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Abstract

Our research examines a permit trading system where all countries participate to achieve a long-term greenhouse gases (GHG) stabilization target. Our main objective is to propose allocation schemes that lead to a fair distribution of net abatement costs among world regions. These costs are good indicators of the need to emit of regions and their opportunities to abate, two criteria that are intuitively appealing, but are difficult to translate into straightforward indicators. These allocation schemes therefore complement the ones based on the more often proposed allocation criteria (population, gross domestic product (GDP), etc.). The World-MARKAL model is used to model the stabilization scenario and to calculate the regional abatement costs which are the basis for the proposed allocations. The optimal solution of the model (before permit trading), as well as the net abatement costs of regions (including permit trading), are presented. Some sensitivity analyses are discussed.

Keywords: Equity, Energy, GHG permit allocations, Abatement costs, World-MARKAL model, Burden sharing.

Résumé

Notre recherche se situe dans un contexte de permis échangeables où tous les pays participent à la réduction pour atteindre une cible de stabilisation des gaz à effet de serre (GES) à long terme. Notre objectif principal est de proposer des schémas d'attribution qui mènent à une distribution équitable des coûts nets de réduction entre les régions du monde. Ces coûts sont de bons indicateurs des besoins d'émettre des régions et de leurs opportunités de réduction, deux critères qui sont difficiles à traduire en indicateurs simples. Ces schémas d'attribution complètent donc ceux basés sur les critères d'attribution traditionnels (population, produit intérieur brut (PIB), etc.). Le modèle MARKAL-Mondial est utilisé pour modéliser le scénario de stabilisation et pour calculer les coûts régionaux de réduction qui servent de base aux attributions proposées. La solution optimale du modèle (avant échanges de permis), ainsi que les coûts nets de réduction (après échanges de permis), sont présentés. Des analyses de sensibilité sont discutées.

1 Introduction

Currently, the United Nations Framework Convention on Climate Change, the objective of which is the stabilization of GHG concentrations in the atmosphere, is the only legal agreement related to climate change mitigation. As for the Protocol of Kyoto, it is still not into force, because it must be ratified by 55 countries whose emissions accounted for at least 55% of the 1990 emissions (UNFCCC, 1997). Currently, 122 countries have ratified the protocol, adding up to 44.2% of the 1990 emissions[1]. A debate between the developed and the developing countries about the next steps in the formulation of climate policies has already begun at the COP8 conference, which took place in New Delhi in 2002 (IISD, 2002). The participation of the developing countries appears to be essential to reach the convention target; their fast economic growth will lead to a considerable increase of their emissions in the next decades.

Our research takes place in a global cooperation context assuming the participation of all countries to achieve a long-term stabilization target (550 parts par million volume (ppmv) by 2100). International cooperation mechanisms, such as a permit trading system, can help achieve global economic efficiency. However, the initial allocation of emission permits raises many debates on equity. Our main objective is to propose permit allocation schemes that lead to a fair distribution of net abatement costs among regions. The World-MARKAL model is used to model a stabilization scenario, and consequently, to calculate the gross abatement cost of each region in a cost-effective solution (how much to reduce in which region at a global minimal cost).

Section 2 introduces the equity issues relative to permit allocations and burden sharing. The following Section 3 presents the allocation methodology, and the World-MARKAL model used to calculate the gross abatement costs (before permit trading) of regions. The results are presented in Section 4: the efficient solution proposed by MARKAL (4.1), the allocation schemes and the net abatement costs (including permit trading) of regions (4.2), and some sensitivity analyses (4.3). The article ends with a conclusion on the main advantages and disadvantages of this approach (Section 5).

2 Equity issues

Many equity principles and criteria have been proposed to allocate emission rights/permits (egalitarianism, polluter pays, historical responsibility, ability to pay, grandfathering, etc.) or abatement costs (horizontality, verticality, comparable costs, etc.) (Aaheim, 1999; Banuri *et al*, 1996; Barrett, 1992; Bayer, 1999; Blanchard *et al*, 1998, 2000; Grubb *et al* 1992; Rayner *et al*, 1999; Rose et Stevens, 1993; Rose *et al*, 1998; Torvanger and Godal, 1999). Authors also presented several allocation proposals during the pre-Kyoto period. Today, more and more

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[1] As on April 15th, 2004. See the official website of the UNFCCC (http://www.unfccc.int) for the status of ratification.

authors are interested in long-term stabilization scenarios involving the participation of all countries (Berk and Den Elzen, 2001 Den Elzen *et al*, 1999; Gupta and Bhandari, 1999; Onigkeit and Alcamo, 2000; Shukla, 1999).

Among others, a decision aid tool has been proposed to provide to the decision makers relevant information on various equitable permit allocation schemes (Vaillancourt, 2003; Vaillancourt and Waaub, 2003; 2004). A dynamic multicriterion model is used to share a global quantity of permits between 15 world regions using 11 allocation criteria, which represent different visions of equity. Several options of weight sets are considered (a weight represents the relative importance one grants to a criterion), in order to simulate various points of view about equity. It provides relevant information to decision-makers. However, the subsequent economic analysis revealed unacceptable cost distributions in some cases; some regions become wealthier in the stabilization context than they would be otherwise (status quo).

This is possibly because the list of criteria is not exhaustive with regard to the economic impacts of the permit allocation schemes. In particular, the traditional criteria do not adequately reflect the regional differences in the need to emit and the opportunities to abate, two criteria that should also be considered for permit allocations. However, these criteria are difficult to take into account at the same level as the other criteria, since it is not easy to translate them into straightforward indicators. They depend upon a complex interaction of multiple factors. We now elaborate on these affirmations.

The need to emit depends upon diverse factors that evolve over time, including climate, geography, structure of the economy, level of economic development, demographic profile and domestic energy resources. The traditional criteria, such as population and GDP, do not adequately reflect these factors, especially in the context of widely different economies. For instance, population per se is not an adequate measure of the need to emit. Only the emissions resulting from a population's real needs at each period of its development are relevant. Let us examine the example of Canada and Morocco, two countries with similar populations. We observe two large differences in their needs to emit: space conditioning and average transportation distances. Looking at the options available: space heating can use oil, gas, electricity, or wood. Electricity is the only option for space cooling. Finally, not all people in Morocco have access to energy intensive amenities now, but they will surely do at some point in the future. Similarly, GDP may not accurately reflect emission needs. Consider country A, with a GDP mainly composed of a service sector, and country B, with similar GDP value, where conventional industry has a significant share. If permits were allocated based on GDP, A and B would get equal amounts, and A would make money by selling some of them to B. Is that fair? Country A developed its service sector in pursuit of its own welfare, not to reduce GHG emissions. In summary, there is a very complex network of forces evolving over time, which determines the business-as-usual (BAU) emission of countries.

The opportunity to abate is based on the resource endowment and inertia of the infrastructure; different countries have different abatement potentials. For example, a region may have untapped hydro electricity potential, while another may have already developed its own potential. A region may have poor industrial equipment and practices, leaving room for efficiency gains, while another may be much more efficient already, leaving less room for further improvement. A region may have a large coal based electricity system, with very low growth, while another may have an electricity system also dominated by coal, but growing rapidly. Since the latter region has the option to make alternate investments, its reductions over the BAU emissions will be cheaper. As in the case of need to emit, there are numerous interacting factors, which are hard to analyze in isolation from one another.

We describe an approach to address these two criteria more explicitly. We propose to use the net regional abatement costs (calculated by a global bottom-up energy model) as an indicator capturing these two criteria. Indeed, the model will allocate much reduction to a region where the need to emit is low and/or the abatement opportunities are large. Therefore, in an efficient reduction scheme, such a region would be assigned large reductions, and almost certainly large gross abatement costs. The equal cost criterion intervenes to allocate more emission rights to this region in order to reduce its net abatement cost so as to bring it in line with those of other regions. Conversely, regions with few abatement opportunities and large need to emit would not be assigned much reductions by the model, and should therefore receive comparatively fewer emission rights.

Another advantage of the equal cost criterion is its face-value appeal, since it addresses directly the key issue of equitably spreading the burden of emission abatement. Although appealing, the equal cost criterion is not easy to introduce in a multicriterion approach such as the one followed in Vaillancourt and Waaub (2003), since the calculation of the indicator itself depends on the initial allocation (which is unknown at the outset), hence creating a circular equation. In this paper, allocation schemes based exclusively on a fair distribution of net costs are therefore proposed as a complement to allocation schemes based on other allocation criteria. Implicitly, these schemes are conceived to avoid the negative costs.

3 Methodology

This section explains the methodology used to allocate permits (3.1) and presents the World MARKAL energy model used to calculate the gross regional abatement costs (3.2).

3.1 The two allocation schemes

Two permit allocation schemes are proposed in this paper. At each period, the objective is to equalize either the net abatement costs per unit of GDP-ppp (purchase power parity) or and the net abatement cost per unit of GDP-ppp Squared. The first scheme (S-GDP) respects the horizontality principle, since it equalizes the net costs across regions as a percent of GDP. The second scheme (S-GDP2) reflects the verticality principle, since it aims at allowing more permits to the poorest regions, those for which the GDP is the lowest**.**

The model is first run without constraint on emissions, to obtain the system's reference cost, and then run with a global constraint on emissions to obtain the optimal (efficient) emission level E_i (t) and the new system cost. The gross abatement cost $C_j(t)$ of each region is the difference between the two system costs. The net abatement cost $x_i(t)$ is defined as the gross abatement cost $C_j(t)$ plus the cost of buying permits (which depends on the allocation of emission rights and may be positive or negative), i.e.:

$$x_i(t) = C_i(t) + y_i(t) \cdot P_W(t) \tag{1}$$

Where $y_i(t)$ is the (as yet unknown) quantity of permits purchased by region i, and $P_W(t)$ is the price of permits (computed by the model). Note that the global net abatement cost is equal to the global gross abatement cost $C_W(t)$ provided by the model. In order to equalize net abatement costs per GDP across regions, the following equations must be satisfied:

$$\frac{x_i(t)}{GDP_i(t)} = \frac{x_j(t)}{GDP_j(t)} = \frac{x_k(t)}{GDP_k(t)} = \frac{\sum_i x_i(t)}{\sum_i GDP_i(t)} = \frac{C_w(t)}{GDP_w(t)} = K \tag{2}$$

i.e.

$$x_i(t) = K \cdot GDP_i(t) \tag{3}$$

or, using (1) above

$$y_i(t) = \frac{1}{P_W(t)}\left[K \cdot GDP_i(t) - C_i(t)\right] \tag{4}$$

Finally, the allocation of rights $a_i(t)$ to region i is equal to the emissions plus permits sold:

$$a_i(t) = E_i(t) - y_i(t) \tag{5}$$

For the second allocation scheme S-GDP2, replace GDP by GDP^2 throughout.

3.2 The World-MARKAL energy model

The equations of the initial MARKAL model appear in Fishbone and Abilock (1981). Since then, many improved versions of the model have been developed for various applications. Currently, different MARKAL models are used in more than 75 institutions and 40 countries for various purposes including economic analysis of climate policies (Kram 1995; 1999).

MARKAL is a linear programming model that represents the entire energy system of a country or a region (Kanudia and Loulou, 1998; 1999; Loulou and Kanudia, 1998). Such a system includes the extraction, transformation, distribution and end-uses of various energy forms and some materials. MARKAL computes a dynamic inter-temporal partial equilibrium on energy markets. End-use demands in the base case are based on socio-economic assumptions and are specified exogenously by the user in physical units (number of houses, commercial area, industrial production, vehicle-kilometers, etc.) over a 50-year horizon. However, contrary to traditional bottom-up models, MARKAL acknowledges that demands are elastic to their own prices. This feature allows the endogenous variation of the demands in constrained runs (e.g. runs with emission constraints).

Each economic sector is described by means of technologies, each of which characterized by its economic parameters (various costs) and its technological parameters (capacity, activity, fuels consumed and produced, efficiency, date of first availability, technical life, etc). The objective function to maximize is the total surplus. This is equivalent to minimizing the total discounted system cost, while respecting environmental constraints. This cost includes investment costs, operation and maintenance costs, plus the costs of imported fuels, minus the incomes of exported fuels, minus the residual value of technologies at the end of the horizon, plus the welfare loss due to endogenous demand reductions. Emission reduction is brought about by technology and fuel substitution, which lead to efficiency improvements and process changes in all sectors, as well as by demand reductions. The main model outputs are future investments and activities of technologies at each period. An additional output of the model is the implicit price of each energy form, material and emission, which is equal to its opportunity cost (shadow price).

The objective function of the World-MARKAL model is the sum of the system costs of individual regions. Costs are expressed in US$ and discounted at 5% to year 2000, in all regions. The model is disaggregated into 15 regions: United States (USA), Canada (CAN), Mexico (MEX), China (CHI), India (IND), Japan (JPN), South Korea (SKO), Australia-New-Zealand (AUS), Western Europe (WEU), Eastern Europe (EEU), Former Soviet Union (FSU), Africa (AFR), Central and South America (CSA), Other Developing Asia (ODA) and Middle-East (MEA). The model is run over a 55-year horizon (1998-2052), divided into 11 five-year periods, centered in 2000, 2005, …, 2050. Fig. 1 illustrates the reference energy system of a region in the World-MARKAL model. The number of technologies in brackets illustrates the level of detail of this global model.

The energy production sector is represented by three distinct blocks: primary production, secondary transformation, and production of electricity and heat. Primary production delivers the raw fossil fuels: crude oil, natural gas, and coal. This block also contains the source of renewable energy and biomass. Secondary transformation transforms the primary energy forms into fuels for end-use sectors. The technology representation in these two blocks is generic. The primary production of each primary energy carrier is configured as a 3-step supply curve, and the secondary transformation section mainly relies on a flexible refinery technology. However, the production of electricity and heat is technologically explicit. Electricity production (and consumption) is tracked in three seasons and two divisions of the day, resulting in six time slices annually. Heat is tracked by season. Fuels produced and consumed in each sector generally represent a mix of different energy commodities (e.g. a mix of distillates, gasoline and other oil products for the residential sector).

For each region, 42 demand segments cover five energy consumption sectors: residential (11 segments), commercial (8 segments), agriculture (1 segment), industrial (6 segments) and transportation (16 segments). Each demand segment is serviced by end-use technologies, whose number varies depending on the segment (see Fig. 1 for the number of technologies and segments in each demand sector).

The model tracks emissions of CO_2, CH_4, and N_2O from the energy system. Combustion emissions are based on the fuel inputs of technologies. For fugitive emissions (due to losses and venting) and emissions related to non-energy consumption (like feedstock), specific emission coefficients are specified at the technology level. In this study, only CO_2 emissions from fossil fuel combustion and industrial processes are considered.

The base period (2000) of the model is calibrated to the International Energy Agency (IEA, 2000) statistics and balances of year 2000, and the future energy-emission trajectory is based on the A1B reference scenario of IPCC (Nakicenovic and Swart, 2000). Under the reduction scenario, the 550 ppmv stabilization path was chosen. A global emission trajectory from the AIM model (Asia-Pacific Integrated Model) was used as a global emission constraint at each period. This trajectory is compatible with the stabilization of atmospheric CO_2 concentration at 550 ppmv. This stabilization level was chosen because it is the one most frequently used in the literature (Morita, 2000; Morita and Robinson, 2001).

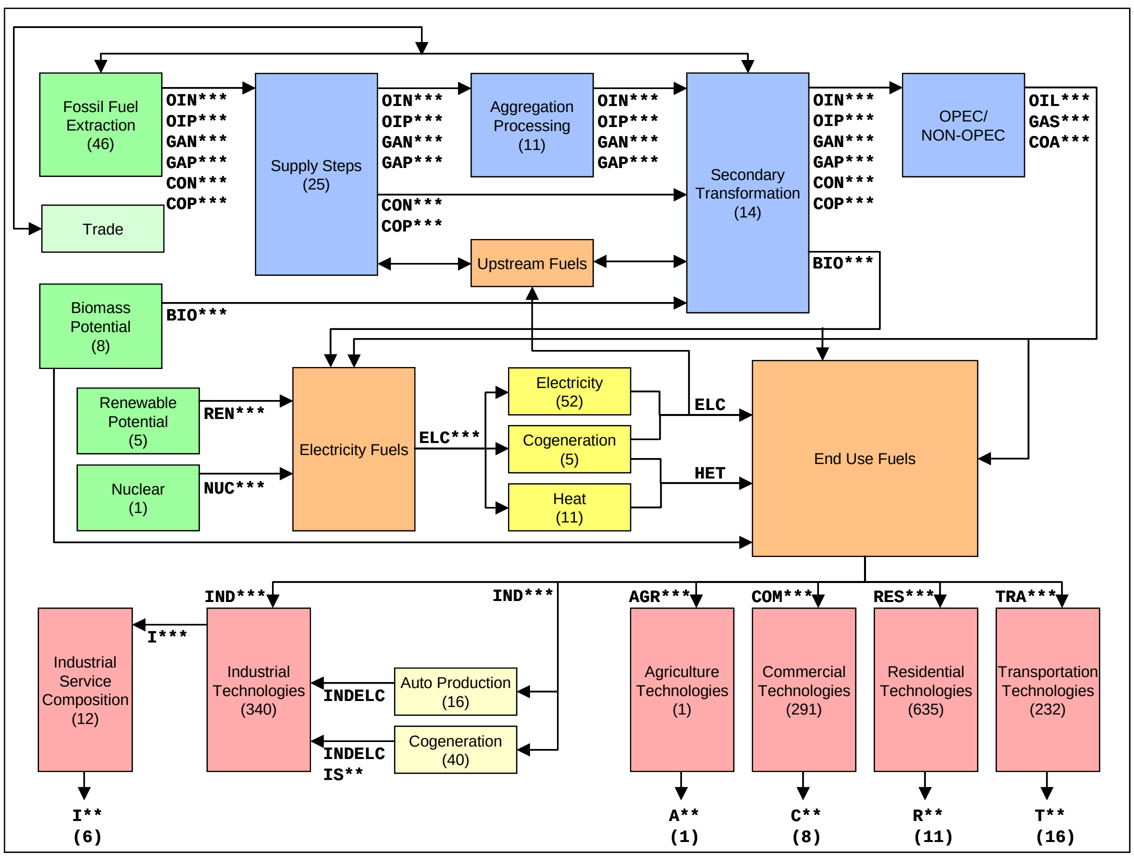

Figure 1: The reference energy system of a region in World-MARKAL

4 Results and discussion

The result section is divided in three parts. The first part (4.1) presents the efficient solution of the World-MARKAL model, i.e. emission reductions and gross abatement costs of regions. These results are obtained by comparing the results of the constrained scenario to those of the base scenario (excluding permit trading). The solution is globally optimal, irrespective of the allocations of permits, and makes it possible to determine the efficient emissions and the efficient gross abatement costs in each region. The second part (4.2) consists in calculating and analyzing the net abatement costs of regions (including permit trading), for both allocation schemes. These allocation schemes lead to situations where there are buyers and sellers of permits. The third part (4.3) contains results of sensitivity analyses on the measurement of GDP and on the stabilization path.

4.1 Emission reductions and gross costs

Global cooperation leads to the equalization of the marginal abatement costs across all regions. The world marginal costs ($/t), as well as the global percentages of reduction (%), are presented for each period in Table 1. The decrease in the marginal cost in 2020 is related to an increase of emissions in the AIM's stabilization trajectory, and consequently, a very low increase in the global percentage of reduction between 2010 and 2020: from 21% in 2010 to 24% in 2020. The increase in the marginal cost for the following periods is explained by higher percentages of reduction: 38% in 2030, 40% in 2040 and 45% in 2050, and by the continued increase in economic activity in all regions.

Table 1: World marginal abatement cost

Period	2000	2010	2020	2030	2040	2050
Marginal cost ($/t)	0	50	35	158	177	423
Global reduction (%)*	0	21	24	38	40	45

* The global reduction (%) is the relative difference between the emission of the base scenario (A1B) and that of the constrained scenario (stabilization at 550 ppmv).

The emission reductions in each region are presented in millions tons of carbon (MtC) in Table 2 for each period. This table also shows the cumulative percentages (%) of reduction, which represents the total quantities of emission reductions at the end of the time horizon. The last two columns relate to the gross abatement costs, discounted at the end of the time horizon, in billion dollars (G$) and per unit of GDP-ppp (%GDP). Since the marginal cost is equalized, the regions where the reductions are most important are generally those for which the gross cost is the highest. For the world, the emission reductions grows from 1950 MtC in 2010 (21%) to 6190 MtC in 2050 (45%), for a total discounted cost of 8043 G$. China and the United States are the regions where the reductions are the highest. However, the United States must bring significant reductions much earlier than China. The gross costs of these two regions are comparable and the highest, i.e. 1518 G$ for China and 1316 G$ for the United States. The Latin America (919 G$), Africa (767 G$) and the Middle East (746 G$) are also regions where the gross costs (and the reductions) are important. On the other hand, the gross cost per unit of GDP is higher for the Middle East (0.80%), Africa (0.73%), Mexico (0.69%) and the FSU (0.61%).

Table 2: Emission reductions and gross costs from World-MARKAL

	Emission reduction (MtC)							**Gross cost**	
Period	**2000**	**2010**	**2020**	**2030**	**2040**	**2050**	**%cum**	**G$**	**% GDP***
Africa	0	191	349	596	660	649	45	767	0.73
Asia	0	92	158	409	427	385	29	520	0.34
Australia-NZ	0	16	38	78	104	133	35	70	0.40
Canada	0	21	31	71	64	56	25	111	0.42
China	0	160	364	950	1243	1185	32	1518	0.58
Eastern Europe	0	43	35	64	77	86	25	103	0.26
FSU	0	116	121	245	276	434	22	464	0.61
India	0	140	224	488	493	346	39	521	0.41
Japan	0	20	26	56	47	53	14	72	0.07
Latin America	0	131	187	278	475	932	38	919	0.55
Mexico	0	48	107	214	286	345	40	395	0.69
Middle-East	0	89	107	340	392	709	24	746	0.80
South Korea	0	26	29	49	52	50	22	68	0.15
United States	0	720	812	910	647	518	36	1316	0.39
Western Europe	0	139	202	262	306	308	21	452	0.15
World	0	1950	2790	5010	5550	6190	31	8043	0.42

* This means that the abatement costs are evaluated per unit of GDP (cost/GDP), i.e. according to the size of the economy of the region, to facilitate the comparisons. However, they do not represent a variation of the GDP itself (reduction or increase in the size of the economy).

The emission reductions have the same marginal cost. However, as already mentioned in Section 2, several factors explain why some regions reduce more than others, and consequently, why some regions have a higher gross abatement cost. The costs are higher for the regions where there are more reduction opportunities (for example in China where the energy system is strongly based on coal, comparatively to Japan where the fossil fuels are much less used). The cost distribution, in space and time, is also influenced by the economic growth rate of regions. When the projected growth is strong, a part of the reduction is carried out naturally by energy efficiency improvements with the penetration of new technologies that are necessary to satisfy the energy demand increase. Consequently, in terms of percentages of reduction compared to their base emissions, some regions must reduce more. At the end of the time horizon, the developing countries must generally reduce their emissions more than other regions, like Africa (45%), the Latin America (38%), India (39%) and Mexico (40%).

4.2 Permit trading and burden sharing: equalizing net abatement costs

It is now possible to use the approach of Section 3 to calculate the net abatement costs for the two permit allocation schemes: S-GDP (Table 3) and S-GDP2 (Table 4). Only the portion related to permit trading varies from one allocation scheme to the other. The permit allocation results are presented in terms of fractions of total permits (%) allocated in periods 2010 and 2050 only. The net discounted costs (over the whole horizon) are presented in absolute terms of B$ and as a percentage of GDP. Their comparison with the gross abatement costs is interesting; it is thus possible to see which regions must buy or sell permits (columns identified by +/-), and can therefore see an increase or decrease of their net abatement cost.

According to the S-GDP scheme, the fraction of permits allocated to the United States is the most important in 2010 (17.3%). China (15.2%) and Western Europe (12.2%) also obtain a significant fraction of permits. In 2050, the allocation to the United States decreases to 11.0% and that to Western Europe decreases to 8.3%, whereas that of China increases to 18.1%. China and the United States are the regions where the absolute net costs are the highest, respectively 1788 G$ and 1094 G$. China receives less permits than it needs to emit and must buy permits (for 270 G$), whereas the United States receives more permits and can sell the surplus (-222 G$). Among the other regions, whose net cost is reduced by the sale of permits, there are Africa, the Latin America and the Middle East, and to a lesser extent, Canada, Australia-New-Zealand and Mexico.

Table 3: Permit allocations and net costs for the S-GDP scheme

Region	% Allocation		Gross cost	Trading	Net cost*	
	2010	2050	B$	+/-	B$	%GDP
Africa	5.8	7.7	767	-377	391	0.37
Asia	7.2	8.0	520	197	717	0.47
Australia-NZ	1.5	1.6	70	-17	53	0.03
Canada	1.9	1.2	111	-40	72	0.27
China	15.2	18.1	1518	270	1788	0.68
Eastern Europe	1.9	1.8	103	97	200	0.49
FSU	9.6	9.0	464	122	586	0.78
India	4.2	8.3	521	10	530	0.42
Japan	3.6	1.2	72	118	190	0.18
Latin America	5.8	7.9	919	-135	784	0.47
Mexico	2.5	4.2	395	-22	373	0.65
Middle-East	9.5	10.3	746	-307	439	0.47
South Korea	1.9	1.4	68	99	167	0.38
United States	17.3	11.0	1316	-222	1094	0.32
Western Europe	12.2	8.3	452	206	658	0.22
World	100.0	100.0	8043	0	8043	0.42

* With this scheme, the net abatement costs per unit of GDP (%GDP) are equalized across regions at each period. However, because of the discounting of the trading costs on one hand and of the GDPs on the other hand, the net abatement costs per unit of GDP percentages are not identical at the end of the time horizon.

The S-GDP2 scheme aims at supporting more the poorer developing regions compared to the S-GDP scheme. The permit allocations are very similar to those of the S-GDP scheme in 2010. In 2050, the most significant differences relate to the increases of permits allocated to the United States (11.8%) and Western Europe (8.8%), and a decrease in the permits allocated to Africa (6.6%), Asia (7.5%) and India (7.6%). Compared to the S-GDP scheme, the net costs are even higher for China (2050 G$) and the United States (1224 G$). The regions, whose GDP is the highest (the United States, the Western Europe, China), face an increase of their net costs compared to the S-GDP scheme. In fact, the same regions receive a higher quantity of permits than their need to emit and can sell the surplus. Only India, which was a buyer of permits for 10 G$ with the S-GDP scheme, becomes a seller of permits for 34 G$ with the S-GDP2 scheme.

Table 4: Permit allocations and net costs for the S-GDP2 scheme

Region	% Allocation		Gross cost	Trading	Net cost	
	2010	2050	B$	+/-	B$	%GDP
Africa	5.8	7.8	767	-429	338	0.32
Asia	7.2	8.0	520	182	702	0.46
Australia-NZ	1.5	1.7	70	-34	37	0.21
Canada	1.9	1.3	111	-64	47	0.18
China	15.2	17.0	1518	532	2050	0.78
Eastern Europe	1.9	2.0	103	53	155	0.39
FSU	9.6	9.3	464	60	523	0.69
India	4.2	8.4	521	-34	487	0.38
Japan	3.5	1.4	72	55	126	0.12
Latin America	5.8	7.5	919	-96	823	0.50
Mexico	2.5	4.5	395	-83	312	0.54
Middle-East	9.4	10.5	746	-367	380	0.41
South Korea	1.8	1.6	68	47	115	0.26
United States	17.5	10.7	1316	-93	1224	0.36
Western Europe	12.2	8.3	452	272	724	0.24
World	100.0	100.0	8043	0	8043	0.42

4.3 Sensitivity analyses

Sensitivity analyses were performed on two aspects of the problem for the S-GDP scheme: the GDP measure and the stabilization path.

In the first case, the GDP measure based on the purchase power parity (ppp) is replaced by the market exchange rates (mex). This change results in the allocations shown in Table 5. The modification of the GDP measure does not have any impact on the gross costs, and thus this sensitivity analysis does not require the modeling of another reduction scenario with World-MARKAL. Moreover, this modification has almost no impact on permit allocations in 2010 and a very mild impact in 2050. At that period, the most significant change relates to the fraction of permits allocated to China, which increases to 18.6%. Its net cost increases to 1656 B$. The impact on net costs is more perceptible than the impact on allocations. The net costs also decrease for India, Africa, the Middle East and Mexico; they receive a greater fraction of permits. This is essentially because the GDP-mex is much lower than the GDP-ppp for these regions, whereas the difference (increase or decrease) is less significant for the other regions. See Fig. 2 for a comparison example of the two GDP measures for the United States (USA) and China (CHI). Using GDP-mex benefits more to the developing regions, which receive thus more permits. Consequently, although the global net cost (8043 B$) is identical in both cases, this cost is higher when it is expressed as a percentage of the GDP-mex (0.51%) than as a percentage of the GDP-ppp (0.42%), since the global GDP-mex is lower than the global GDP-ppp.

Table 5: Permit allocations and net costs for the S-GDP scheme: GDP-mex

Regions	Allocation %		Gross cost	Trading	Net cost	
	2010	2050	B$	+/-	B$	%GDP
Africa	5.8	7.9	767	-436	331	0.61
Asia	7.2	7.6	520	274	794	0.58
Australia-NZ	1.5	1.6	70	-15	56	0.31
Canada	1.9	1.2	111	-39	73	0.29
China	15.2	18.6	1518	139	1656	1.34
Eastern Europe	1.9	1.8	103	107	210	0.67
FSU	9.6	9.0	464	126	589	1.16
India	4.2	8.6	521	-68	453	0.83
Japan	3.6	1.0	72	176	248	0.17
Latin America	5.8	7.8	919	-115	804	0.58
Mexico	2.5	4.3	395	-28	367	0.88
Middle-East	9.5	10.4	746	-329	417	0.66
South Korea	1.9	1.1	68	167	236	0.40
United States	17.4	11.0	1316	-213	1103	0.34
Western Europe	12.2	8.2	452	253	705	0.22
World	100.0	100.0	8043	0	8043	0.51

In the second sensitivity analysis, the stabilization level is increased from 550 ppmv to 650 ppmv (Table 6). This sensitivity analysis requires the modeling of a new reduction scenario with World-MAKRAL, with a different constraint on global emissions. A higher level of stabilization implies a large decrease in the global abatement cost, from 8043 B$ to 2337 B$ (and from 0.42% to 0.12% of the global GDP). See Fig. 3 for a comparison of the world marginal cost trajectories for the two stabilization scenarios. The regional distribution of gross costs is also different, even if the trends are generally the same. For example, the United States and China are still the two regions that face the higher gross costs, but this time, the United States (523 B$) has a higher cost than China (420 B$). The impact on permit allocations, and consequently on the net costs, is therefore significant.

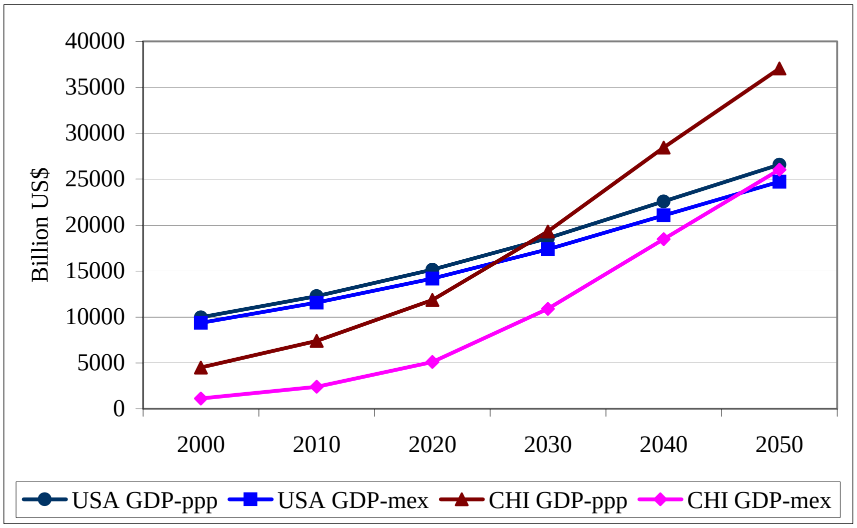

Figure 2: Evolution of the GDP (ppp and mex) for the USA and China

Table 6: Permit allocations and net costs for the S-GDP scheme: 650 ppmv

Regions	Allocation %		Gross cost	Trading	Net cost	
	2010	2050	B$	+/-	B$	%GDP
Africa	6.3	7.7	287	-223	64	0.06
Asia	6.7	7.7	122	122	245	0.16
Australia-NZ	1.4	1.5	30	-15	16	0.09
Canada	1.6	1.0	25	5	30	0.11
China	14.7	19.8	420	-17	403	0.15
Eastern Europe	2.1	1.7	30	24	54	0.13
FSU	10.4	8.6	99	-38	61	0.08
India	4.0	7.9	187	-21	166	0.13
Japan	2.9	0.9	9	113	123	0.11
Latin America	5.6	9.8	170	2	172	0.10
Mexico	2.4	4.9	112	-35	77	0.13
Middle-East	9.8	10.0	138	5	143	0.15
South Korea	1.6	1.0	21	52	73	0.16
United States	19.7	10.4	523	-138	386	0.11
Western Europe	10.8	7.2	161	163	324	0.11
World	100.0	100.0	2337	0	2337	0.12

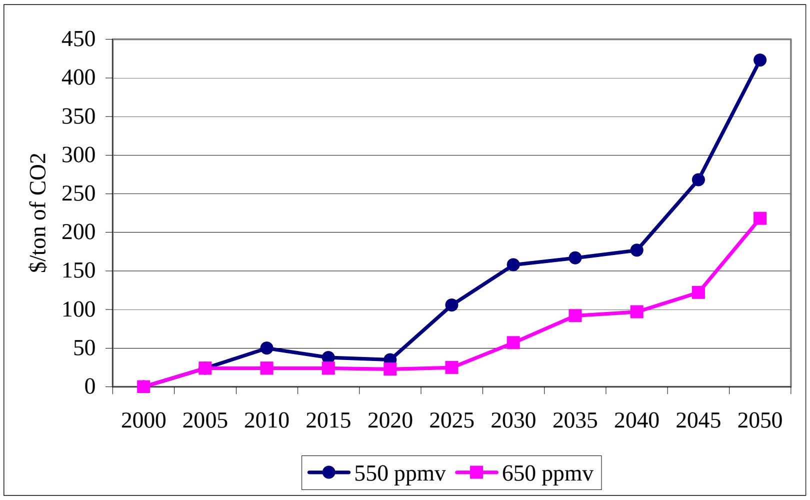

Figure 3: World marginal cost curves for two stabilization levels

5 Conclusion

Permit allocation schemes based on cost distribution allow to obtain solutions with equalized net costs per GDP for all regions. No region faces negative costs with these schemes. The S-GDP2 scheme goes further, as it allocates even more permits to the poorest regions. However, these schemes imply significant reductions in the developing countries on the short-term, and consequently, may not respect the conditions of the developing countries to take part in the existing global mitigation agreements.

This economic approach for permit allocations represents one vision of equity among others. While multicriterion approaches aim at combining several (often conflicting) visions of equity to allocate permits, the economic approach proposes a single criterion to obtain allocation schemes, leading to an equitable burden sharing expressed in monetary units. The two approaches are therefore complementary: whereas the first one provides relevant information on various equitable permit allocation schemes (but may lead to negative costs for some regions), the second directly indicates which allocations are needed to obtain an equitable distribution of abatement costs (according to principles such as the horizontality or the verticality).

6 References

Aaheim, H.A., 1999. The Appropriateness of Economic Approaches to the Analysis of Burden-Sharing. In: F.L. Toth (Editor), *Fair Weather? Equity Concerns in Climate Change*. London, Earthscan Publications, pp. 94-111.

Banuri, T., Goran-Maler, K., Grubb, M., Jacobson, H.K. and Yamin, F., 1996. Chapitre 3 : Équité et considérations sociales. *Changement climatique : Dimensions économiques et sociales*. GIEC, GT III. Cambridge University Press, pp. 79-124.

Barrett, S., 1992. Chapter VI : Acceptable Allocations of Tradeable Carbon Emission Entitlements in a Global Warming Treaty. *Combating Global Warming*. Geneva, United Nations Conference on Trade and Development, pp. 85-113.

Bayer, J.L., 1999. Climate Change and Multiple Views of Fairness. In: F.L. Toth (Editor), *Fair Weather? Equity Concerns in Climate Change*. London, Earthscan Publications, pp. 44-64.

Berk, M.M. and Den Elzen, M.G.J., 2001. Options for differenciation of future commitments in climate policy: how to realize timely participation to meet stringent climate goals? *Climate Policy*, 1:465-480.

Blanchard, O., Criqui, P., Trommetter, M. and Viguier, L., 1998. Différenciation, équité internationale et efficacité dans la lutte contre le changement climatique global. Grenoble, IEPE, Cahier de recherche no 14, 32 pp.

Blanchard, O., Criqui, P., Trommetter, M. and Viguier, L., 2000. Au-delà de Kyoto: Enjeux d'équité et d'efficacité dans la négociation sur le changement climatique. Grenoble, IEPE, 33 pp.

Den Elzen, M., Berk, B., Schaeffer, M., Olivier, J., Hendriks, C. and Metz, B., 1999. The Brazilian Proposal and other Options for International Burden Sharing : an evaluation of methodological and policy aspects using the FAIR model. Netherlands, National Institute of Public Health and the Environment, 103 pp.

Fishbone, L.G. and Abilock, H., 1981. MARKAL, A Linear-Programming Model for Energy Systems Analysis: Technical Description of the BNL Version. *Energy Research*, 5:353-375.

Grubb, M., Sebenius, J., Magalhaes, A. and Subak, S., 1992. Chapter 21 : Sharing the Burden. In: I.M. Mintzer (Editor), *Confronting Climate Change : Risks, Implications and Responses*. Cambridge University Press, pp. 305-322.

Gupta, S., Bhandari, P.M., 1999. An effective allocation criterion for CO2 emissions. *Energy Policy*, 27:727-736.

IISD, 2002. Summary of the Eighth Conference of the Parties to the UN Framework Convention on Climate Change. *Earth Negociations Bulletin*, 12 (209), 15 pp.

International Energy Agency. 2000. Energy Statistics and Balances of OECD and Non-OECD Countries. Electronic version.

Kanudia, A. and Loulou, R., 1998. Robust responses to climate change via stochastic MARKAL: The Case of Québec. *European Journal of Operational Research*, 106:15-30.

Kanudia, A. and Loulou, R., 1999. Advanced Bottom-up Modelling for National and Regional Energy Planning in Response to Climate Change. *International Journal of Environment and Pollution*, 12 (2/3):191-216.

Kram, T., (dir), 1995. New Directions in Energy Modeling. Summary of Annex V (1993-1995). International Energy Agency, Energy Technology Systems Analysis Programme, 21 pp.

Kram, T., (dir), 1999. Dealing with Uncertainty Together. Summary of Annex VI (1996-1998). International Energy Agency, Energy Technology Systems Analysis Programme, 83 pp.

Loulou, R. and Kanudia, A., 1998. The Kyoto Protocol, Inter-Provincial Cooperation, and Energy Trading: A Systems Analysis with Integrated MARKAL Models. *Energy Studies Review*, 9 (1):1-23.

Morita, T., 2000. Global Modeling and Future Scenario for Climatic Stabilization based on SRES World: A comparative analysis on development paths and climatic policies. In: L. Fu-chen, H. Tokuda and N.S. Cooray (Editors), *The Sustainable Future of the Global System III*. Tokyo, Institute of Advanced Studies and The United Nations University, pp. 125-148.

Morita, T. and Robinson, J. (Coordonators), 2001. *Chapter 2: Greenhouse Gas Emission Mitigation Scenarios and Implications. Climate Change 2001 : Mitigation*. IPCC, WG III. Cambridge University Press, pp.115-166.

Nakicenovic, N. and Swart, R. (Editors), 2000. *Emissions Scenarios*. IPCC, WG III. Cambridge University Press, 570 pp.

Onigkeit, J. and Alcamo, J., 2000. A Different Perspective for Global Climate Policy: Combining Burden Sharing and Climate Protection. In: C. Carraro (Editor), *Efficiency and Equity of Climate Change Policy*. Dordrecht, Klumer Academic Publishers, pp. 305-314.

Rayner, S., Malone, E.L. and Thompson, M., 1999. Equity Issues and Integrated Assessment. In: F.L. Toth (Editor), *Fair Weather? Equity Concerns in Climate Change*. London, Earthscan Publications, pp. 11-43.

Rose, A. and Stevens, B., 1993. The Efficiency and Equity of Marketable Permits for CO2 Emissions. *Resource and Energy Economics*, 15:117-146.

Rose, A., Stevens, B., Edmonds, J. and Wise, M., 1998. International Equity and Differenciation in Global Warming Policy. *Environmental and Resource Economics*, 12:25-51.

Shukla, P.R., 1999. Justice, Equity and Efficiency in Climate Change: A Developing Country Perspective. In F.L. Toth (Editor): *Fair Weather? Equity Concerns in Climate Change*. London, Earthscan Publications, pp.145-159.

Torvanger, A. and Godal, O., 1999. A survey of differenciation methods for national greenhouse gas reduction targets. University of Oslo. CICERO, Report 1999:5, 53 pp.

UNFCCC, 1997. The Kyoto Protocole. http://unfccc.int/.

Vaillancourt, K., 2003. Équité et scénarios mondiaux de réduction des émissions de gaz à effet de serre : Une approche multicritère dynamique combinée au modèle énergétique MARKAL . Montréal, Université du Québec à Montréal (UQAM), Département des sciences de l'environnement, Thèse de doctorat, 306 pp.

Vaillancourt, K. and Waaub, J.-P., 2003. Equity and Efficiency in International Greenhouse Gas Abatement Scenarios: A Multicriteria Approach. *European Journal of Operationnal Research*, 157 (2):489-505.

Vaillancourt, K. and Waaub, J.-P., 2004. A decision aid tool for equity and efficiency issues analysis in emission permit allocations. Submitted to *Climate Policy*.