated emission entitlements, not the actual emissions after the international carbon trading.

Of course, equity is not the only criterion that will be decisive for the success or failure of entitlement schemes; political feasibility will also play a crucial role. Although in this paper we do not address politics, we hope that our analysis of the relation between equity principles and quantitative commitments will facilitate assessment of the political acceptability both of the equity principles themselves and any mitigation commitments in which they may result.

Note: Throughout this paper, "tons" always means metric tons (megagrams).

2 Equity Principles

In this section, we summarize equity concepts that have been invoked by other authors as being relevant in the context of global climate change. If one studies the relevant publications in the field, it quickly becomes clear that equity is a multifaceted concept. An assessment of how equitable a rule is must therefore be multidimensional, and it is thus obvious that burden-sharing rules cannot be ranked according to how well they represent equity.

In our review of equity principles we follow Rose and Stevens (1993) who distinguish between "allocation-based" and "outcome-based" equity principles. Allocation-based equity principles deal with fairness in terms of allocations of property rights, or emission entitlements to countries. Outcome-based equity principles involve fairness in sharing welfare changes in the sense of traditional welfare economics. Welfare changes are often approximated by a loss or gain in GDP.

In their analysis of the interplay between equity and efficiency, Bosello et al. (2001) restrict themselves to analyzing the cost allocation of abatement. They can argue therefore that allocation-based equity principles are implemented with reference to abatement cost, whereas outcome-based equity principles require the specification of welfare function for each country. In this paper, we also include the possibility of allocating entitlements, thus this characterization is not possible.

Rose et al. (1998) note that the allocation stage is more immediate and more certain than the outcome, and hence might receive more attention. In contrast to allocation-based equity concepts, outcome-based equity principles are applied in an *ex post* manner because a model – or an equivalent tool – is needed to calculate the numerical implication of the rules for welfare changes.

Table 1 summarizes five equity principles and their relation to the definition of burden-sharing rules in the global climate policy context. The reader is referred to Rose (1992) for a discussion of the conceptual underpinnings of each of the principles. In the following subsections, we will discuss these five equity principles in detail.

Table 1: Five equity principles used in the literature and their implications for global burden-sharing.

Equity principles	Implication for burden sharing in the context of global climate protection
Allocation-based principles	
Egalitarian	Supports equal emission rights per capita
Polluter Pays	Supports historical responsibility
Sovereignty	Supports the status quo
Outcome-based principles	
Horizontal equity	Supports allowance according to countries' specific circumstances (explained in the text below); supporting equal distribution of cost
Vertical equity	Supports differentiation between rich and poor by considering "ability to pay"

2.1 Allocation-based principles

The *egalitarian* equity principle is defined as equal rights for all human beings irrespective of their socioeconomic status (Rose, 1992). Rose et al. (1998) define it in terms of all people having an equal right to pollute and to be protected from pollution. For greenhouse-gas-emission (GHG) entitlements, this would mean that each person would have right to emit in equal amounts.

The *polluter pays* principle was formally adopted by the Organisation for Economic Co-operation and Development (OECD) in 1974 in the context of international environmental policy. It stipulates that the polluter should bear the expenses of carrying out measures of pollution prevention and control to restore the status of the environment before the pollution occurred (OECD, 1974). In the context of climate change, this implies that the abatement burden should be distributed according to the level of emissions. The inclusion of past emissions – to the extent that they are the cause of present atmospheric greenhouse-gas concentrations – leads to the "historical-responsibility" argument. This is a crucial argument for developing countries because, as Rose (1992) notes, "ignoring the past build-up and simply basing reduction requirements on subsequent emissions would be equivalent to penalizing developing countries for their progress, when no such sanction was imposed on industrialized countries." A counterargument to the historical-responsibility concept is that no one should be held responsible for consequences that were not foreseen at the time an action was undertaken (Rowlands, 1997).

Rose et al. (1998) use the term *sovereignty* in connection with the argument that all nations have an equal right to pollute and to be protected from pollution. In the climate change context, sovereignty is often invoked to support the *grandfathering* approach of distributing the reduction commitment in proportion to actual emissions. It seems to us however, that an additional argument, i. e., that a country's right to emit is "legitimized" by past usage and custom (Rose, 1992), is needed so that the status quo may be considered as an inherited right, in pursuance of the sovereignty principle. Moreover, as sovereignty usually refers to the political concept of noninterference, we shall avoid using the term as an equity principle. Rather, we will follow Blanchard et al., (2001) and use the term *proportional equality* as an equity-related principle that supports grandfathering.[1]

2.2 Outcome-based principles

Whereas allocation-based equity concepts deal with the distribution of emission entitlements from the perspective of property-right distribution, outcome-based equity concepts address them from the perspective of distributing cost or, more generally, welfare loss. Unless emission entitlements are allocated retroactively, the assessment of cost usually involves the use of a model.

Horizontal and *vertical* equity are two examples of outcome-based principles. They are defined in terms of how net welfare losses and benefits are distributed among countries, and they differ in that the rich pay more, either in absolute terms or proportionally. Generally speaking, net welfare is measured using a welfare function, but given the hypothetical nature of such a function, the net gain (or loss) of GDP is usually used as an approximation.

The meaning of horizontal and vertical equity is similar to their meaning in relation to tax policy (Cazorla and Toman, 2000). *Horizontal equity* postulates that each entity, in this case a country, is to be treated equally with respect to the specific relative welfare change (measured, for example, as loss of national income as a proportion of GDP). Progressive income taxation is a familiar example of the application of *vertical equity*. Vertical equity is related to the ability to pay and affordability, and therefore postulates that a higher cost[2] (per capita) is to be carried by richer counties.

Ringius et al. (1998) argue that the UNFCCC and the Berlin Mandate reflect the horizontal-equity principle. Their arguments are based on UNFCCC, Article 4.8, which aims at an equalization of welfare losses by emphasizing the need to pay attention to specific situations of countries and their sources of income. The Berlin Mandate, in Article 2(a), underlines that the individual circumstances of developed countries and the differences in their starting points should be taken into account when strengthening commitments to reduce GHG emissions.

At the same time, the differentiation of the burden between developed and developing nations reflects the vertical-equity concept. The Kyoto Protocol thus reflects elements of vertical as well as horizontal equity.

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[1] Blanchard et al., (2001) describe proportional equality as the idea of justice defined by Aristotle, namely, that people are unequal and are therefore treated unequally. According to that idea, social position is the factor that structures distribution and it is considered to be the only criterion for comparing individuals, since the function occupied by an individual in society is supposed to correspond to the value of his work for that society.

[2] Note that here we say “cost” and not “welfare loss” because welfare loss could be defined as utility of consumption, often defined logarithmically, which implies declining marginal utility of consumption. Equal loss of utility of consumption would then automatically reflect vertical equity.

3 Burden-sharing Rules and their Assessment from an Equity Perspective

Burden-sharing rules determine the amount of allocated emission entitlements as a function of some quantitative variables, the most popular of these being population and GDP. Here, we assess the alternative burden-sharing rules with respect to their equity implications.

Our assessment covers ten burden-sharing rules found in the published literature. To structure the rules, we use the common distinction between *reductive* and *distributive* rules. According to this distinction, reductive rules distribute global reductions among countries. In contrast, distributive rules distribute global GHG emission entitlements among countries (Grübler and Nakićenović, 1994).

3.1 Reductive rules

In general, reductive rules are less acceptable to countries that have not yet reached a mature level of economic development as emission reductions are likely to limit their growth aspirations. Given the vast disparity today in the status of economic development between developing and developed countries, the implementation of reductive rules would not appear to be consistent with the "development" part of the concept of sustainable development. Reductive rules that assign emission reductions to developing countries are thus likely to be in conflict not only with both the horizontal- and vertical-equity concept but also with the historical-responsibility concept. Not surprisingly, the application of the reduction-based rules is less controversial in developed countries.

3.1.1 Grandfathering

The *grandfathering* approach is one of the simplest approaches to burden sharing. It refers to a flat-rate reduction of emissions at a given point in the past, that is, a percentage cut of the kind specified in the Kyoto Protocol. According to Merriam-Webster (1997), a grandfather clause is a "clause creating an exemption based on circumstances previously existing", especially "a provision in several southern-state constitutions designed to enfranchise poor whites and disenfranchise Negroes by waiving high voting requirements for descendants of men voting before 1867". This inequitable historical meaning notwithstanding, the *grandfathering* approach has played a dominant role in the climate policy debate.

As we have argued above, we want to use the term *proportional equality* as supporting the *grandfathering* approach. We note that, in practice, proportional equality tends to contradict egalitarian equity, not only because it penalizes countries with higher population growth, but also because it tends to perpetuate any existing inequities. It is also inconsistent with the *polluter pays* equity principle, by not reflecting the historical responsibility for GHG emissions.

3.1.2 Converging carbon intensity of GDP

Rowlands (1997) presents an approach based on *converging carbon intensity of GDP* (carbon emissions per unit of GDP) which is used as an indicator of efficiency (the lower the carbon intensity of an economy, the higher its efficiency). The idea is that more stringent emission reductions should be prescribed for economies where actual efficiency is low. Rowlands' calculations of emission entitlements therefore mandate initial reductions for economies with the highest carbon intensity of GDP. Emission reductions are mandated until the country's carbon intensity of GDP equals that of the country with the next lowest score.

The *converging-carbon-intensity-of-GDP* approach thus reflects horizontal equity because countries with higher carbon intensity – which would be required to reduce a higher percentage of their emissions – can be expected to be able to achieve carbon emission reduction relatively easily as there are still larger opportunities to implement technological improvements. Note that this reasoning therefore also appeals to efficiency arguments. It is at odds, however, with the principle of vertical equity because it puts a heavy economic burden on less-developed nations because of their higher carbon intensity compared to that of most industrial economies.

3.1.3 The efficiency index approach

Gupta and Bhandari (1999) favor an *equal emissions per capita* approach for all countries in the long run. To avoid prescribing abruptly declining emission entitlements for Annex I countries, the authors suggested that the *efficiency index* approach should be applicable to these countries during a transition period.

Their approach in a sense combines the first two approaches summarized here by amending the *grandfathering* approach (equal percentage reduction) to include cost-efficiency. The latter is reflected in the special allowances given to countries that have achieved high efficiency, defined as low carbon intensity of GDP. The authors argue that an efficient economy, assuming it already uses relatively GHG-benign technologies, should not be punished for the efficiency that it achieved in the past. An additional rationale for these extra allowances is that economies with lower efficiencies can be expected to have lower marginal abatement costs. Therefore, the following adjustment is suggested to determine the percentage reduction for a country.

$$\text{A country's percentage reduction}_{time} = \text{total percentage reduction}_{time} * \text{efficiency index} \quad \text{(Eq. 1)}$$

$$\text{Efficiency index}_{country} = (CO_2\ \text{emissions}_{country,\ 1990}/\text{GDP}_{country,\ 1990}) / (CO_2\ \text{emission}_{Annex\ I,\ t})/\text{GDP}_{Annex\ I,\ t}) \quad \text{(Eq. 2)}$$

The efficiency index is thus defined as the carbon intensity of a country, divided by the average carbon intensity of Annex I countries. The efficiency index for a country is assumed time-dependent through its linkage to the average carbon intensity of Annex I countries, which is assumed to decrease at an annual rate of 0.8%.

The overall thrust of Gupta and Bhandari (1999) is the *equal emissions per capita* rule, thus reflecting egalitarian equity. Only during a transition period and only for Annex I countries, they propose reliance on reductions in proportion to base-year emissions, thus reflecting proportional equality. These reductions are corrected using carbon efficiency as a determinant, reflecting the account taken of horizontal equity.

3.1.4 The multicriteria approach

Ringius et al. (1998) proposed three formulae and a set of six indicators (population, CO_2 emissions, CO_2 emissions per GDP, CO_2 emission per capita, GDP, and GDP per capita) to calculate emission reduction targets for OECD countries. Each formula is designed to allocate greater emission reduction, relative to the reference year, to those countries that exceed the OECD average with respect to the indicators included in the formulae. The authors do not give preference to any of the three formulae. Each formula is thus one variant and could therefore be regarded as a "subapproach".

Formula I defines emission reduction for each country as a percentage of emissions in a reference year. The formula includes the following indicators: CO_2 emission per capita (A), GDP (B), emissions per unit of GDP (C), and GDP per capita (D). These are understood as indicators for emission entitlements, size of countries, energy efficiency, and ability to pay.

Formula I is defined as follows

$$X_i = \alpha \cdot \left(w_A \cdot \frac{A_i}{A} + w_B \cdot \frac{B_i}{B} + w_C \cdot \frac{C_i}{C} + w_D \cdot \frac{D_i}{D} \right) \qquad \text{(Eq. 3)}$$

The resulting X_i is the percentage reduction for country i. The parameter α is a scaling factor, determined such that the total emission reductions by countries become equal to the OECD target. The parameters A to D (without subscript) are OECD averages of the respective indicator. w_A to w_D are the weights that add up to 1. The authors do not propose numerical values for the weight of each indicator, therefore opening them up for possible negotiation.

Formula II calculates, in absolute terms, the contribution Y_i of country i in the total emission reduction of the OECD. Countries with a larger population, higher CO_2 emissions, and higher GDP are prescribed a higher CO_2 reduction.

Formula II is defined as follows,

$$Y_i = \left(w_E \cdot E_i + w_F \cdot F_i + w_G \cdot G_i \right) \qquad \text{(Eq. 4)}$$

where E_i is a country's percentage share of population of the OECD total, F_i is a country's share of CO_2 emissions in the base year, and G_i is a country's share of GDP. The three weights w_E, w_F, and w_G are again left unspecified.

Formula III includes GDP (B), emissions per unit of GDP (C), and GDP per capita (D).

$$Z_i = \frac{\left(w_B \cdot B_i - w_C \cdot C_i - w_D \cdot D_i \right)}{\sum_j \left(w_B \cdot B_j + w_C \cdot C_j + w_D \cdot D_j \right)} \qquad \text{(Eq. 5)}$$

As in Formula II, Z_i is the percentage share of country *i* of the total emission reduction commitment for the OECD. Again, the weights are left unspecified.

The *multicriteria* approach tries to address several equity principles at the same time by combining a subset of the six indicators in their formulae. CO_2 emissions per capita can be considered to represent egalitarian equity; GDP per capita addresses vertical equity; emissions per GDP reflect horizontal equity; and CO_2 emission in a base year reflects proportional equality. The authors do not give a reason for including total GDP as a factor. They merely note that total GDP represents the size of economy. From this we conclude that Ringius et al. (1998) want to provide a place in their approach for those who think that size of economy can play a role in determining an equitable allocation of emissions. Presumably, the concept of economy of scale can be used to estimate the size of the influence that total GDP has on the cost of mitigation.

The *multicriteria* approach is thus characterized by a high degree of flexibility. As Phylipsen et al. (1998) note, however, introducing so many indicators together with parameters used for weighting them will increase the risk of losing transparency.

3.1.5 Cutbacks proportional to past contributions

According to the logic of differentiated responsibility, the *cutbacks proportional to past contributions* approach suggests that the emission reduction targets of each country are in direct proportion to that country's share in the total anthropogenic addition to preindustrial levels of atmospheric GHG concentrations. Grübler and Nakićenović (1994) calculated the historical contributions of world regions to total CO_2 concentrations. Their assessment is based on an analysis using the so-called Parametric Framework (Grübler and Fujii, 1991), and includes anthropogenic emissions since 1800.

This approach is based on polluter pays equity and on proportional equality, with the emphasis on the former. By using past contributions, this approach directly addresses historical responsibility but uses the status quo as a counterbalance, giving some weight to the argument that the responsibility for polluting should be restricted to the time after which evidence of a negative impact was scientifically substantiated.

3.2 Distributive rules

In contrast to reductive rules, distributive rules allow increases as well as decreases in emission entitlements relative to a base year. Distributive rules are therefore more flexible than reductive rules, and do not mandate reductions in countries with low emissions in the base year. This suggests that distributive burden-sharing rules are likely to be favored by developing countries because they can more easily accommodate their aspiration for economic growth.

3.2.1 Equal emissions per capita

Allowing equal emissions per capita has an obvious appeal to equity, and burden-sharing rules that incorporate this principle are therefore popular. Grübler and

Nakićenović (1994) used this rule to calculate the distribution of the global emission entitlements of 13 world regions with a target of 38% reduction in CO_2 emissions in 2050 compared to 1988 (equivalent to a reduction to 4 GtC in 2050). The year 2050 was also the target year for the convergence of the per capita emission entitlements.

Gupta and Bhandari (1999) calculated emission allowances for Annex I countries and non-Annex I countries based on equal emission entitlements per capita. For each year, the amount of globally allowable emissions[3] is divided by the global population in that year to determine the average per capita emissions, which is then multiplied by a country's population to obtain the emission allowance for that country.

Allowing equal emissions per capita is a direct application of egalitarian equity. Given the present distribution of carbon emissions to developed and developing regions, this approach clearly reflects vertical equity (ability to pay) because the wealthy regions are required to carry out more reductions while many poorer regions might not be required to reduce their emissions at all.

Sometimes it is argued that an entitlement that is defined per head of actual population (rather than population in a given base year) might provide an incentive for population increase, particularly in developing countries. Against this, Gupta and Bhandari (1999) argue that it would be rather implausible to assume that this "incentive" would carry more weight than policies to limit population and alleviate poverty, or the recognition that there are limits to the availability of resources.[4]

3.2.2 The Triptych approach

The *Triptych* approach, proposed by Phylipsen et al. (1998), has this name because it calculates emission entitlements in three sectors. Somewhat resembling the *multicriteria* approach (described in Subsection 3.1.4 above) the rather sophisticated Triptych approach takes into account the different circumstances of individual countries by specifying separate national emission targets for the power sector, internationally oriented heavy industry, and a "domestic" sector. The approach has contributed significantly to the discussions of emission limits distribution within the European Union (EU), as follows.

The GHG emission target for the power-producing sector is calculated from a hypothetical common limit to the growth of total electricity production (1%/year) with some extra allowance given to less-wealthy countries (i.e., the "cohesion" countries; Greece, Spain, Portugal and Ireland) and from individual targets on shares of electricity production from different technologies.

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[3] The global allowable emission path was taken as the IPCC's WRE (Wigley, Reilly and Edmonds) 550 ppvm stabilization scenario, which covers a time span from 1990 to 2150.

[4] As a "back-of-the-envelope" calculation, one may want to consider the "productivity" of an additional person in terms of additional carbon emission entitlements for a country. With the numbers used below, this would be approximately one tonne of carbon per year. Subtracting from this the actual emissions of the hypothetical person and multiplying this by the carbon price gives an idea of the size of the extra incentive for one birth. Even if this number is positive, it is hard to imagine that it can be big enough to matter in practice.

Differences between countries are taken into consideration by setting country-specific carbon emission intensity (carbon emission per electricity output) targets defined as the result of a hypothetical fuel mix target and electricity conversion efficiency targets of fuels. The fuel mix target is calculated using the following hypotheses, which are defined for the year 2015 and relative to the base year, i.e., (i) 30% reduction of fossil-generated electricity; (ii) an 8% additional share (for example, 10.8% up from 10%) of renewables in total electricity generation; (iii) electricity generated by combined heat and power (CHP) to increase by 15%; and (iv) nuclear power does not increase its share. The remaining electricity is to be produced by natural gas.

The allowance of GHG emissions for internationally oriented heavy (energy-intensive) industry is calculated based on a common target regarding energy efficiency improvement and growth of activity (with extra allowances for the above-mentioned "cohesion" countries). Finally, the targets for an aggregate of all other industries (light industries) and residential, commercial, transportation and agriculture sectors (termed the "domestic sector" in the original publication) are specified so that emissions per capita converge at one point in the future (e.g., in 2030). Countries in particularly cold or hot areas will receive extra allowances that take into consideration the higher demand for space heating or cooling.

The total allowance for each country is the sum of the three sectoral allowances. A comparison of the resulting GHG allowance targets calculated for EU countries shows that the *Triptych* approach allows emission growth in selected countries, while avoiding extreme reduction targets for any country.

Groenenberg et al. (2001) applied the same method in a wider geographical context, that is, to a selection of 48 developing and industrialized countries. The differentiation rule applied there was slightly modified from the one applied to the European Union in Phylipsen et al. (1998). For example, Groenenberg et al. (2001) did not take into account information on national policies regarding the fuel mix in the country's power generation system. Structural changes within the energy-intensive sector were taken into account by differentiated growth rates for various industrial subsectors. Unlike Phylipsen et al. (1998), who calculated the criteria (and sectoral targets for each country) so that the total national targets added up to meet an overall emission reduction objective, Groenenberg et al. (2001) let the total reduction in CO_2 emissions result from the criteria applied, not vice versa.

By considering a large number of specific circumstances, in particular by attempting to avoid "windfall" advantages as well as unjustified hardship in each country, the *Triptych* approach addresses the horizontal-equity principle in a comprehensive way. Such an effort to achieve horizontal equity may be regarded sufficient for an equitable and politically acceptable scheme if the approach is applied just to European countries which do not vary too much in terms of their per capita income. An extension to developing countries that aims simultaneously for equity and acceptability would therefore appear to be bound additionally to consider aspects of *vertical equity* if it is intended to remain within the spirit of the original approach.

One possible drawback of the *Triptych* approach could be its data intensity which arises from the necessity of specifying many country-specific parameters involved in the calculation of allowance adjustments. This may also infringe on the transparency of the approach and may thus complicate the political negotiation on the rule.

3.2.3 Historical responsibility

The *historical-responsibility* approach, also known as the *Brazilian* approach, specifies that each country receives a burden that corresponds to its past contribution to climate change (UNFCCC, 1997). Unlike the *cutbacks-proportional-to-past-contributions* approach described above, the *Brazilian* approach proposes using "effective emissions" as a measure of the responsibility. Effective emissions are measured in terms of their calculated contribution to the global temperature increase relative to preindustrial levels. The name, effective emissions, is designed to express that the concept takes into account the initial concentrations of GHGs in 1990, due to previous emissions, to explain the historical responsibility. It also takes into account GHG sinks.

To give an idea of the quantitative implications of their proposal, the authors calculated emission entitlements assuming a maximum permissible temperature increase by using a simple box-diffusion model based on the Second Assessment Report of the Intergovernmental Panel on Climate Change (IPCC).

The *historical-responsibility* approach is the direct application of the *polluter pays* equity.

3.2.4 Equal per capita emissions throughout the generations

Fujii (1990) proposed *equal emission entitlements per capita throughout the generations*, an approach that allocates an equal emission allowance for each person irrespective not only of geographical location but also of the generation the person belongs to. The uniqueness of this approach is that it includes past and future generations (i.e., people born between 1800 and 2100). The author calculated a per capita emission allowance of 1.37 tC/year, assuming that the CO_2 concentration level is allowed to rise from 280 to 560 ppmv by 2100.

This approach is based on an expanded egalitarian equity. It addresses intergenerational equity, which, so far, we have not discussed here.

3.2.5 Multisector convergence

The Centre for International Climate and Environmental Research (CICERO) and the Energy research Centre of the Netherlands (ECN) have proposed the *multisector convergence* approach, in which seven different sectors have been distinguished (Jansen et al., 2001). This approach sets the global averages of CO_2 emission per capita for each sector, and commitments are made only for those countries that exceed the global averages. Those countries must reduce CO_2 emission per capita by the convergence year to the global average of the sectors. Countries' emission entitlements are calculated based on the sum of the countries' reduction targets for the seven sectors. It is also proposed to include special allowances in calculating sectoral targets for each country.

4 Quantitative Analysis of National Emission Entitlements Calculated under Three Selected Burden-sharing Rules

Although not reported here, all the studies reviewed in Section 3 give quantitative examples of the distribution of the entitlements in the original papers (a summary of the emission allocation calculated in the original papers are provided in Klaassen et al., 2002). Their results were not comparable, however, because calculations were usually done for a single rule and based on different assumptions. Moreover, numerical results reported by different authors are not always globally comprehensive mainly because, in general, they do not necessarily add up to one and the same total global emission limit.

In this section, we present the emission entitlements that we calculated using three selected burden-sharing rules, one and the same global emission target, and a consistent set of assumptions with respect to population growth, GDP growth, structural change of economies, growth of electricity production and others, calculated as a result of a single model run. Our criteria for selecting rules for inclusion in this comparative assessment were mainly the popularity of the rule and its simplicity.

4.1 Assumptions and methods used for quantitative analysis of three selected burden sharing rules

The geographical basis for our calculations were 67 countries (see Table 5). All other countries were aggregated into one region, called ROW-67. This disaggregation was chosen so as to permit the calculation of emission limits for the nine world regions of the MERGE model (Manne and Richels, 2001) either directly or by simple aggregation. In particular, MERGE's ROW region is identical with our ROW-67 (Klaassen et al., 2003).

The global CO_2 emission target used in our calculations was taken from the B2-550KP scenario generated by MERGE (based on an emulation of the IIASA-SRES B2 scenario formulated by IIASA's MESSAGE model). The B2-550KP scenario stabilizes CO_2 concentrations at a level of 550 parts per million by volume in 2100 (Figure 1). It also assumes that countries that ratified the Kyoto Protocol achieve their respective targets (Klaassen et al., 2003).[5]

[5] More specifically, we calculated the emissions in 2010 with the following assumptions: for the USA the emissions would be 1.725 GtC (with the USA following domestic policy, as calculated by Kydes, 2002); the sum of emissions of WEU, Japan, and CANZ (Canada, Australia, and New Zealand) would be 1.573 GtC; and the emission for EEFSU (Eastern Europe and former Soviet Union) to be less than 1.1 GtC. For detailed description (see Klaassen et al., 2003).

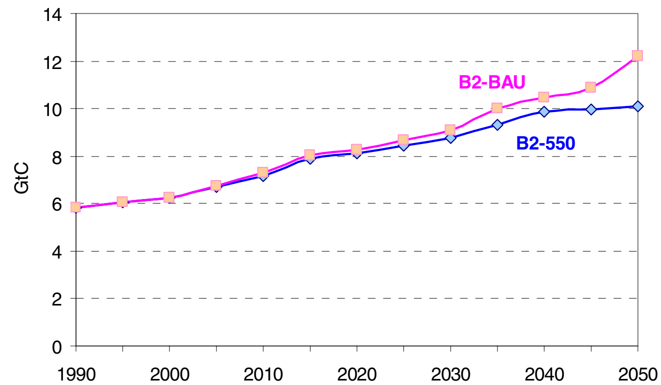

Figure 1: Global CO_2 emission target, taken from a run of the MERGE model including a 550 ppmv constraint on atmospheric GHG concentrations and the emission limits prescribed in the Kyoto Protocol (except for the USA) For comparison, business-as-usual (BAU) emissions are added (upper line).

This global total was then distributed to the 67 countries and ROW-67 using the following three rules as a basis, one at a time:

(1) Equal emissions per capita;

(2) *Carbon-intensity* approach;

(3) Triptych.

To make the three approaches applicable to all countries of the world and to use them to distribute the global target of global CO_2 emission trajectory, we had to slightly modify rules (2) and (3).

For all three approaches, we calculated emission entitlements for different time periods for different countries. For countries with a 2010 emission limit under the Kyoto Protocol, we used this as their emission entitlement for the year 2010 and applied our rules thereafter. For the USA, emissions for 2010 are taken as specified in footnote 5 and our rules applied from then onwards. For all other countries, the period for calculating emission entitlements according to the three rules begins in 2015. In all cases, emission entitlements are calculated at 5-year intervals.

In order to avoid drastic breaks of past emission trends in the calculated time trajectories of the emission entitlements, we chose the year 2050 as the target year for complying with the spirit of the respective rule. For rule (1), equal emission rights per person, this means, e. g., that the total emission entitlements of a country become proportional to the country's population (of that year) only in 2050.

As the variable to be used for smoothing the transition between a country's shares in global emissions in the initial year (1990 or 2010 respectively) and those allocated in the end year of our calculations (2050), we amended a method proposed by Global Commons Institute (2003) for calculating shares of emissions. For the calculation of intermediate-year shares for the *equal emissions per capita* and *equal emissions per GDP* (carbon intensity) rules, we use the following formula

$$S_{Y+1} = S_Y - (S_Y - P_{Y+1})t \quad \text{(Eq. 6)}$$

Where S_Y is the emission share of a country in year Y, P_Y is its share of global population or global GDP respectively in year Y, t is the fractional time elapsed between the starting year (in Annex-B countries 2010, in non-Annex-B countries 1990) and 2050 (target year), i.e., t=0 for starting year and t=1 at the target year. The advantage of this method is that the shares always add up to the global total and therefore to the global target. (This would not be the case if we used simple linear interpolation between the values in starting year and end year, which would necessitate the use of correction factors to scale down or up to the global total.)

Before presenting the numerical results of applying the three rules in Section 4.2, we summarize, in the following subsection, the numerical assumptions used in the calculations.

4.1.1 Equal emissions per capita

We first calculate carbon emission entitlements in 2050 by dividing global carbon emissions according to our trajectory by global population as projected by the United Nations Population Division (1998). (We illustrate this population projection for selected countries and world regions in Figure 2.) We then calculated emission allowances for 67 countries and ROW-67 in a straightforward way, that is, by multiplying per capita emission entitlements with the respective population.

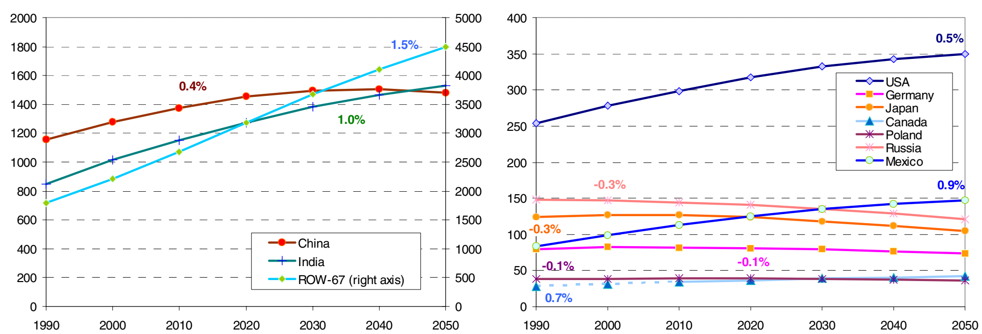

Figure 2: Population development, UN middle-growth case, for 9 selected countries and ROW-67, million people. Numbers in the figures refer to the average annual growth rate in percentage terms between 1990 and 2050.

The original projection is defined for the time up to 2050. In that year, China and India have approximately 1.5 billion inhabitants each. The biggest population in that year, however, is in the aggregated ROW-67 region, which is projected to be home to 4.5 billion people or 50% of the world population. Total global population eventually saturates and remains below 10 billion.

4.1.2 The carbon-intensity approach

The original *carbon-intensity* approach as proposed by Rowlands (1997) and the *efficiency-index* approach as proposed by Gupta and Bhandari (1999) which uses it, are defined for emission reductions only. We therefore slightly amended it to also cover the possibility of increasing entitlements, at the same time trying to retain its spirit, which we understand as avoiding punishment for efforts toward efficiency made in the past.

Our version thus uses the carbon intensity of GDP to calculate a country's emission entitlement. Again we used 2050 as the year in which emission entitlements are calculated in full consistency with the rule; that is, carbon emission entitlements per GDP in that year are the same for all countries. For intermediate years (2015, 2020, 2030, and 2040), emission entitlements are again calculated with equation (6).

The future values of GDP for all individual countries are derived by multiplying the actual GDP value of a country in 1990 with the GDP growth rates that our MERGE B2 scenario projects for one of the nine MERGE world regions to which the country belongs. GDP values in 1990 for each country were taken from the United Nations Systems of National Account (United Nations, various years). The resulting GDP values for the nine MERGE world regions are summarized in Figure 3.

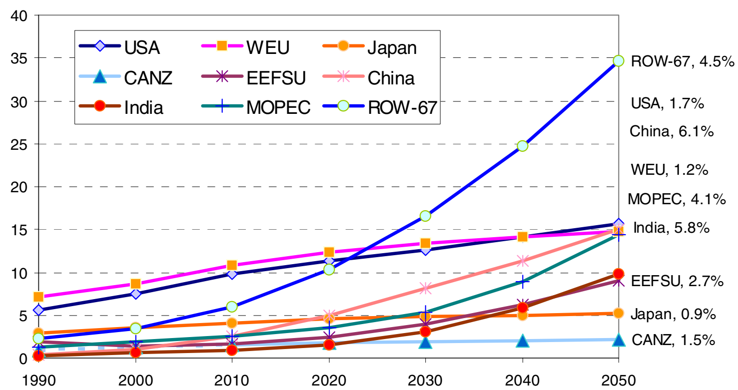

Figure 3: GDP assumptions in MERGE B2, for nine world regions, trillion (10^{12}) US dollars (1990 prices), and average annual growth rates between 1990 and 2050.

Here, global GDP in 2050 is assumed to reach 120 trillion (10^{12}) US dollars (1990 prices), which corresponds to a global average annual growth rate between 1990 and 2050 of 2.8%. The growth is significantly higher than this global average for developing regions such as China (6.1%) and India (5.8%).

4.1.3 Triptych

As we described in Subsection 3.2.2 above, the original *Triptych* approach calculates emission entitlements as the sum of emission entitlements for three energy-demand sectors: electricity generation, heavy industry, and a so-called domestic sector (residential and commercial sectors plus other industry sectors including light industry and service industry). Calculating entitlements for the three sectors separately allows several country-specific characteristics to be taken into account.

However, introducing the same set of country-specific circumstances as in the original approach into the calculation for all countries and regions of the world would make it impractical to try to specify all the necessary parameters (which are fairly uncertain anyway), and, as a consequence, the transparency of the calculations would be in jeopardy. We therefore simplified the *Triptych* approach, retaining from the original idea that emission entitlements should take account of the economic structure of an economy in terms of three aggregated sectors.

Because of data limitations, we could not separate light and heavy industry. We therefore included all manufacturing sectors in the industry sector. The global emission target for the electricity generation sector is again given by the emissions of the power sector in the MERGE B2-550 stabilization scenario. For the industry and the domestic sectors, MERGE does not calculate the CO_2 emissions separately. Thus we took the shares of industry and the domestic sector in nonelectric carbon emissions as calculated in the B2-550 stabilization scenario generated by the MESSAGE model (Riahi and Roehrl, 2000). Multiplying these shares by the nonelectric global carbon emissions calculated in the MERGE B2-550 scenario, we obtained the global carbon emission target for industry and the domestic sector. Figure 4 shows the resulting global emission targets for the three sectors.

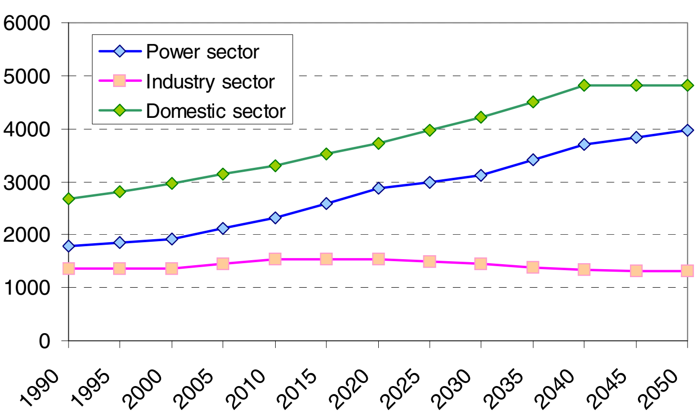

Figure 4: Global emission targets for the power, industry, and domestic sectors, million tons of carbon (MtC).

For the emission targets for the power sectors of each country we first calculated total electricity production in that country by using the region-specific growth rates for electricity production, taken from the MERGE B2 scenario (Klaassen et al., 2003). We did not account for differences in future fuel mixes because this information is difficult to obtain for the countries we used. Instead, we calculated emission entitlements assuming that the carbon intensity of total power generation (CO_2 emissions per kilowatt-hour) would decrease at the same rate for all regions.

We calculated the rates such that the total emission entitlements of all world regions for the electricity sector correctly add up to the emission entitlement given for the global electricity sector (as explained above). The resulting carbon intensity targets of the electricity sector for the periods 1990-2010, 2010-2015, 2015-2020, 2020-2030, 2030-2040, and 2040-2050 are summarized in Table 2.

Table 2: Carbon intensity targets for the electricity sector, all world regions.

	1990	2010	2020	2030	2040	2050
Carbon intensity target (index)	1.00	0.80	0.74	0.63	0.61	0.58

For the industry sector, we again calculated identical annual reduction rates of carbon intensity for all countries and regions in a way that matches the global emission entitlement described above for the industry sector (see Table 3). Because of limitations in data availability, we were not able to separate light and heavy industry.

Table 3: Carbon intensity targets for the industry sector, all world regions.

	1990	2010	2020	2030	2040	2050
Carbon intensity target (index)	1.00	0.35	0.19	0.10	0.09	0.04

For the domestic sector, we followed the original *Triptych* approach. In other words, we calculated emission entitlements in the domestic sector using the rule of converging emissions per capita.

The following data were used for the calculation of our modified Triptych approach. The electricity generation of each country for 1990 was taken from IEA's Energy Balance (IEA, 2002). The future electricity output of a country was calculated using the country's 1990 value multiplied by its growth rate given by the MERGE model (B2 scenario) for the world region to which the country belongs.

Data on the industrial output of each country for 1990 were taken from the International Industrial Statistics of the United Nations Industrial Development Organization (UNIDO) (UNIDO, 2000). Future values of industrial output per country were calculated in a similar way to electricity output; we took the 1990 value of each country and applied identical rates for all countries belonging to one MERGE world region.

The regional growth rates of industrial output were approximated by the growth rate of value added of the industrial sector (GDP from industry), which was calculated by multiplying GDP (taken from the MERGE B2 scenario) by the GDP share of industry of Scenario B, IIASA-WEC (Nakićenović et al., 1998).

For calculating targets in the domestic sector, future population assumptions were used as described under the *equal emissions per capita* approach. The numerical values of these variables are summarized in Table 4.

Table 4: Assumptions used in the calculations of the sectoral emission entitlements under the *Triptych* approach.

	USA	WEU	Japan	CANZ	EEFSU	China	India	MOPEC	ROW-67
Industrial output (billion US$) and CO_2 intensity in the industry sector									
Industrial output in 1990	2861	4005	2246	448	818	350	141	220	797
CO_2 intensity in 1990 (gC/$)	60.3	40.8	30.4	91.5	333.3	783.2	372.1	326.6	308.2
Industrial output									
A.A.G.R., 1990-2020	1.93	1.51	0.85	1.74	0.91	9.84	6.53	4.32	5.48
A.A.G.R., 2020-2050	0.58	0.48	0.69	2.04	2.50	2.13	3.35	2.90	2.01
Industrial output in 2050	6282	7180	3051	896	3773	26822	8002	4105	15682
CO_2 intensity in 2050 (gC/$)	2.4	1.7	1.2	3.7	13.5	31.8	15.1	13.3	12.5
Electricity generation (TWh) and CO_2 in the power sector									
Electricity in 1990	3182	2322	851	669	2157	621	289	418	1311
CO_2 intensity in 1990 (gC/kWh)	154.7	110.9	92.3	96.7	237.3	261.6	193.1	168.1	76.8
Electricity									
A.A.G.R., 1990-2020	1.43	2.17	1.66	2.12	1.59	4.92	3.61	5.09	4.24
A.A.G.R., 2020-2050	1.01	1.06	0.32	1.03	1.75	1.43	2.92	2.90	2.46
Electricity in 2050	6737	6266	1537	1746	6213	4355	2311	5196	10753
CO_2 intensity in 2050 (gC/kWh)	90.2	64.7	53.8	56.4	138.3	152.5	112.6	98.0	44.8
POP (million) and CO_2 per capita in the domestic sector									
Population in 1990	254	377	124	48	410	1155	851	272	1792
CO_2 per capita in 1990, kgC	2705	1351	989	2183	1348	156	53	634	166
CO_2 per capita									
A.A.G.R., 1990-2020	-3.4	-1.9	-1.3	-3.2	-1.9	3.4	6.8	-0.9	-3.4
A.A.G.R., 2020-2050	-2.2	-1.3	-0.9	-1.6	-1.3	0.6	0.8	0.2	-2.2
Population in 2050	349	343	105	73	386	1478	1529	613	4490
CO_2 per capita in 2050, kgC	515	515	515	515	515	515	515	515	515

Regarding country-specific CO_2 emissions in 1990, the shares of CO_2 emissions by three sectors are taken from the IEA (IEA, 2000). By multiplying them by the national CO_2 emissions for each country[6], we calculated CO_2 emissions from three sectors for 1990. Figure 5 illustrates the shares of CO_2 emissions by the three sectors in 1990.

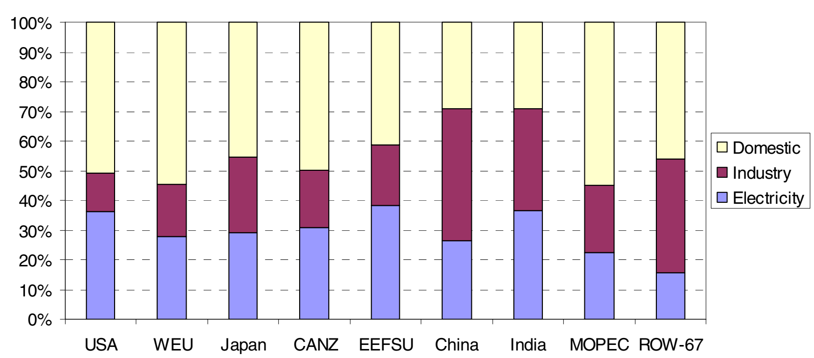

Figure 5: Shares of CO_2 emissions in three sectors in 1990 for each MERGE world region, in percent.

[6] Data were taken from the CO_2 database compiled by Marland et al. (2001), and FCCC/CP/1997/7/Add.1: UNFCCC, 1998.

Table 5 summarizes the emission entitlements according to the three burden-sharing rules for the 67 countries of our study and for ROW-67. In the next subsection, we discuss the results for selected countries.

Table 5: Summary of emission entitlement for 67 countries and ROW-67, calculated with three burden-sharing rules, MtC.

	1990	2010	2020			2030			2040			2050		
			EPC	CI	TRIP	EPC	CI	TRIP	EPC	CI	TRIP	EPC	CI	TRIP
USA														
USA	1352	1725	1312	2040	928	883	1899	829	531	1666	847	377	1313	802
WEU														
Austria	16	15	13	27	11	11	34	10	10	35	10	8	28	9
Belgium	31	29	23	42	20	18	46	17	13	44	17	10	34	15
Denmark	14	13	11	23	14	9	28	13	7	28	14	5	22	13
Finland	15	14	11	24	11	9	29	10	7	29	10	5	23	9
France	100	92	86	188	60	79	243	51	73	258	49	65	207	43
Germany	276	254	206	366	211	153	395	191	106	376	193	79	289	182
Greece	22	21	18	25	23	15	23	22	12	20	23	9	14	21
Iceland	1	1	1	1	0	1	1	0	0	1	0	0	1	0
Ireland	8	8	7	11	7	6	11	7	6	10	7	5	8	7
Italy	117	108	94	191	89	77	233	79	59	239	77	44	189	71
Luxembourg	3	3	2	3	1	1	3	1	1	2	1	0	2	0
Netherlands	46	42	35	61	32	27	67	28	20	64	28	15	49	25
Norway	10	10	9	19	5	7	24	4	6	25	3	5	20	3
Port	11	11	11	15	12	11	16	11	10	16	12	9	12	11
Spain	71	65	59	100	59	51	112	55	42	109	55	33	85	50
Sweden	17	15	14	34	11	12	46	9	11	49	9	9	40	8
Swiss	12	11	10	30	6	10	43	5	9	48	5	7	40	4
UK	159	147	124	212	133	98	230	124	76	219	127	61	169	121
JAPAN														
Japan	269	253	221	456	195	182	551	167	143	557	160	113	434	140
CANZ														
Canada	125	117	95	156	80	72	158	69	54	147	71	46	116	65
Australia	79	85	67	101	72	49	93	69	34	79	74	28	60	70
New Zealand	7	7	7	10	5	6	11	5	6	11	5	6	9	4
EEFSU														
Albania	2	--	3	2	2	4	1	3	5	1	3	5	1	3
Bosnia and Herzegovina	1	--	3	2	3	4	3	3	4	4	4	4	5	3
Bulgaria	23	21	17	19	16	13	13	17	9	9	18	6	9	18
Croatia	5	4	5	5	4	5	6	4	5	8	4	4	10	4
Czech Republic	46	43	33	38	30	23	25	29	13	16	32	8	14	32
Yugoslavia	13	0	14	12	16	13	10	18	13	10	20	11	11	21
Hungary	20	18	16	18	15	13	14	14	10	14	15	8	15	15
Poland	113	106	88	92	87	68	58	86	50	32	94	39	24	96
Romania	47	43	37	38	36	30	26	37	23	17	41	18	16	41
Slovakia	16	15	12	13	9	9	9	8	7	7	8	5	6	8
Slovenia	3	3	3	4	3	2	4	3	2	6	3	2	7	3
Armenia	1	--	3	3	2	4	3	3	4	5	3	4	6	3
Azerbaijan	15	--	14	12	13	12	10	13	12	9	15	11	9	15
Belarus	29	--	23	27	22	17	23	22	12	24	24	9	26	24
Estonia	10	10	7	9	10	4	6	11	2	5	12	1	5	13
Georgia	5	--	6	6	4	6	6	4	6	8	4	6	9	4
Kazakhstan	78	--	55	61	57	39	42	57	26	30	65	20	29	66
Kyrgyzstan	3	--	5	4	4	6	4	5	7	4	6	8	5	6
Latvia	6	6	5	6	5	4	6	4	2	7	5	2	8	5
Lithuania	6	5	5	6	5	4	6	5	4	7	5	3	8	5
Moldova	6	--	6	7	6	6	6	6	5	7	7	5	8	7
Russia	651	652	504	606	477	343	456	469	203	387	520	131	397	530
Tajikistan	6	--	8	6	7	9	5	8	11	5	10	12	5	10
Turkmenistan	9	--	8	7	8	8	5	8	8	5	10	8	5	10
Ukraine	186	164	131	153	120	94	116	116	61	100	126	42	103	126
Uzbekistan	35	--	38	29	33	39	22	35	43	19	40	44	20	41
CHINA														
China	617	--	1214	800	2128	1441	945	2266	1648	1173	2321	1593	1261	2277

INDIA														
India	153	--	828	227	702	1173	315	889	1542	552	1080	1648	817	1168
MOPEC														
Mexico	84	--	120	122	139	136	136	161	156	187	201	158	250	227
Bahrain	3	--	2	3	4	2	3	5	1	3	6	1	4	7
Iran	49	--	78	166	79	94	234	93	116	370	116	124	511	130
Iraq	11	--	27	21	25	38	26	32	52	38	41	59	52	46
Israel	8	--	9	19	18	9	25	22	10	38	29	10	52	35
Jordan	2	--	7	3	6	11	2	8	15	3	10	18	4	12
Kuwait	10	--	7	11	14	5	11	15	4	14	20	4	18	24
Lebanon	2	--	4	2	5	4	2	6	5	2	8	6	3	9
Oman	3	--	4	5	5	5	6	7	7	8	9	9	11	11
Qatar	3	--	2	4	4	2	4	4	1	5	5	1	7	6
Saudi	81	--	66	75	93	58	63	104	57	65	133	59	79	159
Syria	8	--	18	11	17	25	13	20	33	17	26	37	23	29
Turkey	35	--	69	61	70	85	73	83	104	106	103	109	143	114
UAE	14	--	10	18	22	7	19	25	5	24	32	4	32	39
Yemen	2	--	19	5	14	33	6	21	52	9	29	63	12	32
ROW-67	644	--	2158	1260	1809	3091	1723	2264	4257	2455	2787	4841	2897	2990
Global Total	5827	--	8133	8133	8133	8787	8787	8787	9847	9847	9847	10099	10099	10099

4.2 Results for nine major countries and ROW-67

In this subsection, we present and briefly characterize the results of each of the three approaches for nine representative countries (USA, Germany, Japan, Canada, Poland, Russia, China, India, and Mexico) as well as for ROW-67. In the following Section 5, we analyze these results comparatively.

In 1990, CO_2 emissions differed significantly in the selected countries. The biggest CO_2 emitter was the USA, emitting 1350 MtC, followed by Russia, ROW-67 and China, each emitting more than 600 MtC; Germany and Japan each emitted about 270 MtC; India, Canada, Poland each emitted between 110-150 MtC.

According to the MERGE B2 baseline (that is, unmitigated) scenario, this ranking will have changed significantly by the year 2050. Then, the biggest emitter will be ROW-67, emitting 3.4 GtC. The USA will continue to be a big emitter, with 2.2 GtC. It is followed by China, Eastern Europe and the former Soviet Union (EEFSU) and Mexico and OPEC (MOPEC), emitting 1.6 GtC, 1.3 GtC, and 1.0 GtC respectively. Japan will emit less than the 1990 value, 225 MtC. The increase in emissions from Western Europe by 2050 compared to 1990 is rather small, i.e., 1000 MtC in comparison to 929 MtC in 1990.

4.2.1 Equal emissions per capita

Figure 6 shows the developments of emission entitlements for nine major countries and ROW-67 under the *equal emissions per capita* approach. The emission entitlements according to this approach represent a radical break with present trends of CO_2 emissions in the industrialized regions. Although this is not a surprising result, given the current carbon emissions and the forecast population distribution, it is still worth noting that this burden-sharing rule imposes a severe emission reduction requirement on the five OECD countries and Russia, even though our convergence year (2050) was assumed to be quite late compared with convergence years used by other authors. (One popular convergence year is 2030.)

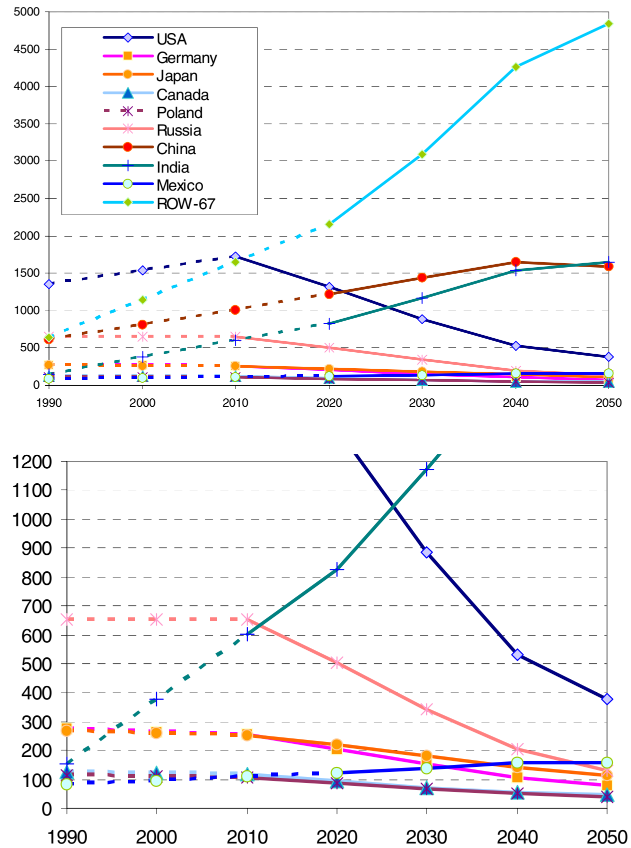

Figure 6: *Equal emissions per capita* approach: Emission entitlements for nine countries and ROW-67 (upper) and enlarged figure (lower), MtC.

Under the *equal emissions per capita* approach, three of the nine countries included in this comparison (China, India, Mexico) and ROW-67 are allowed to increase their carbon emissions, but all other countries of this selection are not allowed to increase emissions beyond the 1990 level (or, in the case of Annex B countries, the 2010 level).

This rule particularly favors India and ROW-67, where high population growth is expected (see the population development illustrated in Figure 2). By 2050, India receives the biggest increase (by a factor of more than 10) in emission allowances compared to 1990. ROW-67 obtains an increase by a factor of 7.5. China and Mexico obtain comparatively modest increases (factors of 2.6 and 1.9 respectively relative to their 1990 emissions). Although Mexico is expected to have rather high population growth, it is interesting to note that the other two rules allocate a larger emission entitlement for Mexico.

In sharp contrast, the USA and Germany face entitlements corresponding to reductions of more than 70% compared to their 1990 levels. Canada and Poland also faced severe reduction requirements, that is, by almost two-thirds from 1990 levels in 2050. By the same year, Japan is entitled to no more than half of its 1990 emissions. The most radical reduction assignment is calculated for Russia which would be allowed to emit only 20% of its 1990 CO_2 emissions in 2050.

4.2.2 Carbon-intensity approach

Figure 7 presents the emission entitlements calculated with the modified *carbon intensity* approach. Under this approach, Japan and Germany are allowed to actually increase their emissions in 2050 compared to 1990. Three developing countries and ROW-67 are likewise allowed to increase their emissions substantially, reflecting the higher GDP growth assumed for these countries.

The USA and Canada would be required to reduce their emissions in 2050 by 3% and 7% respectively, also compared with 1990. The USA would be allowed to increase emissions until 2020 although the USA target for 2050 is below the 1990 level. Bigger reductions would be required for Canada, but the general picture of Canada's emission entitlements is similar to that of the USA.

India's entitlements increase by a factor of more than five, and her emission allowance increases gradually over time. Entitlements for ROW-67 increase similarly to those of India. The biggest emission reduction commitment is allocated to Poland and Russia by 2050. Their entitlements in 2050 are only 20% (Poland) and 60% (Russia) of their respective 1990 levels.

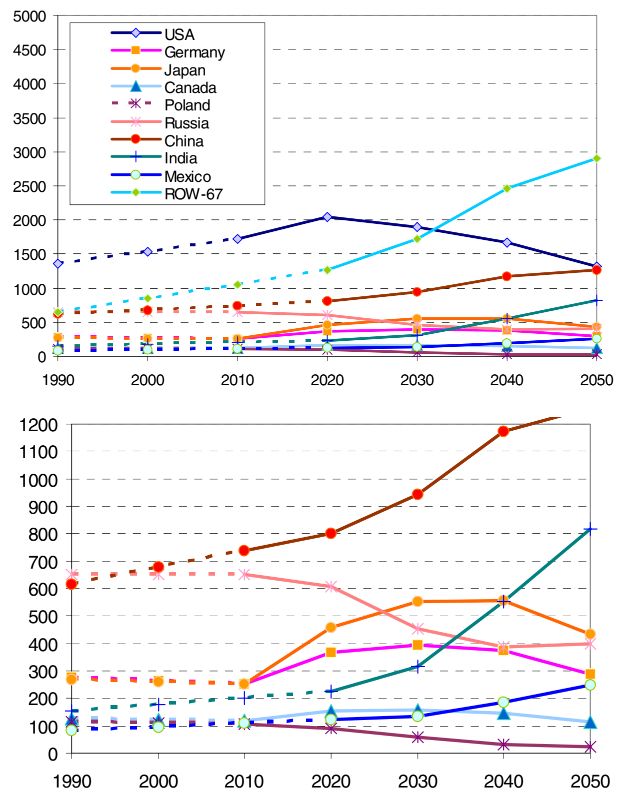

Figure 7: *Carbon intensity* approach: Emission entitlements for nine countries and ROW-67, (upper) and enlarged (lower), MtC.

The global emission entitlement per GDP in the year 2050 is calculated at 84 gC per US dollar (Table 7) using the GDP growth assumption adopted here. Although the *carbon intensity* approach gives equal entitlements in terms of carbon emission per GDP for all countries, the reduction rate of the carbon intensity differs from country to country, reflecting the differences in the 1990 level. For example, the 84 gC target for Japan implies only an 8% reduction of the 1990 carbon intensity whereas for China, the same target amounts to a 95% reduction. Reduction rates for Poland (96%) and Russia (88%) are also particularly high. Table 6 summarizes the percentage of the emission entitlement per GDP in 2050 of the selected countries compared with their 1990 levels.

Table 6: Percentage of the emission entitlement per GDP in 2050 compared with 1990 emission level per GDP.

USA	Germany	Japan	Canada	Poland	Russia	China	India	Mexico	ROW-67
34.3	50.6	92.3	38.4	4.4	12.4	5.3	16.7	26.1	30.4

4.2.3 A modified Triptych approach

Figure 8 shows the emission entitlements under our modified *Triptych* approach. For most of the regions except Poland, Russia and China, whose energy intensities were particularly high in 1990, the distributions of the entitlements were somewhat in between the other two approaches. All developed countries are allocated emission allowances below their 1990 emissions.

China receives the biggest emission entitlements both during the intermediate years and at the end year under this rule. Poland and Russia also have to reduce (16% and 19% respectively).

Figure 9, Figure 10, and Figure 11 show emission entitlements calculated for each country for electricity generation, industry, and the domestic sector, respectively. For the electricity sector (Figure 9), all countries receive CO_2 emission entitlements that increase compared to their 1990 emissions from this sector.

For developed countries, the emission allowance calculated for the electricity sector is the main source of emission entitlements. For example, Russia's allowance from this sector is 85% of the country's total.

For developing countries, emission entitlements for this sector increase significantly compared with 1990 emission levels. In particular, Mexico sees a significant increase in its entitlements compared with its 1990 emissions. In contrast, emission entitlements calculated for the industrial sector (Figure 10) show different pictures for developed and developing countries. Emission entitlements for four developed countries (Canada, Germany, Japan, and USA) in 2050 are calculated to be as low as between 6% and 9% of the level of their sectoral emissions in 1990. For Russia and Poland they are 20% and for Mexico and ROW-67, 80%. India and China receive very high emission entitlements for this sector compared with their 1990 levels (210% increase for China and 130% increase for India). For China in particular, the industry sector accounts for 37% of the national entitlement, a much higher percentage of the industry sector than that of other countries. Big differences in the reduction rates among countries are due partly to the difference in the industrial output growth rate, but mainly to allowed CO_2 intensity differences among countries (see Table 4). For example, for China, the target CO_2 intensity in 2050 is approximately the 1990 Japan level. In 2050, the difference in target CO_2 intensity between Japan and China is a factor of about 25.

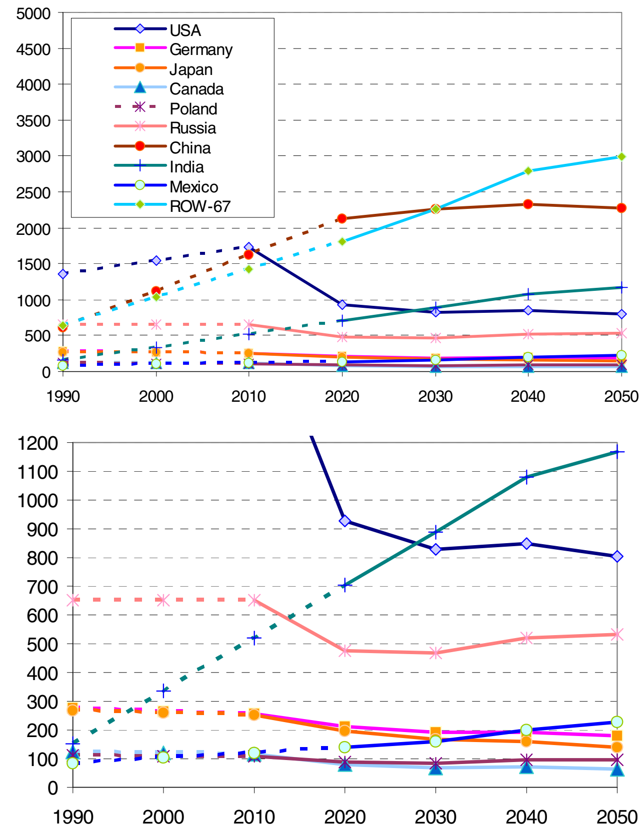

Figure 8: Modified *Triptych* approach: Emission entitlements for nine countries and ROW-67 (upper) and detail (lower), MtC.

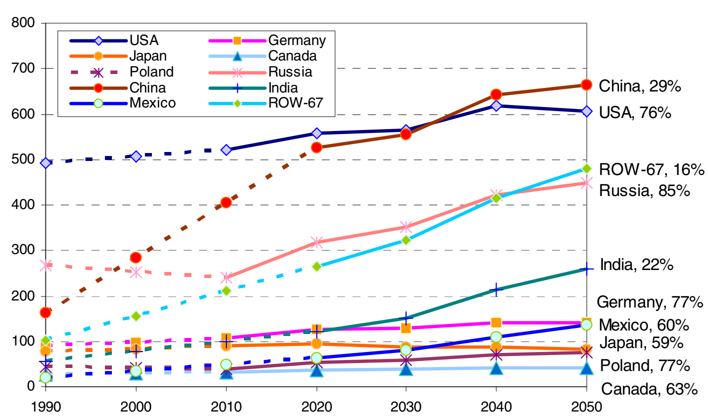

Figure 9: Modified *Triptych* approach, emission targets calculated for the electricity sector, in MtC. Percentages at the right refer to the share of power sector entitlements in the respective country total in 2050.

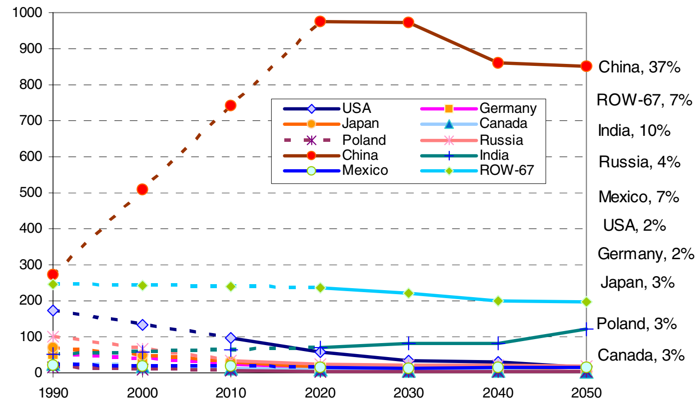

Figure 10: Modified *Triptych* approach, emission targets calculated for the industry sector, MtC. Percentages at the right refer to the share of the industry sector in national emission entitlements.

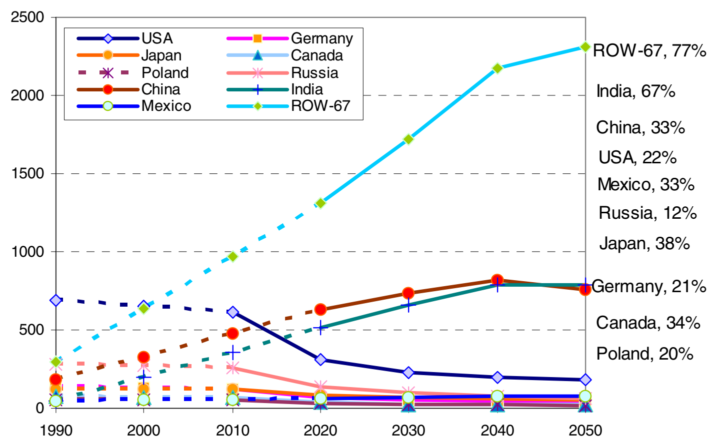

Figure 11: Modified *Triptych* approach, emission target calculated for domestic sector, MtC. The percentages on the right-hand side refer to the share of the domestic sector in the respective country total.

The global emission target for the domestic sector is the highest of the three sectors (recall Figure 4). As a consequence of the rule adopted for this sector, the resulting distribution of the emission entitlements to countries looks somewhat similar to those resulting from the *equal emissions per capita* approach (Figure 6). Developed countries, as well as transition countries, receive entitlements amounting to 22%-44% of their 1990 emission levels. India, ROW-67, and China in 2050 are allocated 764%, 464%, and 369% respectively of their 1990 emissions.

5 Comparing the Three Burden-sharing Rules from an Equity Perspective

In this section, we compare the emission entitlements according to the three selected rules and assess their equity implications. As we have argued above in Section 2, *egalitarian* equity can be related to per capita emission entitlement, and the emission entitlement per GDP can serve as an indicator of *horizontal* equity. Emission entitlements in terms of percentage change relative to 1990 reflect *proportional equality*.

We therefore base the following comparison of emission entitlements according to the three selected burden-sharing rules (equal entitlements per capita, equal entitlements per GDP, and Triptych) one at a time on the three indicators: (i) entitlements relative to 1990 emission; (ii) per capita entitlement; and (iii) entitlement per unit of GDP. To keep this comparison within reasonable limits, we restrict ourselves to nine typical countries and to the largest world region, ROW-76. We add graphical illustrations using the three indicators here. In order to avoid too much duplication we provide in the appendix a four-part table (Table 7) with absolute entitlements (in MtC) and entitlements expressed with the three indicators.

5.1 Calculated carbon emission entitlements and egalitarian equity

Because of the one-to-one correspondence between the egalitarian equity and the emissions per capita indicator, it seems obvious to begin the comparison with this indicator. We shall therefore look at Figure 12, which shows the entitlements per capita according to all three rules. The corresponding numerical values are given in Table 7(c).

In 1990, average global CO_2 emissions were 1.1 tC per person, with India (0.2 tC) on the low end and the USA (5.3 tC) on the high end of the 9 selected countries and ROW-67. All developing countries were below the global average level in 1990. To grandfather these would obviously not be equitable under the egalitarian principle.

The global per capita emission entitlement in 2050 is 1.08 tC per year under the assumptions on population growth and carbon emissions adopted here. The largest deviation from this value is for India under the *carbon intensity* rule (0.53 tC). On the high side, the largest deviation is for Russia under *Triptych* with 4.4 tC.

Before 2050, the per capita emission entitlements of India and ROW-67 remain below the global average level under all three rules. The *carbon intensity* rule gives a wider range of emission entitlements per capita than the *Triptych* approach. The ratio between the highest and the lowest emission entitlements under the *Triptych* rule in 2050 is 3.9, but this excludes Russia, whose entitlement comes out rather high (at 4.4 tC per capita): the result of higher emission entitlements allocated to the electricity sector.

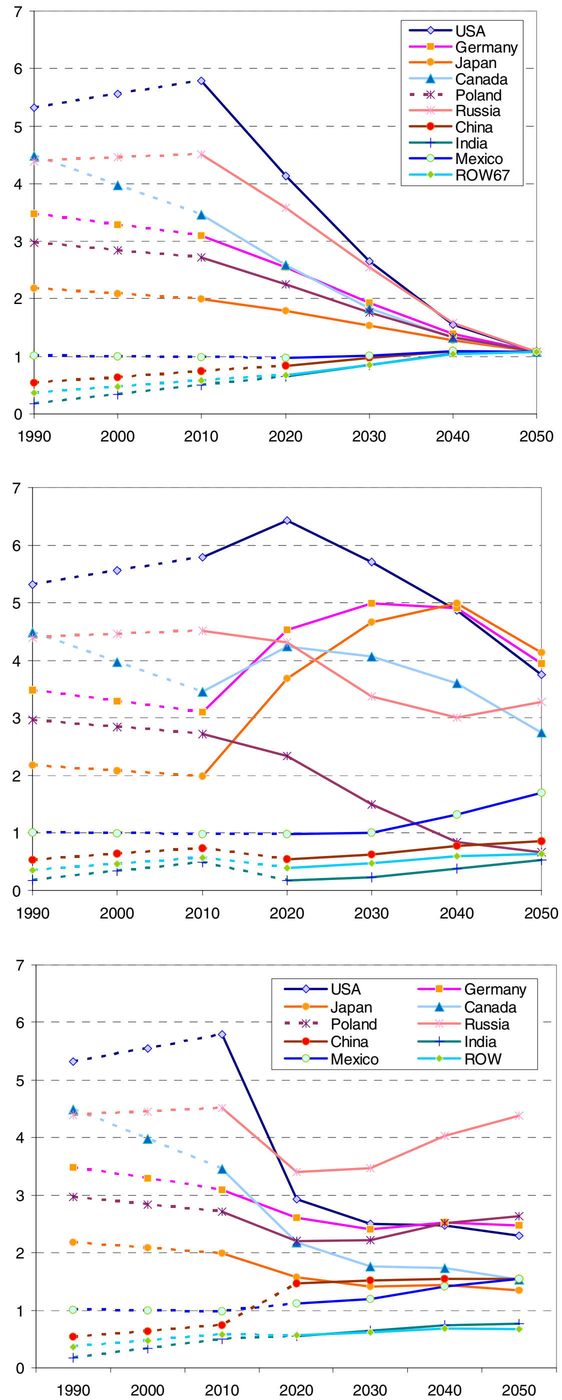

Figure 12: Comparing emission entitlements per capita, in tC per year per capita. Entitlements under the *equal emissions per capita* rule, the *carbon intensity* approach, and the modified *Triptych* approach from top to bottom for 10 countries and regions).

5.2 Calculated carbon emission entitlements and horizontal equity

As we mentioned above, equal carbon emission entitlements reflect the *horizontal-equity principle*, which postulates an equal burden for all. How well this principle is reflected by the carbon-intensity indicator can be discussed, but we believe that expressing emission entitlements relative to GDP allows horizontal equity to be discussed as fully as it can be within the scope of this paper. We therefore present, in Figure 13, the entitlements per unit of GDP according to all three rules. The corresponding numerical values are given in Table 7 (d).

In 1990, the average global carbon intensity of GDP was of the order of 256 tons of carbon (tC) per million US dollars. Perhaps it would be more indicative to say 256 grams of carbon per US dollar (gC/US$). Of the nine countries and ROW-67, which we selected for this comparison, Japan was the most carbon-efficient (with 91 gC/US$), followed by Germany (165 gC/US$), Canada (218 gC/US$), and the USA (243 gC/US$). Poland and China had by far the highest CO_2 emission per GDP (1919 and 1692 gC/US$ respectively). Russia, India, Mexico also had rather high carbon intensities of GDP in 1990 (674, 500, and 320 gC/US$ respectively). ROW-67 emissions per unit of GDP were not much bigger than those of the USA (275 gC/US$).

Under the assumptions on economic growth and carbon emissions adopted here, the aggregate global carbon emission entitlement per unit of GDP in the year 2050 is 83.6 gC/US$. This value determines the carbon emission entitlements under the *carbon intensity* rule in 2050 for all countries and regions by definition, and carbon emission entitlements per GDP converge in 2050.

The second best (after the *carbon intensity* rule) in terms of horizontal equity – expressed as equal carbon intensity of GDP – is the *Triptych* approach which in 2050 leads to a factor of 6 between the highest and the lowest carbon intensities of the nine countries and ROW-67. For the *equal emissions per capita* approach, this factor is 8, which is still considerably lower than in 1990, when it equaled 20. Still, horizontal equity does not score well in either of the other two rules.

In absolute terms, under the *equal emissions per capita* rule, the industrialized countries USA, Germany, and Japan are allowed carbon intensities not much higher than 20 gC/US$. For the USA, this value amounts to a reduction by a factor of 10 between 1990 and 2050, which averages an annual reduction rate of 3.8%? For Japan, which began with 91 gC/US$ in 1990, the reduction is relatively smaller, but still implies an average annual rate of 2.4%

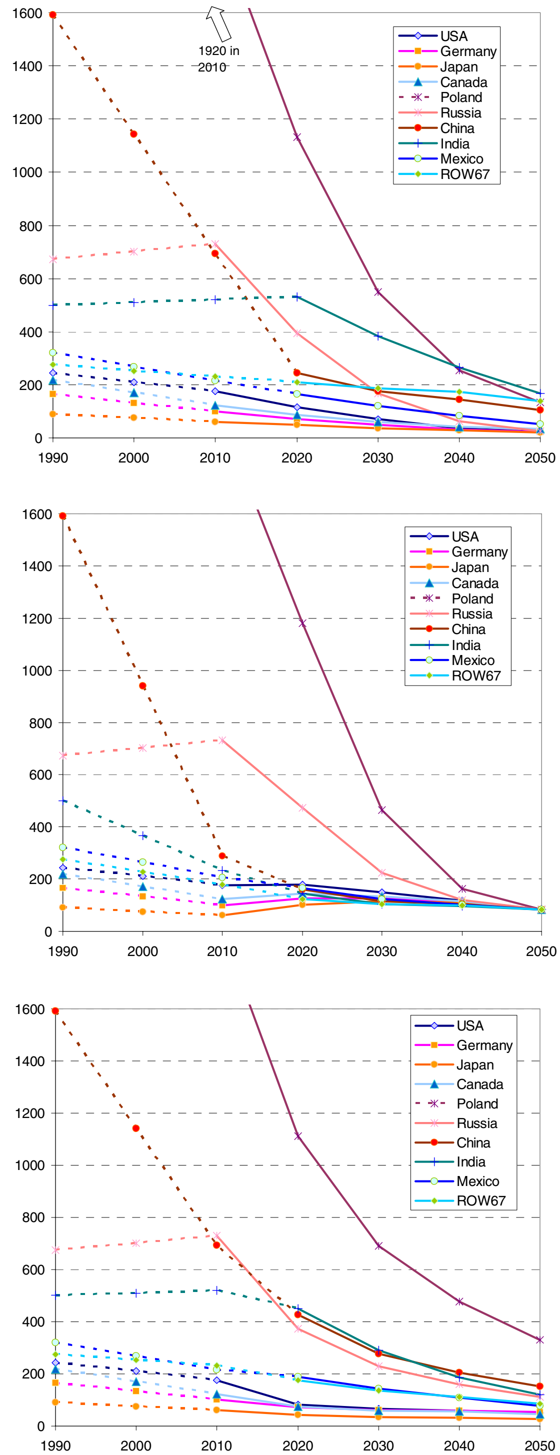

Figure 13: Comparing emission entitlement per GDP, in gC/US$. Entitlements under the *equal emissions per capita* rule, the *carbon intensity* approach, and the modified *Triptych* approach from top to bottom for 10 countries and regions).

5.3 Calculated carbon emission entitlements and proportional equality

As an indicator of *proportional equality* we now present in Figure 14 the emission entitlements according to the three burden-sharing rules relative to actual 1990 emissions. Let us note here that these are the "units" of reduction used in the Kyoto Protocol.

None of the three rules analyzed here implies similar percentage reductions across all countries. The modified *Triptych* rule leads to less discrepancy in this indicator (measured as the ratio between the highest and lowest numbers), which falls between 52% (Japan, Canada) and 764% (India) in 2050. Moreover, India has the highest entitlements (in terms of 1990 emissions) of the 10 countries and regions under all three rules.

Looking separately at developing and developed regions, we find that, within both, the modified *Triptych* approach results in rather similar reduction rates across developed countries (USA, Germany, Japan, Canada, Poland, and Russia) and across developing regions (China, India, Mexico and ROW-67).

The USA, Germany, Japan, and Canada receive either higher or lower emission entitlements compared to 1990 depending on the rule. Under the *equal emission per capita* rule, these countries must reduce their CO_2 emission to 30%-40% of their 1990 levels by 2050. The *carbon intensity* approach allows fewer emissions for developing countries and more for developed countries compared to the other two approaches, in particular during the intermediate years.

The transition countries Poland and Russia are prescribed particularly strict emission reductions compared to 1990 under the *equal emissions per capita* approach and the *carbon intensity* approach.

India, China, Mexico, and ROW-67 are allocated increases in CO_2 emissions compared to 1990 under all three rules. In particular, under the *equal emission per capita* rule, India and ROW-67 are allowed significant increases in CO_2 emissions compared to 1990.

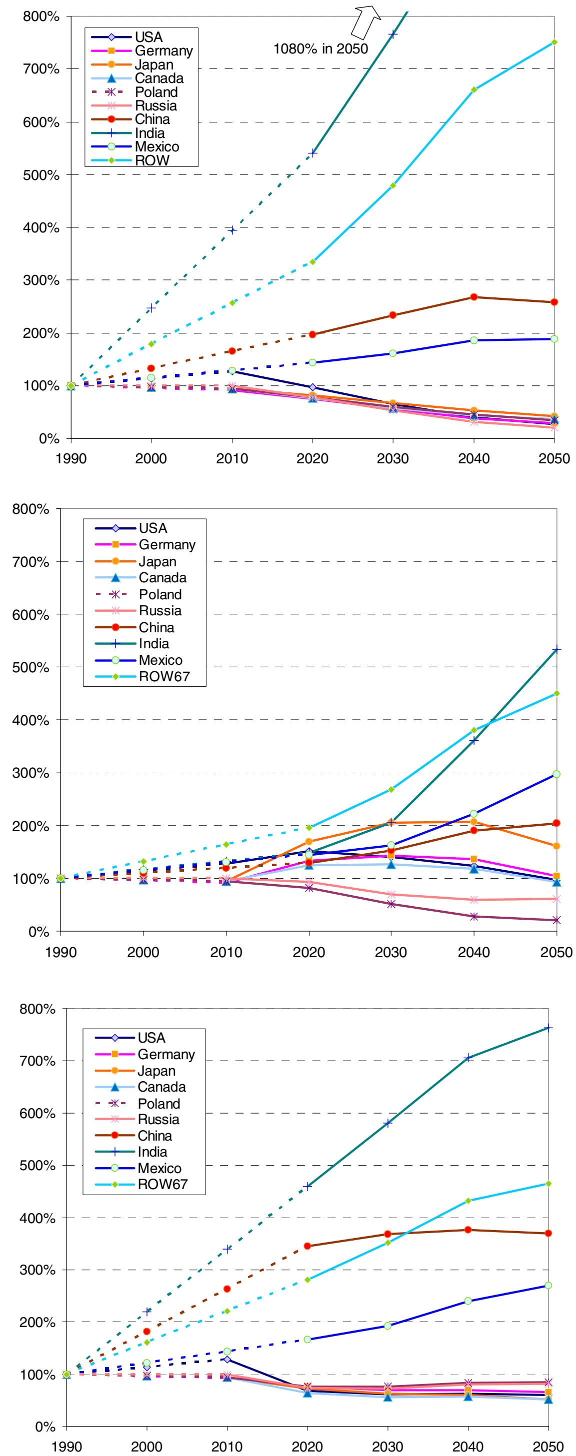

Figure 14: Comparing emission entitlements relative to 1990 emissions. Entitlements under the *equal emissions per capita* rule, the *carbon intensity* approach, and the modified *Triptych* approach from top to bottom for 10 countries and regions). Units: 1990=100%.

5.4 Comparison from a country perspective

So far in this section, we have assessed the three burden-sharing rules from an equity perspective. In terms of political acceptability, the size of the burden (cost) that is inflicted on any country under a given rule will also be an important matter. Although here, the maximum permitted carbon intensity can be regarded as an indicator of the economic burden implied by a rule, we think that a better approximation of the to-be-expected burden is the comparison with business-as-usual emissions.

As we have used the MERGE model for producing a global carbon emission trajectory consistent with atmospheric CO_2 concentrations that also remain below 550ppmv in the long run, we use the same model for a comparison between unconstrained world-regional emissions and entitlements according to the three rules. Figure 15 show cumulative business-as-usual emissions between 1990 and 2050 as well as cumulative entitlements according to the three rules. To emphasize the difference, we also show the cumulative entitlements as a fraction of cumulative business-as-usual emissions in Figure 16. Using a MERGE scenario naturally means that we carry out this assessment for the nine world regions considered by that model.

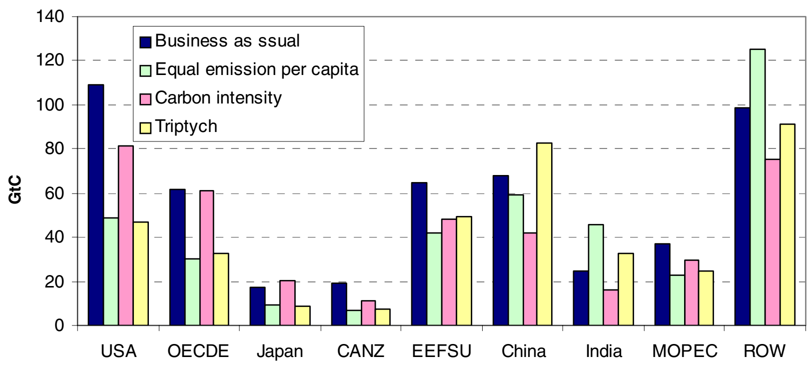

Figure 15: Cumulative CO_2 emissions in the business-as-usual (BAU) case and cumulative emission entitlements calculated under the three rules, GtC.

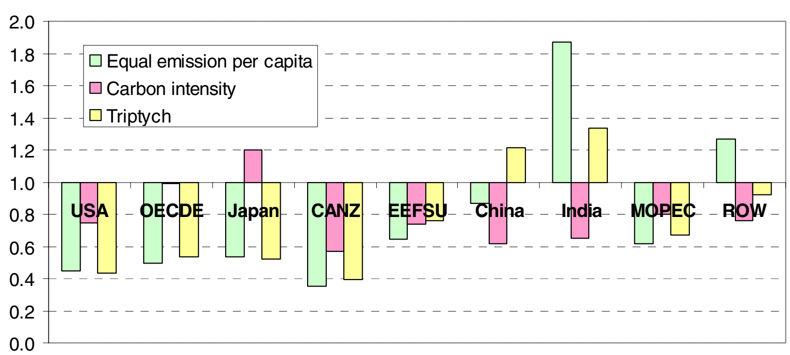

Figure 16: Cumulative emission entitlements calculated under the three rules as fractions of cumulative business-as-usual CO_2 emissions.

In "post-Kyoto language", the implementation of any of the three schemes would create "hot air". Curiously perhaps, the *carbon intensity* rule would allocate more entitlements than BAU emissions to one industrialized country, i.e., Japan. This is because emissions projected in MERGE for Japan in 2050 are lower than those in 1990. The mirror image of this result holds for India, which would be allocated more emissions than needed by the other two rules (*equal emissions per capita* and *Triptych*). The *Triptych* approach also creates hot air for China, and *equal emissions per capita* for the ROW region.

For the countries and regions of the OECD, the *carbon intensity* rule clearly is the most advantageous, and the difference between the other two rules (*equal emissions per capita* and *Triptych*) is comparatively minor. No such disparity between these two rules can be claimed for the developing countries: India and ROW should prefer *equal emissions per capita*, whereas China and MOPEC should prefer *Triptych*. The *carbon intensity* rule is also clearly the least advantageous for China, India, and ROW. The least differences in entitlements have been calculated for the reforming economies (EEFSU). All three rules lead to reductions of BAU emissions. The most severe reductions are specified by *equal emissions per capita*, followed by *carbon intensity* and *Triptych*.

6 Summary and Conclusions

Equity and fairness figure explicitly in the UNFCCC, and they must be considered important criteria for any future agreements by Parties to the UNFCCC on how jointly to avert dangerous human interference with the global climate. Accordingly, several authors have presented different equity principles and discussed their implications for sharing the burden of global climate mitigation.

In some cases authors have used equity principles to formulate emission allocation rules. In other studies, rules were proposed first and equity principles were used to assess them. In this connection, it is important to note that equity principles and burden-sharing rules do not correspond in a one-to-one manner: one rule may contain several aspects of equity and one equity principle can be reflected in different rules at the same time.

For this paper, we first surveyed equity principles and different schemes of allocating emission entitlements to countries proposed in the relevant literature and then systematically related them to each other. We found that in doing so, it is useful to use three concepts as "red threads" to organize the discussion of equity. The first is to interpret equity as an equal right for everyone to pollute or, equivalently, to enjoy a pollution-free atmosphere (egalitarian equity). This concept leads in a straightforward way to a rule that allocates equal emissions to each person. The second concept is that of horizontal equity which conceptually aims at an equal distribution of welfare loss due to climate mitigation. The third concept is that of proportional equality, which supports one of the more popular burden-sharing rules, i.e., proportional cutbacks of base-year emissions (grandfathering).

Another important aspect that complements the three concepts is vertical equity. Vertical equity describes the idea of progressive burden allocation, for instance progressively higher taxes imposed on higher incomes. Vertical equity thus takes ability to pay into account.

Mathematically speaking, horizontal equity is a linear concept whereas vertical equity is a non linear one. As there are many more nonlinear than linear functions, it is understandable that horizontal equity plays a dominant role in those schemes that distribute joint emission limits to a number of countries of comparable wealth. Such an approach is the *Triptych* approach, originally proposed for the countries of the European Union. Although there, the disparity among countries is smaller than the disparity worldwide, provisions were specified to accommodate the special situation of the "cohesion" countries – Greece, Spain, Portugal and Ireland. Specifying such provisions can be seen as adding vertical equity to a horizontally equitable scheme. Attempting to follow a similar strategy during the design of global schemes would obviously be a major and challenging task.

Looking at the issue of equal rights to emit and equal percentage reduction of emissions, it is plain that the *equal emissions per capita* rule turns out to be more vertically equitable than any version of the *grandfathering* rule because it puts a greater mitigation burden on those countries that emit more and whose ability to pay is greater.

Suggesting equal permission rights for each person, given its simplicity and its appeal to the equity of all individuals, may convince many that this is the most appropriate guiding principle for allocating emission rights. Political reality prevents the straightforward implementation of this approach, however, because the approach implies huge reduction commitments for industrialized and nonbinding commitments to developing countries; moreover, the argument for equal burdens will weigh heavily for high-emission countries. Would this then mean that political reality will render equity principles superfluous? Not at all. In our opinion, it means simply that equity and political feasibility can be considered as two conflicting objectives, and that each proposed scheme of burden sharing will be evaluated in terms of both. Let us also note that public acceptance of any rule also depends on how equitable it is perceived to be.

Conflicting objectives were of course well-known even before climate change was on the international political agenda. One problem with equity, however, is that it is difficult to measure unambiguously – if it is possible at all. This ambiguity may be considered analytically more difficult, but, at the same time, it also presents an opportunity for international negotiations because, at least conceivably, equity principles can be combined to lead to many different outcomes in terms of emission allocations. This possibility of "bundling" equity principles quite naturally increases the number of possible agreements and therefore the likelihood of international negotiators agreeing on a set of equity principles that lead to politically feasible agreements of global burden sharing.

This paper gives an indication of the ranges of emission entitlements that could be supported by different equity principles. No attempt was made here to propose a "compromise" that attempts to balance the arguments for and against each principle. That would, in our opinion, not only be futile, but also interfere unduly with the job of international negotiators. We regarded it as our job to do the analysis and as the negotiators' job to do the assessment in terms of political reality.

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Appendix

Table 7. Summary of indicators related to emission entitlement for 10 countries and region based on three principles.

(a) Emission entitlement (MtC)

	1990	2020			2050		
		EPC	CI	TRIP	EPC	CI	TRIP
USA	1352	1312	2040	928	377	1313	802
Germany	276	206	366	211	79	289	182
Japan	269	221	456	195	113	434	140
Canada	125	95	156	80	46	116	65
Poland	113	88	92	87	39	24	96
Russia	651	504	606	477	131	397	530
China	617	1214	800	2128	1593	1261	2277
India	153	828	227	702	1648	817	1168
Mexico	84	120	122	139	158	250	227
ROW-67	644	2158	1260	1809	4841	2897	2990

(b) Emission entitlement in terms of percentage reduction/increase relative to 1990

	1990	2020			2050		
		EPC	CI	TRIP	EPC	CI	TRIP
USA	100	97	151	69	28	97	59
Germany	100	75	133	76	29	105	66
Japan	100	82	170	73	42	161	52
Canada	100	76	125	64	37	93	52
Poland	100	78	81	77	35	21	84
Russia	100	77	93	73	20	61	81
China	100	197	130	345	258	204	369
India	100	541	148	459	1077	534	764
Mexico	100	143	145	166	188	297	270
ROW	100	335	196	281	752	450	464

(c) Emission entitlement per population (tC per person)

	1990	2020			2050		
		EPC	CI	TRIP	EPC	CI	TRIP
USA	5.32	4.14	6.43	2.93	1.08	3.76	2.30
Germany	3.48	2.54	4.52	2.60	1.08	3.95	2.48
Japan	2.18	1.79	3.68	1.58	1.08	4.13	1.34
Canada	4.49	2.59	4.24	2.17	1.08	2.74	1.53
Poland	2.97	2.25	2.34	2.20	1.08	0.67	2.64
Russia	4.39	3.58	4.31	3.39	1.08	3.27	4.37
China	0.53	0.83	0.55	1.46	1.08	0.85	1.54
India	0.18	0.65	0.18	0.55	1.08	0.53	0.76
Mexico	1.01	0.96	0.97	1.11	1.08	1.70	1.55
ROW	0.36	0.68	0.40	0.57	1.08	0.65	0.67

(d) Emission entitlement per GDP (tC per million US dollar)

	1990	2020			2050		
		EPC	CI	TRIP	EPC	CI	TRIP
USA	243.4	115.3	179.3	81.6	24.0	83.6	51.1
Germany	165.2	71.3	126.8	72.9	22.8	83.6	52.5
Japan	90.6	48.6	100.2	42.9	21.8	83.6	27.1
Canada	217.8	87.6	143.7	73.5	32.9	83.6	46.6
Poland	1918.8	1132.5	1181.6	1111.4	135.1	83.6	330.3
Russia	673.5	394.0	474.1	373.2	27.5	83.6	111.7
China	1591.1	243.4	160.4	426.5	105.6	83.6	151.0
India	500.1	531.0	145.5	450.7	168.7	83.6	119.6
Mexico	319.7	164.9	166.6	190.6	53.0	83.6	76.0
ROW	274.6	210.4	122.8	176.4	139.7	83.6	86.3