Climate Economics at the NCCR Climate

The Feasibility of a World-wide Tax on Anthropogenic Emissions of Greenhouse Gases: Levels and impacts of world-wide taxes on greenhouse gases

By
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Research Paper
2007/04

NCCR CLIMATE
Swiss Climate Research

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Abstract

A harmonized worldwide carbon tax, implemented at regional or national level, can be enforced only with an international collective action which takes into account inherent interests of all countries. The purpose of this study is to assess the impact of the implementation of such a tax by means of different scenarios based on realistic assumptions. We endeavor to design a world tax on anthropogenic greenhouse-gases emissions which can be politically acceptable and technically feasible. To do so, we also address international equity through lump-sum transfer and transfers based on countries' financial capacity. After defining the reference scenario (a so called "business-as-usual" scenario), we carry out a meta-analysis of previous attempts to estimate the marginal abatement costs produced by 26 different models. The meta-analysis helps us to define a starting point for devising a politically acceptable and technologically feasible tax. From there, we implement different scenarios which introduce carefully considered principles of international equity in the search for politically acceptable and technologically feasible world tax schemes. In performing those simulations, we are concerned about both tax efficiency — societal welfare impact — and tax effectiveness — climate impact. This basket of efficiency considerations leads us to set up the simulations in a way that addresses these two issues simultaneously in a concise manner.

*Research lab on the Economics and Management of the Environment, École Polytechnique Fédérale de Lausanne. This study has been funded with a contract for the Swiss Federal Office for the Environment and supported by the National Centre of Competence in Research (NCCR) Climate. We also thank C.Hope for providing us with damage data of the Stern Review.

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1 Introduction

A harmonized worldwide carbon tax, implemented at regional or national level, can be enforced only with an international collective action which takes into account inherent interests of all countries. The purpose of this study is to assess the impact of the implementation of such a tax by means of different scenarios based on realistic assumptions. We endeavor to design a world tax on anthropogenic greenhouse-gases emissions which can be politically acceptable and technically feasible. To do so, we also address international equity through lump-sum transfer and transfers based on countries' financial capacity.

After defining the reference scenario (a so called "business-as-usual" scenario), we carry out a meta-analysis of previous attempts to estimate the marginal abatement costs produced by 26 different models. The meta-analysis helps us to define a starting point for devising a politically acceptable and technologically feasible tax. From there, we implement different scenarios which introduce carefully considered principles of international equity in the search for politically acceptable and technologically feasible world tax schemes.

In performing those simulations, we are concerned about both tax efficiency — societal welfare impact — and tax effectiveness — climate impact. This basket of efficiency considerations leads us to set up the simulations in a way that addresses these two issues simultaneously in a concise manner.

Section 2 briefly presents the GEMINI-E3 model which has been used to perform the simulations. Section 3 presents the main assumptions of the reference scenario. In section 4, the tax level is set exogenously and uniformly according to the meta-analysis previously conducted and defines the starting point in our simulations. Section 5 and 6 present the simulations results when an endogenous tax is applied. In one set of simulations (Section 5) the tax is set endogenously according to damage costs of climate change; in another set of simulations (Section 6) the tax is set with a view to adaptation costs. In these sections, we thus strive to devise a scheme where equity among tax contributors is attained in order to ensure participation. Finally we conclude in section 7. A sensitivity analysis is performed in appendix 8.

2 Modeling Framework

The GEMINI-E3 is a dynamic-recursive CGE model which represents the world economy in 28 regions and 18 sectors, and contains a highly detailed representation of indirect taxation (Bernard and Vielle, 1998, 2007). The version of GEMINI-E3 used in this study is formulated as a Mixed Complementarity Problem (MCP), which is solved using GAMS and the PATH solver (Ferris and Munson, 2000; Ferris and Pang, 1997). GEMINI-E3 is built on a comprehensive energy-economy data set, the GTAP-6 database (Dimaranan, 2006), that provides a consistent representation of energy markets in physical units, a detailed Social Accounting Matrix

(SAM) for a large set of countries or regions, and bilateral trade flows between them. The reference year of the database is 2001. Given that, this year is quite old, we integrate in an ad hoc way the main recent trends in the energy market, like for example the increase in energy prices (see section 3.1). Also, we have complemented the data from the GTAP database with information on indirect taxation and government expenditures from the International Energy Agency (2002a,b, 2005), the Organisation For Economic Co-operation and Development (2005, 2003) and the International Monetary Fund (2004). For non CO_2 greenhouse gases (GHG), data on emissions and abatement costs comes from the United States Environmental Protection Agency (2006). The first version of GEMINI-E3 and its successors, have been especially designed to calculate the social Marginal Abatement Costs[1] (Bernard and Vielle, 2003).

The original version of GEMINI-E3 is described in Bernard and Vielle (2007) and on the internet[2]. Various versions of the model have been used to analyze the implementation of economic instruments allowing for GHG emissions reductions in a second-best setting (Bernard and Vielle, 2000). The following studies are examples of various analyses carried out with GEMINI-E3: the assessment of the strategic allocation of GHG emission allowances in the enlarged EU market (Viguier et al., 2006), the analysis of Russia's behavior with respect to the Kyoto Protocol ratification process (Bernard et al., 2002, 2003), the assessment of the Protocol implementation cost in Switzerland with and without international emissions trading schemes (Bernard et al., 2005), the assessment of oil prices increase effects on global en regional GHG emissions (Vielle and Viguier, 2007).

Apart from a comprehensive description of indirect taxation, the specificity of the model is to simulate all relevant markets: e.g. commodities (through relative prices), labour (through wages) as well as domestic and international savings (through interest rates and exchange rates). Terms of trade (i.e. real income transfers between countries resulting from variations of imports and exports relative prices) and "real" exchange rates can also be accurately represented.

Time periods are linked in the model through endogenous real interest rates, which are determined by the equilibrium between savings and investments. GEMINI-E3 is a model based on recursive dynamics. Expectations of agents are based on adaptative rules and the model does not presume perfect foresight. National and regional models are linked by endogenous real exchange rates resulting from constraints on foreign trade deficits or surpluses.

GEMINI-E3 provides the following outputs for each region or country and for each year: carbon taxes, marginal abatement costs, price of tradable permits (when relevant), abatement of GHG emissions, net sales of tradable permits (when relevant) and total net welfare loss, which is also available in a disaggregated manner as net loss from terms of trade, pure deadweight loss of taxation, net purchases

[1]MAC, i.e. the welfare loss of a unit increase in pollution abatement.

[2]For a complete description of the model, please refer to all technical documents available at: http://gemini-e3.epfl.ch.

of tradable permits when relevant. Macroeconomic aggregates such as production, imports and final demand are also provided by the model, as well as real exchange rates, real interest rates and sectorial data such as changes in production or use of production factors.

The welfare indicator used in this study is consumer surplus. It has been explained elsewhere that, in the case of General Equilibrium Model (Bernard and Vielle, 2003) demonstrate that neither GDP at constant prices nor households' final consumption at constant prices can provide relevant measures of the economic costs climate change policies.

In effect, one — even the major — effect of the considered policy is to change relative prices, precisely in order to favor the desirable, and least costly, substitutions. Any measure by an aggregate quantity at constant prices, in line with the rules of national accounting, cannot capture the very part of the welfare loss (eventually gain) resulting from this change in relative prices. Surplus provides a reliable measure by representing the effect of change in relative prices by an equivalent income loss. In particular, the sign of surplus is the same as the sign of utility change, positive if utility increases and negative if utility decreases. In order to compare surplus among countries we divide this measure by household consumption. So, in the following pages, the welfare impact is expressed in percentage of household consumption.

Finally, for this study we use an aggregated version of the model, 14 regions rather than the original 28 (see table 1).

Table 1: GEMINI-E3 Regional Description

Name	Countries
EUR	European Union (25)
XEU	Other European Countries
FSU	Former Soviet Union (except Baltic States)
USA	United States of America
CAN	Canada
AUZ	Australia and New Zealand
JAP	Japan
MEX	Mexico
CHI	China
IND	India
ASI	Rest of Asia
LAT	Central and Latin America
MID	Middle East
AFR	Africa

3 The Reference Scenario

The reference or "Business as usual" scenario is used to quantify the economic and GHG emissions path of the world up to 2050, considering all energy policies enforced in all regions up to 2001, which is the base year of the GTAP database. The reference scenario we use is calibrated by means of the different procedures explained below.

3.1 International Energy Prices

The oil price projections used in this reference scenario are mainly taken from the International Energy Outlook (IEO) published by the US Department of Energy (DOE) (Energy Information Administration, 2006a). The DOE expects lower investments and oil production in key oil producing regions; this being mainly due to restrictions on access and contracting, which affect oil exploration and production costs.

In our reference scenario we assume that oil prices in 2010 are at 36 USD per barrel at 2004 prices and increase linearly to 57 USD in 2030. After 2030, oil prices rise linearly up to 69 USD per barrel in 2050. Table 2 shows a comparison of several oil price projections collected by the DOE (Energy Information Administration, 2006b).

Table 2: Forecast of world oil prices (USD_{2004} per barrel)

	2010	2020	2030	2040	2050
GEMINI-E3	35.80	50.70	56.97	62.93	69.51
International Energy Outlook 2006					
Reference	47.29	50.70	56.97		
High price	62.65	85.06	95.71		
Low price	40.29	33.99	33.73		
International Energy Agency	35.00	37.00	39.00		
International Energy Agency (*deferred investment*)	41.00	46.00	52.00		
Petroleum Industry Research Associates	44.10	63.35			
Petroleum Economics Ltd.	47.84	49.80			
Global Insight Inc.	37.82	31.53	34.50		
Altos Partners	27.58	34.02	40.03		
Energy and Environmental Analysis Inc.	46.74	42.79			
Strategic Energy and Economic Research Inc.	29.54	32.00	36.50		

Source: Energy Information Administration (2006b)

Concerning other fossil energies, we assume an indexation of natural gas prices to oil prices of 0.5 (i.e. the price of gas increases by 5% when the oil price increases by 10%) and stability of coal prices in real USD[3].

3.2 GDP, Energy Demand and GHG Emissions

The reference scenario for each region is calibrated with projections of CO_2 emissions, energy consumption, GDP and populations for the years 2000 to 2030, as provided by the Energy Information Administration (2006a). From 2030 to 2050,

[3] In this report, unless otherwise specified all prices are in 2001 USD

we suppose that the annual growth of GDP per capita will linearly converge to 2% in industrialized regions (except Japan, Canada and Australia) and to 2.5% in developing regions. Table 3 summarizes the projected annual GDP growth for each region.

Table 3: Projected Average Annual Growth in GDP

	2001–2010	2010–2020	2020–2030	2030–2040	2040–2050
EUR	2.2%	2.2%	2.1%	1.9%	1.9%
XEU	2.2%	2.2%	2.1%	1.8%	1.8%
FSU	5.4%	3.7%	3.2%	2.8%	2.8%
USA	3.3%	3.0%	2.8%	2.3%	2.2%
CAN	2.8%	2.2%	1.7%	1.4%	1.3%
AUZ	2.7%	2.4%	2.4%	2.0%	1.9%
JAP	1.9%	1.4%	0.9%	1.1%	1.1%
MEX	3.5%	4.2%	4.1%	3.7%	3.6%
CHI	7.9%	5.7%	5.1%	4.3%	3.9%
IND	6.3%	5.3%	5.0%	4.3%	4.3%
ASI	3.8%	3.4%	3.1%	2.6%	2.6%
LAT	4.0%	3.6%	3.5%	2.8%	2.8%
MID	5.2%	3.9%	3.6%	2.5%	2.5%
AFR	5.0%	4.3%	4.1%	3.2%	3.2%
World	3.3%	3.0%	2.8%	2.5%	2.5%

Figure 1 shows the projected world final energy consumption we have used in the reference scenario. Final energy consumption increases by 1.7% annually whereas the global annual economic growth reaches 2.8% . High oil and natural gas prices make coal and electricity more competitive and attractive (Vielle and Viguier, 2007).

As a result, coal consumption grows by 2.3% per year and electricity by 1.7%. By contract, petroleum products and natural gas consumption, as a consequence of the high prices, increase only by 1% and 0.9% per year respectively.

Figure 2 shows the global emissions of the various GHG. The share of CO_2 emissions increases slightly from 71% in 2001 to 75% in 2050 whereas the shares of nitrous oxide and high GWP gases remain stable. The proportion of methane decreases from 18% in 2001 to 15% in 2050. Table 4 presents GHG emissions projections by regions. World GHG emissions start at 9.1 GtC in 2001 to reach 18.5 GtC in 2050. In 2001, developing countries GHG emissions represent 47% of world emissions. This share reaches respectively 56% in 2020 and 66% in 2050. These emissions projections are in line with a recent OECD report (see Organisation For Economic Co-operation and Development (2007)).

We use the climate module of the MERGE model to compute the impacts of emissions on temperature changes. This climate module comprises a description of the carbon cycle and the earth radiative balance (Manne and Richels, 2005). We also adjust its ocean lag parameter (the number of years for the oceans to be as warm as the atmosphere) following the changes of Knutti and Meehl (2005). Ta-

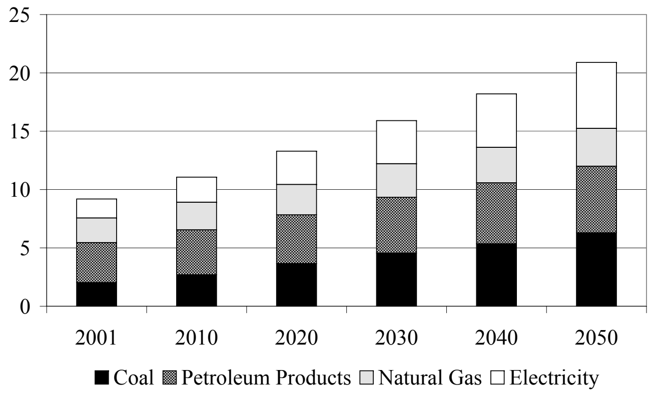

Figure 1: World energy consumption in Gtoe

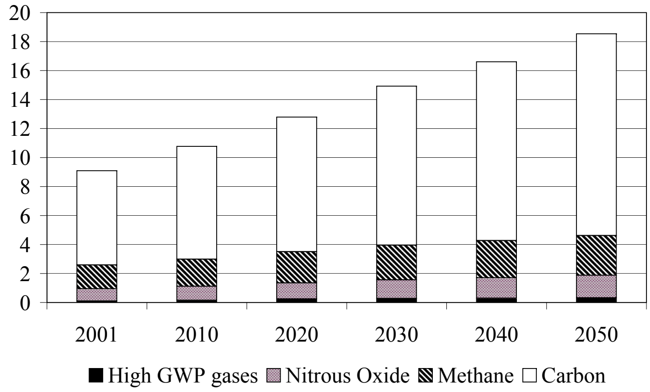

Figure 2: World GHG emissions in GtC-eq

Table 4: Baseline GHG Emissions in MtC-eq per year

	2001	2010	2020	2030	2040	2050
EUR	1 302	1 339	1 391	1 431	1 465	1 512
XEU	139	148	160	164	164	166
FSU	812	951	1 086	1 171	1 213	1 275
USA	1 899	2 057	2 232	2 393	2 473	2 567
CAN	194	211	225	223	216	211
AUZ	170	182	194	197	195	193
JAP	340	346	341	321	307	296
MEX	157	184	229	265	295	331
CHI	1 262	1 877	2 735	3 786	4 784	5 897
IND	437	583	767	1 014	1 249	1 535
ASI	763	889	1 018	1 133	1 193	1 257
LAT	598	708	836	965	1047	1 130
MID	469	610	738	848	882	920
AFR	555	684	839	1 015	1 128	1 254
World	9 097	10 769	12 789	14 926	16 613	18 542

ble 5 presents the temperature increase from the pre-industrial era in the reference scenario with 3 different climate sensitivities from 2 °C to 3 °C. Climate sensitivity corresponds to the change in global mean surface temperature at the equilibrium for a doubling of the atmospheric CO_2-equivalent concentration (McCarthy et al., 2001). In 2050, temperature projections vary then from 1.47 °C to 1.88 °C. Climate sensitivity is an important parameter because it alters the damages estimates values. From the literature, the mean climate sensitivity is about 3 °C. In this report, we retain lower values as mentioned in a recent OECD report (Organisation For Economic Co-operation and Development, 2007).

Table 5: Temperature increase from the preindustrial era

Climate sensitivity in °C	2	2.5	3
Year	Temperature °C		
2000	0.6	0.6	0.6
2001	0.61	0.61	0.61
2010	0.69	0.71	0.73
2020	0.83	0.89	0.94
2030	1.02	1.12	1.21
2040	1.23	1.38	1.53
2050	1.47	1.68	1.88

4 Building on Previous Estimates

Many studies over recent years have set out to provide policy makers with estimates of the marginal abatement costs for GHG. Recently a new generation of models has included endogenous technological change (ETC) in their framework, improving the ability of models to capture reality. To account for these recent developments in modeling climate change, we perform a meta-analysis of the marginal abatement costs calculated by 26 different models, most of them incorporating ETC, which provide us with 103 estimates of the marginal abatement costs (Bicchetti et al., to appear).

A meta-analysis is the pooling of several different studies that address a set of related hypotheses in an attempt to overcome problems related to the interpretation of contradictory or flawed results depending on the assumptions made to realize the study. Analyzing the results of different studies may provide a more comprehensive and accurate view of a given topic.

In the case of the marginal cost of carbon emissions, the various studies have provided researchers and policy makers with a wide range of estimates starting from almost nothing to huge amounts like over 400 USD/tC depending on different assumptions (about the pure rate of time preference for instance). In this context it is quite difficult to make a judgement about a meaningful value estimate for the marginal costs of carbon emission. Performing a meta-analysis on this topic can certainly yield a more precise range of central estimates concerning the costs of carbon. Given the fact that current trends focus on ETC and adaptation policy to mitigate climate change, a meta-analysis incorporating the latest models with ETC can be expected to yield pertinent results. Therefore we have focused on estimates published between 1999 and 2007 for our meta-analysis; but we nonetheless incorporate some studies which did not include ETC in their model.

We gather our 103 marginal abatement cost estimates for the year 2010 from 13 different studies realized with 26 different models and we construct the probability density function of the 103 gathered estimates (see Figure 3). We find that the modal score of the distribution equals 15 USD. Therefore, we take 15 USD/tC as a starting point for a world carbon tax in the next simulations presented in section 4.

4.1 World Carbon Tax Redistributed Within Each Region

4.1.1 World Carbon Tax of 15 USD

In this scenario we assume that a carbon tax 15 USD_{2001} per ton of carbon is enforced at the world level over the whole time horizon of the simulation (i.e. 2007–2040). As already said, 15 USD corresponds to the distribution mode of these marginal costs (see Figure 3). The carbon tax revenue is collected in each region and redistributed to the households of the same region through a lump-sum transfer in order to maintain the same government budget deficit or surplus as computed in the reference scenario. We have a textbook efficient pollution tax, since it is applied to all sources at the same rate. This carbon tax has a low impact on emissions reductions and temperature changes. The main explanation is the inherent climate inertia and the short time horizon.

Table 7 shows the contribution of each region to CO_2 emissions reductions.

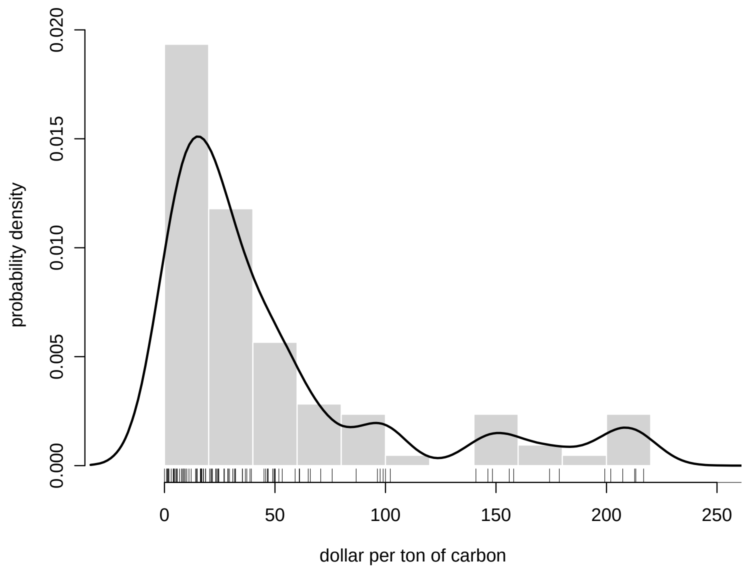

Figure 3: Distribution of the carbon taxes from the literature (USD_{2001})

Table 6: Carbon Tax and World GHG Emissions — Scenario World Carbon Tax of 15 USD with Regional Redistribution

	2010	2020	2030	2040
Carbon tax in USD	15	15	15	15
Carbon tax revenue in billion USD	107	125	144	158
GHG Emissions variation	-5.9%	-7.8%	-9.4%	-11.1%
CO_2 Emissions variation	-7.9%	-10.4%	-12.5%	-14.6%
Temperature increase in $^\circ$C	0.71	0.88	1.10	1.34
Difference w.r.t. baseline in $^\circ$C	-0.00	-0.01	-0.02	-0.04

Table 7: CO_2 Emissions change in % — Scenario World Carbon Tax of 15 USD with Regional Redistribution

	2010	2020	2030	2040
EUR	-2.6%	-2.6%	-2.5%	-2.4%
XEU	-3.8%	-4.0%	-3.8%	-3.8%
FSU	-4.8%	-5.1%	-5.5%	-6.0%
USA	-4.2%	-4.2%	-4.1%	-4.0%
CAN	-2.6%	-2.3%	-2.1%	-1.9%
AUZ	-4.2%	-4.4%	-4.4%	-4.3%
JAP	-2.0%	-2.1%	-2.1%	-2.1%
MEX	-2.1%	-1.7%	-1.7%	-1.8%
CHI	-25.8%	-30.2%	-32.9%	-35.5%
IND	-10.2%	-12.1%	-13.8%	-15.4%
ASI	-3.9%	-4.5%	-4.8%	-5.0%
LAT	-2.1%	-2.0%	-2.0%	-2.1%
MID	-2.6%	-2.3%	-2.4%	-2.5%
AFR	-4.4%	-4.8%	-5.4%	-5.8%
World	-7.9%	-10.4%	-12.5%	-14.6%

note that the greatest reductions are obtained in China and India, where the greatest potentials for low-cost emission reduction are available. Those efforts are reflected in the welfare impacts in Table 8, but the correlation between abatement effort and welfare loss is not very strong. Indeed, terms of trade effects also play a role. They lead to positive welfare impacts in Europe (EUR) and in Japan (JAP), regions that are big importers of fossil fuels. They benefit from lower fossil fuels prices due to the decrease in energy demand. The opposite effect increases the loss for fossil fuels exporting countries (MID, FSU and AFR) (Barnetta et al., 2004; Ghanem et al., 1999). Similarly, China, which is endowed with large reserves of coal gains nothing from lower fossil fuel prices, contrary to the situation for India.

In Table 6, we can note a -14.6% change in CO_2 emissions but a relatively minor impact on temperature increase with respect to the reference scenario (-0.04°C) in 2040. To increase effectiveness we consider an alternative tax level derived from the literature.

Table 8: Welfare impact in percent of household consumption — Scenario World Carbon of 15 USD Tax with Regional Redistribution

	2010	2020	2030	2040
EUR	0.04%	0.05%	0.05%	0.04%
XEU	-0.14%	-0.15%	-0.13%	-0.11%
FSU	-0.26%	-0.27%	-0.22%	-0.18%
USA	-0.01%	-0.01%	-0.01%	-0.01%
CAN	-0.09%	-0.10%	-0.09%	-0.09%
AUZ	-0.34%	-0.30%	-0.24%	-0.20%
JAP	0.06%	0.07%	0.05%	0.04%
MEX	-0.09%	-0.07%	-0.06%	-0.04%
CHI	-0.28%	-0.25%	-0.23%	-0.21%
IND	-0.07%	-0.04%	-0.04%	-0.04%
ASI	0.14%	0.14%	0.12%	0.10%
LAT	-0.08%	-0.07%	-0.06%	-0.05%
MID	-0.54%	-0.46%	-0.38%	-0.31%
AFR	-0.35%	-0.33%	-0.28%	-0.23%
World	-0.03%	-0.03%	-0.03%	-0.06%

4.1.2 World Carbon Tax of 348 USD

Tol Tol (2005) in a literature review finds that a tax set at 95 USD/tCO_2 represents the 95 percentile of a probability density function of marginal damage estimates. The already quoted OECD report (Organisation For Economic Co-operation and Development, 2007) performs also a simulation with a tax rate of 95 USD/tCO_2.

Converting the tax into units per ton of carbon, we obtain a tax of 348 USD/tC. Such a high tax would undoubtedly have a strong impact on carbon emissions. Simulation results are presented in Table 9 .

Table 9: Carbon Tax and World GHG Emissions — Scenario World Carbon Tax of 348 USD with Regional Redistribution

	2010	2020	2030	2040
Carbon tax in USD $	348	348	348	348
Carbon tax revenue in billion USD	1643	1905	2186	2388
GHG Emissions variation	-29.0%	-30.5%	-32.0%	-33.5%
CO2 Emissions variation	-37.5%	-39.6%	-41.7%	-43.5%
Temperature increase in °C	0.71	0.86	1.03	1.22
Difference w.r.t. baseline in °C	-0.00	-0.03	-0.09	-0.16

The tax has a significant impact on emissions trends since emissions of CO_2 are -43.5% lower in 2040 with respect to the baseline. Also it brings tangible results concerning climate change since the calculations signal a temperature increase of 1.22°C in 2040 which 0.16°C below the baseline. Moreover, such a tax generates also a huge revenue, which reaches 2388 billion USD in 2040.

As shown in Table 10, the greatest CO_2 emissions change (relative to the ref-

Table 10: CO_2 Emissions change in % — Scenario World Carbon Tax of 348 USD with Regional Redistribution

	2010	2020	2030	2040
EUR	-20.5%	-19.8%	-18.3%	-17.0%
XEU	-28.2%	-26.9%	-26.0%	-25.2%
FSU	-38.9%	-37.4%	-37.0%	-37.0%
USA	-34.0%	-32.6%	-31.6%	-30.6%
CAN	-26.3%	-23.9%	-22.5%	-21.2%
AUZ	-53.9%	-36.7%	-35.5%	-34.5%
JAP	-18.5%	-18.0%	-17.2%	-16.5%
MEX	-24.2%	-20.3%	-19.5%	-18.9%
CHI	-64.9%	-68.2%	-69.9%	-71.4%
IND	-48.6%	-52.3%	-53.8%	-55.0%
ASI	-31.9%	-32.4%	-32.6%	-32.7%
LAT	-22.3%	-19.8%	-18.9%	-18.0%
MID	-31.7%	-28.2%	-27.4%	-26.4%
AFR	-36.7%	-37.2%	-38.3%	-38.9%
World	-37.5%	-39.6%	-41.7%	-43.5%

erence scenario) occurs in China, with an impressive -71.4% in 2040. This is due to the fact that China has large coal reserves and therefore its GHG emissions have a high carbon intensity. Generally, developing countries' (DC) emissions vary significantly relative to the reference scenario, because their marginal abatement costs are lower and because they do not have access easily to cleaner production techniques. Among OECD countries EUR and JAP have an emissions variation below 20%. This can be explained by the fact that EUR and JAP already have a heavy tax policy on fossil energy and that they have already done a lot to promote cleaner production techniques.

Table 11 presents the welfare impact in percent of household consumption. As expected, with such a high tax, countries whose exports are energy intensive are the hardest hit by the tax. For instance, FSU and MID welfare decrease by 11.67% and 13.14% respectively (with respect to the baseline). Despite the tax effectiveness (in terms of reduced climate change pressures) and relative allocative efficiency (all countries pay the same tax which induces less "distortion"), its acceptability is far from certain. All of FSU, CHI, MID and AFR must bear major costs if such a policy were implemented because those regions are the major exporters of fossil energy while the main net importers (EUR, JAP and ASI) benefit from lower energy prices.

Therefore, we return to consideration of simulations with a flat 15 USD tax but we endeavor to increase effectiveness by broadening the tax base of the world tax to all GHG emissions (and not only carbon emissions).

Table 11: Welfare impact in percent of household consumption — Scenario World Carbon Tax of 348 USD with Regional Redistribution

	2010	2020	2030	2040
EUR	0.61%	0.83%	0.88%	0.88%
XEU	-4.32%	-4.15%	-3.84%	-3.55%
FSU	-19.91%	-15.65%	-13.39%	-11.67%
USA	-0.57%	-0.27%	-0.16%	-0.09%
CAN	-2.68%	-2.14%	-1.97%	-1.81%
AUZ	-5.74%	-2.22%	-1.46%	-1.11%
JAP	0.91%	1.07%	0.98%	0.88%
MEX	-2.47%	-2.23%	-1.90%	-1.57%
CHI	-4.62%	-3.58%	-2.82%	-2.15%
IND	-2.77%	-1.61%	-0.81%	-0.17%
ASI	0.72%	1.35%	1.34%	1.24%
LAT	-2.63%	-2.20%	-1.90%	-1.64%
MID	-21.54%	-16.76%	-14.96%	-13.14%
AFR	-11.20%	-9.61%	-8.65%	-7.67%
World	-1.47%	-1.12%	-0.93%	-1.75%

4.2 World GHG Tax Redistributed Within Each Region

In this section, we are concerned with increasing the tax effectiveness and efficiency with respect to the scenario *World Carbon Tax of 15 USD with Regional Redistribution*. To this end, we introduce a flat world tax of 15 USD per ton of carbon equivalent on GHG emissions. As in the previous simulation, the tax revenue is collected in each region and it is redistributed then to the households of the region through lump-sum transfers.

In Table 12, GHG emissions variation is slightly more important (-15.5%) than with respect to the *World Carbon Tax of 15 USD with Regional Redistribution* computed in the previous simulation. However, the impact on temperature change is 100% greater (-0.08°C w.r.t -0.04°C), showing a better effectiveness (for the same tax effort) than the previous scenario. The global welfare impact is close to that of the *World Carbon Tax of 15 USD with Regional Redistribution*, i.e., about -0.07% of 2040 consumption.

Table 12: GHG Tax and World GHG Emissions — Scenario World GHG Tax with Regional Redistribution

	2010	2020	2030	2040
GHG tax in USD	15	15	15	15
GHG tax revenue in billion USD	144	167	192	210
GHG Emissions variation	-10.8%	-12.8%	-14.1%	-15.5%
CO_2 Emissions variation	-8.0%	-10.5%	-12.6%	-14.7%
Temperature increase in °C	0.71	0.87	1.07	1.30
Difference w.r.t. baseline in °C	-0.00	-0.02	-0.04	-0.08
Welfare impact in percent of household consumption	-0.04%	-0.04%	-0.04%	-0.07%

The impact of the world GHG tax on CO_2 emissions is nearly identical to that of the world carbon tax of same rate (-14.7% w.r.t -14.6% in 2040). However the impact on GHG emissions is improved since this time the variation reaches -15.5% in 2040, which is 40% better with respect to the World Carbon Tax scenario (-11.1%). In terms of temperature difference with respect to the baseline, we obtain in 2040 -0.08°C instead of -0.04°C for the carbon tax, which represents again a gain of 100%. This improvement in effectiveness can be explained by the fact that the abatement cost for GHG other than the CO_2 is lower (see Reilly et al., 2006; Vuuren et al., 2006; Weyant et al., 2006). By examining carefully the results, the principal GHG responsible for those results is CH_4, which has a lifetime much lower than other GHG, about 12 years (McCarthy et al., 2001; Reilly et al., 2006) against 100 years for CO_2. With this relatively short lifetime, reducing emissions produces a tangible and quick impact on temperature. Also by taxing all GHG, we get a stronger reduction in GHG emissions, improving the effectiveness for tackling global warming, and in the meantime by enlarging the tax base we also increase the tax revenue, gaining in redistribution opportunities. To sum up, a GHG tax improves the efficiency, fiscal and redistribution opportunities, and environmental gains, at a similar cost in terms of welfare impact.

However, despite the fact that the GHG tax is almost twice as effective as the carbon tax, there is considerable doubt about its feasibility. After CO_2, CH_4 is the most important GHG and it is primarily a by-product of agricultural activities (paddy fields, cattle breeding, etc.). Taxing all GHG emissions poses the problems of observability and verifiability, in short the problem of monitoring.

It requires emissions accounting for which some Developing Countries (DC) may not have sufficient resources. Such a tax policy therefore not easy to implement rigorously, due to these monitoring considerations and administrative capabilities.

A tax policy based on other GHG should be easier to implement since most of them are like CO_2, produced through industrial processes. However, their lifetime in some cases are much longer (up to 50 000 years) (McCarthy et al., 2001; Reilly et al., 2006) and therefore impacts of such policy would require much more time before yielding tangible results.

For all these reasons, the next set of simulations focuses on variations of world carbon tax policies.

4.3 International Carbon Tax Revenue Redistribution Based on Income and Population

In this scenario, we return to the pure carbon tax at 15 USD per ton and add to our simulations considerations about equity. To this end, the carbon tax global revenue is redistributed on the basis of a GDP per capita criterion and each world region receives part of the tax revenue according to shares based on this equity criterion.

Tables 13 and 14 show the shares of the total revenue attributed to each region and their evolution until the year 2040. The shares (α_{it}) for the region i at time t

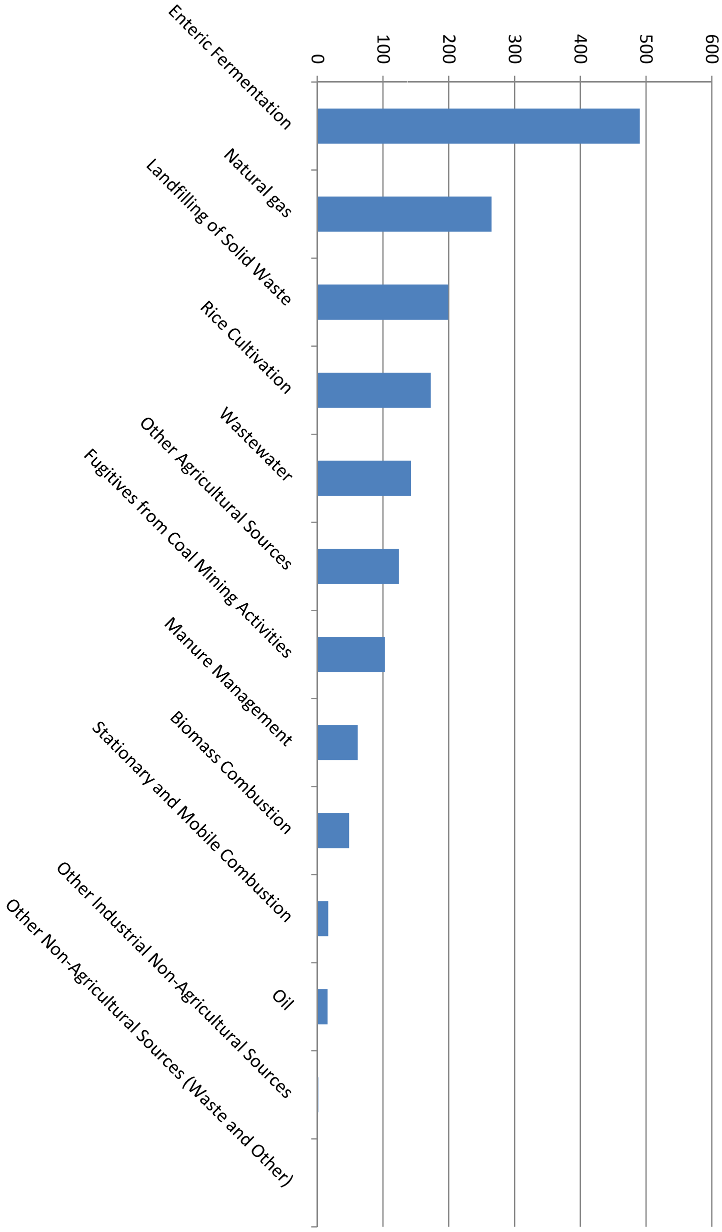

Figure 4: World CH_4 Sources in 2001 in GtC-eq

are computed with the following formulas:

$$\beta_{it} = \frac{\frac{\sum_j GDP_{jt}}{\sum_j Pop_{jt}}}{\frac{GDP_{it}}{Pop_{it}}} \tag{1}$$

and

$$\alpha_{it} = \frac{\beta_{it} \cdot Pop_{it}}{\sum_j \beta_{jt} \cdot Pop_{jt}}. \tag{2}$$

Table 13: Revenue allocation based on GDP per capita

	GDP 2001 millions USD	Population 2001 thousand	GDP per capita USD	Share 2001 %
EUR	8 364 387	451 993	18 506	0.42
XEU	563 650	62 971	8 951	0.12
FSU	410 541	267 162	1 537	3.01
USA	10 337 035	284 154	36 378	0.14
CAN	712 479	30 689	23 216	0.02
AUZ	417 041	22 889	18 220	0.02
JAP	4 161 916	127 034	32 762	0.07
MEX	611 564	100 088	6 110	0.28
CHI	1 294 329	1 273 979	1 016	21.68
IND	463 642	1 021 084	454	38.88
ASI	1 473 994	957 451	1 539	10.75
LAT	1 363 068	422 841	3 224	2.27
MID	788 804	236 161	3 340	1.22
AFR	540 159	812 466	665	21.13
World	31 502 611	6 070 962	5 189	100.00

Table 14: Evolution of allocations shares

	2001	2010	2020	2030	2040
EUR	0.42%	0.45%	0.45%	0.45%	0.42%
XEU	0.12%	0.12%	0.11%	0.11%	0.09%
FSU	3.01%	2.23%	1.79%	1.49%	1.22%
USA	0.14%	0.15%	0.16%	0.17%	0.18%
CAN	0.02%	0.03%	0.03%	0.04%	0.04%
AUZ	0.02%	0.03%	0.03%	0.03%	0.04%
JAP	0.07%	0.07%	0.08%	0.08%	0.08%
MEX	0.28%	0.33%	0.33%	0.30%	0.27%
CHI	21.68%	15.49%	11.97%	9.23%	7.00%
IND	38.88%	37.76%	34.79%	30.90%	26.64%
ASI	10.75%	13.11%	14.73%	16.23%	17.10%
LAT	2.27%	2.63%	2.80%	2.86%	2.85%
MID	1.22%	1.41%	1.63%	1.80%	2.00%
AFR	21.13%	26.19%	31.11%	36.31%	42.08%
Sum	100.00%	100.00%	100.00%	100.00%	100.00%

Carbon tax revenues amount to only about 0.3% of world GDP, so that international redistribution has little aggregate impact. Indeed, the impact of the tax on global GHG emissions and temperature change are virtually identical to the scenario with regional redistribution (compare Tables 15 and 6).

Table 15: Carbon tax and world GHG emissions — Scenario world carbon tax with international redistribution

	2010	2020	2030	2040
Carbon tax in USD	15	15	15	15
Carbon tax revenue in billion USD	98	114	131	144
GHG Emissions variation	-5.7%	-7.6%	-9.3%	-11.0%
CO2 Emissions variation	-7.8%	-10.3%	-12.5%	-14.6%
Temperature increase in °C	0.71	0.88	1.10	1.34
Difference w.r.t. baseline in °C	-0.00	-0.01	-0.02	-0.04

Tables 16 and 17 show that Africa is the main winner and its welfare gains reach 4.84% of household consumption in 2040, which is significantly different from the results obtained with a regional redistribution (-0.23% in Table 8). Other winners are India and Asia with welfare gains evaluated at 3.53% and 0.73% of household consumption.

Table 16: Welfare impact in percent of household consumption — Scenario world carbon tax with international redistribution

	2010	2020	2030	2040
EUR	-0.26%	-0.20%	-0.15%	-0.12%
XEU	-0.51%	-0.42%	-0.33%	-0.27%
FSU	-2.93%	-2.35%	-2.04%	-1.76%
USA	-0.37%	-0.32%	-0.28%	-0.24%
CAN	-0.74%	-0.60%	-0.49%	-0.40%
AUZ	-1.07%	-0.84%	-0.68%	-0.55%
JAP	-0.15%	-0.13%	-0.10%	-0.08%
MEX	-0.42%	-0.32%	-0.28%	-0.25%
CHI	-0.34%	-1.06%	-1.35%	-1.40%
IND	10.07%	7.88%	5.45%	3.53%
ASI	0.69%	0.75%	0.77%	0.73%
LAT	-0.24%	-0.15%	-0.12%	-0.10%
MID	-1.28%	-0.92%	-0.76%	-0.60%
AFR	5.05%	4.70%	4.77%	4.84%
WORLD	-0.02%	-0.02%	-0.02%	-0.05%

Despite the fact that China receives an important share of the tax revenue (7%), it also pays a significant part of it. Its net contribution equals -26 billions USD (see table 17), thus making China's net welfare variation negative (-1.4%). Other regions also have a decrease in terms of welfare with respect to the scenario World Tax with national redistribution scheme.

As expected, we find that the tax revenue allocation has a strong impact on

Table 17: Net revenue of the world carbon tax in billions USD

	2010	2020	2030	2040
EUR	-13	-13	-13	-14
XEU	-1	-1	-1	-1
FSU	-7	-9	-10	-11
USA	-23	-25	-27	-28
CAN	-2	-2	-2	-2
AUZ	-2	-2	-2	-2
JAP	-4	-4	-4	-3
MEX	-1	-1	-2	-2
CHI	0	-8	-17	-26
IND	32	33	31	27
ASI	5	8	11	14
LAT	-1	-1	-1	-1
MID	-4	-5	-6	-6
AFR	22	31	42	54
sum	0	0	0	0

the regional costs distribution of a world carbon tax. Similarly to the process of allocating initial emission quotas within an international emissions trading scheme, the choice of the tax revenue allocation rule may largely determine the distribution of the economic cost. In this scenario, the allocation criterion gives a real incentive to participate to the poorest regions like India and Africa but is unfavorable to other developing countries such as China or Latin America.

4.4 OECD Carbon Tax Revenue Redistribution Based on Income and Population

In the previous section, we concluded that only some of the DC have an incentive to participate to a world carbon tax even with international tax revenue redistribution based on GDP per capita. As already pointed out, China and Latin America are made relatively worse off with this form of redistribution. In this section we address this issue by introducing a carbon tax for OECD countries only, of 15 USD per ton. OECD encompasses the following world regions: EUR, XEU, USA, CAN, AUZ, JAP and MEX. They account for more than 40% of GHG emissions in 2010 and 29% in 2040. We exclude FSU from the industrialized group, first, because it is a major exporter of gas and crude oil and therefore the tax hits directly one of its major sources of national revenue (about 60% of Russian exports in 2005[4]).

The declining energy demand induces an important cost for this region, as it does also for the MID region (Organisation For Economic Co-operation and Development, 2007). Second, the introduction of any tax penalizes FSU strongly and combined with the declining energy demand, FSU would support a large share of the tax-induced burden. Therefore, as with the Kyoto Protocol, FSU does not have

[4]COMTRADE (UNSD, 2007)

an effective binding constraint (Kotov, 2002; Paltsev, 2000) and for this reason we choose to exclude FSU from the industrialized countries bound by carbon tax (Hovi and Holtsmark, 2006). For a variant around this point, refer to the sensitivity analysis appendix, *OECD and FSU Carbon Tax with Climate Change Compensation*.

Table 18: OECD Carbon Tax Revenue Redistribution Based on Income and Population and World GHG Emissions

	2010	2020	2030	2040
Carbon tax in USD	15	15	15	15
Carbon tax revenue in billion USD	47	50	52	53
GHG Emissions variation	-1.1%	-0.9%	-0.8%	-0.7%
CO_2 Emissions variation	-1.7%	-1.4%	-1.2%	-1.0%
Temperature increase in °C	0.71	0.89	1.12	1.38
Difference w.r.t. baseline in °C	0.00	0.00	0.00	-0.00

Table 18 shows that the carbon tax revenue is relatively minor, only 53 billion USD, which are redistributed among all countries based on GDP per capita. The impact on the temperature with respect to the baseline is null. This illustrates the extent of carbon leakage. Indeed, although the OECD carbon tax still applies to some 40% of world GHG emissions, it obtains only 22% (in 2010) to 7% (in 2040) of the CO_2 emissions reduction obtained with the World Tax (compare Table 15 and Table 18). The GHG and CO_2 emissions variation is small and brings no tangible results concerning global warming.

To explore options for overcoming this weakness, we now propose that the tax level in the next simulations be set endogenously on the basis of the damage costs estimated for DC. In so doing, the principle is that the aggregate tax revenue will cover the damage costs.

5 Devising a Carbon Tax on the Basis of Damage Costs of Climate Change

5.1 Damages Costs Estimates of Climate Change

Several studies have attempted to estimate damage costs due to climate change as a percentage of GDP (see table 19). Among the most recent studies, Kemfert (2005), using the WIAGEM model, predicts substantial damage costs in India and Asia in 2050 (5.89%) as well as high damage costs for China and Sub-Saharan Africa. Earlier work by Kemfert (2002), also with the WIAGEM model, found significant damage costs for Canada, New Zealand and Australia (3.13% for 2050 and 3.55% for 2100).

Nordhaus and Boyer (2000), using the RICE-99 model and contrary to Kemfert, found high damage costs in Europe (2.83%). Nevertheless, their estimates for India and Sub-Saharan Africa are relatively similar (4.93% and 3.91%). The FUND model developed by Tol (2002) predicts climate change gains for the USA, Europe and Russia among others for the year 2050 with 1°C temperature increase. However, Tol also expects substantial loss for Africa (4.10%).

Table 19: Damages Costs of Climate Change in % of GDP*

	WIAGEM[1]		WIAGEM[2]	RICE[3]	FUND[4]
	2050	2100	2050	2100(2.5°C)	2050(1°C)
USA	1.13%	1.22%	0.67%	0.45%	-3.40%
EU15	0.84%	0.85%	0.72%	2.83%	-3.70%
Canada, New Zeal., Australia	3.13%	3.55%	0.76%		
Japan	0.61%	0.59%	0.69%	0.50%	-1.00%
Russia	0.51%	0.85%	1.31%	-0.65%	-2.00%
Eastern and Central Europe	0.51%	0.85%	1.31%	0.71%	-2.00%
China	3.12%	2.54%	3.54%	0.22%	-2.10%
India	4.85%	5.49%	5.89%	4.93%	1.70%
Latin America	0.85%	0.95%	2.23%		0.10%
Asia	4.85%	5.49%	5.89%		1.70%
Mexico	0.87%	1.01%			
Middle East	0.65%	0.95%		1.95%	-1.10%
North Africa	0.65%	0.95%			
ROW	1.95%	2.15%	0.82%		
Subsaharian Africa	2.21%	3.66%	2.26%	3.91%	4.10%

Source: [1]Kemfert (2002), [2]Kemfert (2005), [3]Nordhaus and Boyer (2000), [4]Tol (2002)
*positive sign denotes damages

Recently, the Stern Review Stern (2007) has reported relatively high estimates based on the PAGE2002 model developed by Wahbaa and Hope (2006). In the next scenarios, the tax rate is endogenously determined by the GEMINI-E3 model and varies according to the estimated damage costs for DC. The idea is that the tax revenue must cover those costs as reported by the Stern Review. However some of assumptions made for our reference scenario differ from the assumptions made by the Stern Review. Therefore, we interpolate (see table 20) the results of the PAGE2002 model with respect to the temperature increase of our reference scenario. Table 20 provides the tax revenue target which equalizes the global warming impact as percent of GDP in DC as already mentioned. For our simulations, data has been personally and kindly provided by C. Hope using his PAGE2002 model but, contrary to the model version used by the Stern Review, neither balanced growth equivalents nor equity weights have been taken into account to compute the estimated damage costs for DC.

In each of the following scenarios in this chapter, the total tax revenue equals the sum of damage costs for DC, and it is then redistributed only to DC according to the estimated damages they suffer. In other words, the tax is set endogenously. Only the tax base varies according to the scenario considered (e.g., type of GHG emissions taxed, countries participating in the tax scheme) and the tax base parameters are precisely defined for each scenario.

Given the small impact of the tax on temperature increase (< 0.1°C) found in the next scenarios and the large uncertainties on climate sensitivity, we do not re-estimate the damage costs when the tax is applied.

Table 20: Temperature increase and damage costs for developing countries

	2010	2020	2030	2040
Temperature increase Reference scenario	0.71	0.89	1.12	1.38
Impacts as % of GDP				
MEX	0.20%	0.25%	0.31%	0.39%
CHI	0.00%	0.00%	0.01%	0.01%
IND	0.83%	1.04%	1.30%	1.61%
ASI	0.83%	1.04%	1.30%	1.61%
LAT	0.20%	0.25%	0.31%	0.39%
MID	0.50%	0.63%	0.79%	0.98%
AFR	0.50%	0.63%	0.79%	0.98%
Impacts in millions of USD				
MEX	1 831	3 480	6 119	9 055
CHI	109	235	480	784
IND	8 726	18 841	38 921	65 085
ASI	20 042	33 223	51 481	66 830
LAT	4 473	7 586	13 128	18 688
MID	7 580	13 910	25 766	37 378
AFR	5 054	9 357	17 223	25 551
Sum	47 815	86 632	153 118	223 372

5.2 OECD Carbon Tax with Climate Change Compensation

In the following scenario, we suppose that the tax on carbon emissions is only applied to OECD countries (EUR, XEU, USA, CAN, AUZ, JAP and MEX). In this case, MEX pays the tax but also receives part of the tax revenue on the basis of the estimated damage costs it suffer. The tables 21, 22, 23 and 24 present the results of this simulation. The tax is much higher in comparison with the last scenario but impacts only weakly on the level of emissions reduction. Table 22 shows a small increase of CO_2 emissions in DC (+2% in 2040) coming from two well known channels (Paltsev, 2001). First, the decrease in energy demand in OECD induces a decline in international energy prices which in turn increases energy demand in DC. Second, the loss of competitiveness for energy intensive industries in industrialized regions leads to relocation of some production to DC.

In addition, the money transfers from the OECD increase purchasing power and thereby energy consumption by DC households. As expected, DC are better off than under the previous scenario as they receive larger money transfers from OECD. Recall that damage costs of climate change are not deducted from their welfare in these calculations. In fact, when the welfare gains from their policy are compared with the damage costs in Table 20, it appears that all regions with the exception of China are overcompensated. The result is that the welfare loss of OECD is more important, and some regions like CAN, AUZ and XEU would be strongly affected. In this scenario, the main contributors to the international transfer would be USA and EUR with contributions estimated respectively at 118 and 62 billions USD in 2040.

Table 21: Carbon Tax and World GHG Emissions — Scenario OECD Carbon Tax with Climate Change Compensation

	2010	2020	2030	2040
Carbon tax in USD	16	28	49	72
Carbon tax revenue in billion USD	48	87	153	223
GHG Emissions variation	-1.1%	-1.7%	-2.3%	-2.6%
CO_2 Emissions variation	-1.5%	-2.3%	-3.2%	-3.6%
Temperature increase in °C	0.71	0.89	1.11	1.37
Difference w.r.t. baseline in °C	0.00	0.00	-0.00	-0.01

Table 22: CO_2 Emissions change in % — Scenario OECD Carbon Tax with Climate Change Compensation

	2010	2020	2030	2040
EUR	-3.1%	-5.2%	-7.8%	-9.9%
XEU	-4.3%	-7.3%	-10.8%	-13.6%
FSU	0.3%	0.3%	0.5%	0.7%
USA	-4.4%	-7.6%	-11.6%	-14.8%
CAN	-2.9%	-4.7%	-7.0%	-8.8%
AUZ	-5.2%	-9.1%	-13.9%	-17.7%
JAP	-2.9%	-5.1%	-7.8%	-10.0%
MEX	-2.3%	-3.5%	-5.8%	-8.0%
CHI	0.3%	0.4%	0.4%	0.4%
IND	1.2%	1.0%	1.3%	2.0%
ASI	0.9%	1.1%	1.5%	1.9%
LAT	0.6%	0.8%	1.3%	1.7%
MID	0.7%	0.9%	1.4%	1.8%
AFR	0.7%	1.0%	1.4%	1.7%
World	-1.5%	-2.3%	-3.2%	-3.6%

When looking at Tables 23 and 24, we see that some OECD countries may not be willing to participate in such a scheme. As already mentioned, it is quite penalizing for countries like XEU, CAN and AUZ in terms of welfare. The USA may also be reluctant to participate given the amount involved in international transfers. This leads us to consider a scenario where some OECD opt out of the carbon tax scheme.

Table 23: Welfare impact in percent of household consumption — Scenario OECD Carbon Tax with Climate Change Compensation

	2010	2020	2030	2040
EUR	-0.35%	-0.47%	-0.64%	-0.77%
XEU	-0.53%	-0.72%	-1.01%	-1.23%
FSU	-0.11%	-0.27%	-0.45%	-0.60%
USA	-0.32%	-0.46%	-0.63%	-0.74%
CAN	-0.74%	-1.03%	-1.42%	-1.68%
AUZ	-0.91%	-1.22%	-1.60%	-1.80%
JAP	-0.21%	-0.28%	-0.38%	-0.45%
MEX	0.02%	-0.01%	-0.17%	-0.31%
CHI	-0.09%	-0.09%	-0.10%	-0.09%
IND	3.28%	4.92%	6.90%	8.15%
ASI	2.22%	2.79%	3.20%	3.20%
LAT	0.54%	0.63%	0.79%	0.86%
MID	1.22%	1.27%	1.72%	1.91%
AFR	1.17%	1.33%	1.77%	2.00%
WORLD	-0.01%	-0.02%	-0.03%	-0.09%

Table 24: International transfers in billions USD — Scenario OECD Carbon Tax with Climate Change Compensation

	2010	2020	2030	2040
EUR	-14	-25	-43	-62
XEU	-1	-3	-4	-6
FSU	0	0	0	0
USA	-24	-45	-81	-118
CAN	-2	-4	-6	-9
AUZ	-2	-3	-5	-7
JAP	-4	-7	-11	-15
MEX	0	0	0	-1
CHI	0	0	0	1
IND	9	19	40	67
ASI	20	34	53	68
LAT	5	8	13	19
MID	8	14	26	38
AFR	5	10	18	26
sum	0	0	0	0

5.3 Carbon Tax in Europe, Japan and Mexico With Climate Change Compensation

In this scenario, we assume that some OECD countries are reluctant to participate in an international environmental agreement on global warming. In line with typical commentaries and our above results, we suppose the USA, CAN, AUZ and MEX would not take part in such an agreement. The tax now applies only to the carbon emissions of EUR, XEU and JAP, which amount to 17% of world emissions in 2010 and 12% in 2040 (see Table 4). Tables 25, 27 and 28 summarize the results. As can easily be seen, the impact on climate change is insignificant, the temperature does not change with respect to the baseline and GHG emissions variations are minimal even though the tax reaches incredible levels (up to 194 USD/tC in 2040).

Table 25: Carbon Tax and GHG Emissions – Scenario Carbon Tax on European and Japanese Emissions with Climate Change Compensation

	2010	2020	2030	2040
Carbon tax in USD	38	71	130	194
Carbon tax revenue in billion USD	48	87	153	223
GHG Emissions variation	-0.7%	-1.1%	-1.3%	-1.3%
CO_2 Emissions variation	-1.0%	-1.5%	-1.8%	-1.9%
Temperature increase in °C	0.71	0.89	1.12	1.38
Difference w.r.t. baseline in °C	0.00	0.00	0.00	-0.00

Table 26: CO_2 Emissions change in % — Scenario Carbon Tax on European and Japanese Emissions with Climate Change Compensation

	2010	2020	2030	2040
EUR	-6.8%	-11.0%	-15.2%	-18.0%
XEU	-9.0%	-14.4%	-19.6%	-23.2%
FSU	0.4%	0.6%	1.0%	1.3%
USA	0.2%	0.3%	0.3%	0.4%
CAN	0.3%	0.4%	0.5%	0.6%
AUZ	1.7%	2.1%	2.2%	2.5%
JAP	-6.5%	-10.5%	-14.5%	-17.3%
MEX	-5.6%	-8.4%	-13.1%	-16.9%
CHI	0.5%	0.5%	0.6%	0.5%
IND	1.2%	0.9%	1.1%	1.7%
ASI	0.9%	1.0%	1.3%	1.5%
LAT	0.5%	0.7%	0.9%	1.2%
MID	0.6%	0.9%	1.3%	1.7%
AFR	1.0%	1.3%	1.7%	2.1%
World	-1.0%	-1.5%	-1.8%	-1.9%

The OECD that pays for the tax must bear a large impact on their welfare in terms of household consumption. EUR and JAP must pay the huge sums of 150 and 37 billion USD respectively in 2040 in international transfers.

Table 27: Welfare impact in percent of household consumption – Scenario Carbon Tax on European and Japanese Emissions with climate change compensation

	2010	2020	2030	2040
EUR	-0.85%	-1.21%	-1.73%	-2.10%
XEU	-1.16%	-1.56%	-2.24%	-2.68%
FSU	-0.12%	-0.27%	-0.46%	-0.62%
USA	0.01%	0.00%	0.00%	-0.01%
CAN	0.00%	-0.01%	-0.03%	-0.04%
AUZ	-0.18%	-0.19%	-0.14%	-0.10%
JAP	-0.50%	-0.71%	-0.98%	-1.16%
MEX	-0.44%	-0.71%	-1.27%	-1.68%
CHI	-0.07%	-0.06%	-0.06%	-0.05%
IND	3.28%	4.92%	6.91%	8.17%
ASI	2.23%	2.81%	3.23%	3.23%
LAT	0.56%	0.66%	0.84%	0.92%
MID	1.35%	1.44%	1.96%	2.21%
AFR	1.15%	1.33%	1.78%	2.03%
WORLD	-0.04%	-0.07%	-0.10%	-0.26%

Table 28: International transfers in billions USD – Scenario Carbon Tax on European and Japanese Emissions with Climate Change Compensation

	2010	2020	2030	2040
EUR	-32	-58	-103	-150
XEU	-3	-6	-10	-15
FSU	0	0	0	0
USA	0	0	0	0
CAN	0	0	0	0
AUZ	0	0	0	0
JAP	-10	-17	-28	-37
MEX	-2	-4	-9	-16
CHI	0	0	0	1
IND	9	19	40	67
ASI	20	34	53	68
LAT	5	8	13	19
MID	8	14	26	38
AFR	5	10	18	26
sum	0	0	0	0

5.4 World Carbon Tax with Climate Change Compensation

In the following scenario we are concerned about improving the tax efficiency with respect to climate change. Thus, we suppose that a world uniform tax is applied to all CO_2 emissions emitted in the world. The level of the tax is set to meet the revenue target, which corresponds to total estimated damages from climate change for DC. That revenue is then redistributed according to the regional damage costs of climate change exposed in Table 20. The tables 29 to 32 present the results of this scenario. All countries participate significantly in world emissions reduction efforts, which in turn slightly lowers global warming, the temperature decreasing by 0.04°C with respect to the reference scenario in 2040. In comparison with the *OECD Carbon Tax with Climate Change Compensation* scenario, the tax rate is divided by three and the decline in GHG emissions is multiplied by almost six.

Table 29: Carbon Tax and World GHG Emissions — Scenario World Carbon Tax with Climate Change Compensation

	2010	2020	2030	2040
Carbon tax in USD	7	11	18	25
Carbon tax revenue in billion USD	48	87	153	223
GHG Emissions variation	-3.2%	-6.4%	-10.5%	-14.5%
CO_2 Emissions variation	-4.3%	-8.6%	-14.1%	-19.3%
Temperature increase in °C	0.71	0.88	1.10	1.34
Difference w.r.t. baseline in °C	-0.00	-0.00	-0.02	-0.04

Table 31 presents the relative welfare impacts of this scenario. The welfare changes due to the costs or gains due to climate changes are not accounted for. All the developing countries benefit from the implementation of this tax, except China for which a welfare loss is estimated at 2.75% of household consumption. This is a consequence of the fact that the estimated damage costs of climate change for China are rather small and that China is a positive net contributor with regard to the tax revenue; its contribution is more important that of the USA (see Table 32)

Concerning OECD, the welfare losses are modest except for FSU whose welfare losses are equal to 3.44% of household consumption. This is mainly coming from loss of terms of trade (decrease of fossil energy prices due to the declining demand).

Table 30: CO_2 Emissions change in % — Scenario World Carbon Tax with Climate Change Compensation

	2010	2020	2030	2040
EUR	-1.2%	-2.0%	-3.0%	-3.9%
XEU	-1.9%	-3.1%	-4.6%	-6.0%
FSU	-2.6%	-4.4%	-7.1%	-9.9%
USA	-2.0%	-3.3%	-5.0%	-6.5%
CAN	-1.2%	-1.9%	-2.7%	-3.4%
AUZ	-1.9%	-3.4%	-5.4%	-7.2%
JAP	-0.9%	-1.7%	-2.7%	-3.8%
MEX	-0.9%	-1.3%	-2.1%	-2.9%
CHI	-15.8%	-25.7%	-36.4%	-44.6%
IND	-4.3%	-9.2%	-15.0%	-20.2%
ASI	-1.4%	-3.2%	-5.5%	-7.9%
LAT	-0.9%	-1.5%	-2.4%	-3.3%
MID	-0.9%	-1.4%	-2.4%	-3.3%
AFR	-1.9%	-3.6%	-6.1%	-8.8%
World	-4.3%	-8.6%	-14.1%	-19.3%

Table 31: Welfare impact in percent of household consumption — Scenario World Carbon Tax with Climate Change Compensation

	2010	2020	2030	2040
EUR	-0.15%	-0.17%	-0.21%	-0.24%
XEU	-0.29%	-0.34%	-0.44%	-0.50%
FSU	-1.78%	-2.19%	-2.96%	-3.44%
USA	-0.17%	-0.24%	-0.32%	-0.38%
CAN	-0.36%	-0.46%	-0.59%	-0.66%
AUZ	-0.54%	-0.65%	-0.79%	-0.85%
JAP	-0.07%	-0.09%	-0.11%	-0.12%
MEX	0.24%	0.34%	0.39%	0.40%
CHI	-1.23%	-1.80%	-2.42%	-2.75%
IND	2.34%	3.54%	5.06%	6.09%
ASI	1.88%	2.33%	2.60%	2.52%
LAT	0.31%	0.35%	0.42%	0.44%
MID	0.64%	0.70%	0.98%	1.13%
AFR	0.70%	0.79%	1.04%	1.18%
WORLD	-0.01%	-0.02%	-0.03%	-0.10%

Table 32: International transfers in billions USD — Scenario World Carbon Tax with Climate Change Compensation

	2010	2020	2030	2040
EUR	-6	-11	-17	-24
XEU	-1	-1	-2	-2
FSU	-5	-8	-14	-20
USA	-11	-19	-33	-46
CAN	-1	-2	-2	-3
AUZ	-1	-1	-2	-3
JAP	-2	-3	-4	-6
MEX	1	2	4	5
CHI	-8	-17	-33	-51
IND	6	14	29	49
ASI	17	27	41	51
LAT	3	4	7	10
MID	5	9	16	24
AFR	3	6	11	16
sum	0	0	0	0

5.5 World GHG Tax with Climate Change Compensation

In this scenario, we assume that all the world GHG emissions are taxed (and not only CO_2) and that revenue is redistributed according to the estimated climate damages for DC. The tables 33 to 36 present the results of this scenario. In terms of welfare, differences with the scenario *World Carbon Tax with Climate Change Compensation* come mainly from the situation of each country with respect to non CO_2 emissions and from its dependency on energy imports (or energy exports). Countries in which non CO_2 emissions represent an important share in total GHG emissions, suffer relatively more from the introduction of a GHG tax. This is the case of AFR and LAT where the share of non CO_2 emissions in their GHG emissions is equal respectively to 62% and 57% in 2001. For these two regions the welfare gain is respectively equal to 0.63% (against 1.18%) and 0.15% (against 0.44%). Moreover, in this scenario the CO_2 emissions reduction and energy demand are smaller. This also explains why energy exporters are relatively better off, like FSU -2.87% (against -3.44%) and MID +1.35% (against 1.13%).

Table 33: GHG Tax and World GHG Emissions — Scenario World GHG Tax with Climate Change Compensation

	2010	2020	2030	2040
GHG tax in USD	5	8	13	18
GHG tax revenue in billion USD	48	87	153	223
GHG Emissions variation	-5.5%	-8.9%	-13.0%	-16.6%
CO_2 Emissions variation	-3.3%	-6.7%	-11.4%	-16.1%
Temperature increase in °C	0.71	0.88	1.08	1.32
Difference w.r.t. baseline in °C	-0.00	-0.01	-0.03	-0.06

As regards the tax effectiveness, the simulation predicts -0.06 °C difference for the temperature indicator, with respect to the baseline. This result once again stems from the fact that methane (CH_4) emissions are also targeted and this brings tangible effects rapidly as already explained.

Table 34: CO_2 Emissions change in % — Scenario World GHG Tax with Climate Change Compensation

	2010	2020	2030	2040
EUR	-0.9%	-1.5%	-2.3%	-2.9%
XEU	-1.4%	-2.3%	-3.5%	-4.5%
FSU	-2.1%	-3.3%	-5.4%	-7.6%
USA	-1.5%	-2.4%	-3.7%	-4.8%
CAN	-0.9%	-1.4%	-2.0%	-2.5%
AUZ	-1.4%	-2.4%	-3.9%	-5.2%
JAP	-0.6%	-1.2%	-1.9%	-2.7%
MEX	-0.7%	-1.1%	-1.7%	-2.3%
CHI	-12.3%	-20.6%	-30.4%	-38.6%
IND	-3.1%	-6.8%	-11.4%	-15.7%
ASI	-1.0%	-2.3%	-3.9%	-5.6%
LAT	-0.7%	-1.2%	-1.9%	-2.6%
MID	-0.6%	-1.0%	-1.7%	-2.3%
AFR	-1.4%	-2.5%	-4.4%	-6.4%
World	-3.3%	-6.7%	-11.4%	-16.1%

Looking at the tax level, it can be seen that using a larger GHG tax base instead of carbon tax, lowers the tax level from 25 to 18 USD. Despite this fact, China still pays a great amount since it is taxed for about 52 billion USD. From a narrowly economic perspective, this solution appears as a first best policy. The tax base includes all the various sources of global warming (GHG) and all countries. This solution brings definitively better overall results.

Table 35: Welfare impact in percent of household consumption — Scenario World GHG Tax with Climate Change Compensation

	2010	2020	2030	2040
EUR	-0.14%	-0.16%	-0.20%	-0.23%
XEU	-0.26%	-0.31%	-0.39%	-0.43%
FSU	-1.59%	-1.95%	-2.56%	-2.87%
USA	-0.14%	-0.20%	-0.27%	-0.32%
CAN	-0.33%	-0.43%	-0.53%	-0.58%
AUZ	-0.50%	-0.62%	-0.76%	-0.81%
JAP	-0.07%	-0.08%	-0.10%	-0.11%
MEX	0.22%	0.30%	0.37%	0.39%
CHI	-1.20%	-1.67%	-2.29%	-2.63%
IND	2.28%	3.53%	5.03%	6.02%
ASI	1.82%	2.25%	2.50%	2.42%
LAT	0.15%	0.14%	0.15%	0.15%
MID	0.72%	0.77%	1.13%	1.35%
AFR	0.39%	0.42%	0.55%	0.63%
WORLD	-0.01%	-0.02%	-0.03%	-0.07%

Table 36: International transfers in billions USD — Scenario GHG World Tax with Climate Change Compensation

	2010	2020	2030	2040
EUR	-6	-9	-15	-20
XEU	-1	-1	-2	-2
FSU	-4	-8	-13	-18
USA	-10	-16	-27	-37
CAN	-1	-2	-2	-3
AUZ	-1	-1	-2	-3
JAP	-2	-2	-4	-4
MEX	1	2	3	5
CHI	-8	-17	-33	-52
IND	6	14	29	48
ASI	16	26	40	50
LAT	1	2	3	4
MID	5	9	17	25
AFR	2	3	6	9
sum	0	0	0	0

6 Devising a Carbon Tax on the Basis of Adaptation Costs of Climate Change

Setting the revenue target according to the estimated damage costs may be a bold goal since, as it has been shown, some key global players may be reluctant to take part in such an agreements. Therefore in this section we set the target revenue to cover the adaptation costs. Various studies have shown that adaptation can bring numerous benefits at a lower cost (for instance, refer to the World Bank report (2006)). In Table 37, the adaptation costs are assumed to be equal to 20% of the damage estimates (see Table 20). This threshold of 20% is a compromise a several rough estimates. For instance, R.S.J. et al. (June 1998) suggest that the optimal adaptation costs lie between 7 and 25% of damage estimates. Recently, a World Bank report (2006) assumed that the adaptation costs amount to some 40 billion USD per year but could range from a few billion to up to 100 billion.

Thus, there is no coherent set of estimates for climate change adaptation as whole, meaning that the calculations presented here are subject to much uncertainty and engage some relatively arbitary conventions.

Table 37: Adaptation costs in millions of USD

	2010	2020	2030	2040
MEX	366	696	1224	1811
CHI	22	47	96	157
IND	1745	3768	7784	13017
ASI	4008	6645	10296	13366
LAT	895	1517	2626	3738
MID	1516	2782	5153	7476
AFR	1011	1871	3445	5110
Sum	9563	17326	30624	44674

In view of this, we perform a sensitivity analysis around our main assumptions, by fixing the adaptation costs at 10% and 30% of the estimated damages (refer to the appendix). In all the following scenarios, the tax revenue collected is redistributed according to the estimated adaptation costs of DC.

6.1 OECD Carbon Tax for Climate Change Adaptation

In this scenario, we assume that only OECD countries are subject to the carbon tax and that the tax revenue is fixed to match the adaptations costs over the period 2010 to 2040 (see Table 37). Table 38 presents the results of this scenario. The tax level is very low since it starts at 3 USD per ton of carbon in 2010 and reaches 13 USD in 2040. The impact on climate change is negligible (less than 1% on emissions variation and no temperature difference with respect to the baseline).

Table 39 presents the CO_2 emissions variation. As expected the variation are relatively modest and since the tax has little impact in OECD countries we do not

Table 38: Carbon Tax and World GHG Emissions — Scenario OECD Carbon Tax for Climate Change Adaptation

	2010	2020	2030	2040
Carbon tax in USD	3	5	9	13
Carbon tax revenue in billion USD	10	17	31	45
GHG Emissions variation	-0.2%	-0.4%	-0.5%	-0.7%
CO2 Emissions variation	-0.3%	-0.5%	-0.7%	-0.9%
Temperature increase in °C	0.71	0.89	1.12	1.38
Difference w.r.t. baseline in °C	0.00	0.00	0.00	0.00

observe strong carbon leakage phenomena. AUZ and XEU are the regions that undergo the greatest emissions changes.

Table 39: CO_2 Emissions change in percent — Scenario OECD Carbon Tax for Climate Change Adaptation

	2010	2020	2030	2040
EUR	-0.6%	-1.2%	-1.8%	-2.5%
XEU	-0.9%	-1.6%	-2.7%	-3.6%
FSU	0.1%	0.1%	0.1%	0.2%
USA	-0.9%	-1.6%	-2.7%	-3.6%
CAN	-0.6%	-1.0%	-1.5%	-2.0%
AUZ	-1.1%	-2.0%	-3.4%	-4.7%
JAP	-0.6%	-1.2%	-1.9%	-2.7%
MEX	-0.5%	-0.7%	-1.2%	-1.8%
CHI	0.1%	0.1%	0.1%	0.1%
IND	0.3%	0.2%	0.3%	0.5%
ASI	0.2%	0.2%	0.4%	0.5%
LAT	0.1%	0.2%	0.3%	0.4%
MID	0.1%	0.2%	0.3%	0.4%
AFR	0.2%	0.2%	0.3%	0.4%
World	-0.3%	-0.5%	-0.7%	-0.9%

As Table 40 shows, the impact on welfare is small enough to facilitate the adoption of this carbon tax in a global framework. USA loss is only -0.15% with respect to the baseline. CHI loss is extremely low, only -0.02%, and as already pointed out in the previous simulations, IND is the biggest winner since it gains 1.82% with respect to the baseline. The biggest loosers are XEU, CAN and AUZ (-0.24%, -0.32% and -0.39% respectively).

Table 40: Welfare impact in percent of household consumption — Scenario OECD Carbon Tax for Climate Change Adaptation

	2010	2020	2030	2040
EUR	-0.07%	-0.09%	-0.13%	-0.15%
XEU	-0.11%	-0.14%	-0.20%	-0.24%
FSU	0.03%	-0.04%	-0.08%	-0.11%
USA	-0.06%	-0.09%	-0.12%	-0.15%
CAN	-0.14%	-0.20%	-0.27%	-0.32%
AUZ	-0.19%	-0.25%	-0.34%	-0.39%
JAP	-0.04%	-0.06%	-0.07%	-0.09%
MEX	0.00%	0.00%	-0.02%	-0.05%
CHI	-0.02%	-0.02%	-0.02%	-0.02%
IND	0.68%	1.04%	1.51%	1.82%
ASI	0.45%	0.57%	0.65%	0.65%
LAT	0.11%	0.13%	0.16%	0.17%
MID	0.24%	0.26%	0.36%	0.40%
AFR	0.24%	0.27%	0.36%	0.41%
WORLD	0.00%	0.00%	-0.01%	-0.01%

6.2 World Carbon Tax with Climate Change Adaptation

In this scenario the carbon tax is applied worldwide in order to collect funds for climate change adaptation. Table 41 summarizes the main results. By increasing the tax base, the rate is lower and efficiency is also enhanced. Since the tax is applied worldwide, effectiveness against climate change is reinforced with respect to the previous scenario despite its relatively minor impact (CO_2 emissions variation is -5.9% in 2040, and temperature difference w.r.t. the baseline is only -0.01°C). It also allows a very low tax rate, only 4 USD/ton of carbon in 2040.

Table 41: Carbon Tax and World GHG Emissions — Scenario World Carbon Tax for Climate Change Adaptation

	2010	2020	2030	2040
Carbon tax in USD	1	2	3	4
Carbon tax revenue in billion USD	10	17	31	45
GHG Emissions variation	-0.7%	-1.5%	-2.9%	-4.5%
CO2 Emissions variation	-0.9%	-2.1%	-3.8%	-5.9%
Temperature increase in °C	0.71	0.89	1.11	1.37
Difference w.r.t. baseline in °C	0.00	0.00	-0.00	-0.01

Table 41 shows the detailed CO_2 emissions variation per world regions. CHI is the region that reduces the most its emissions: by -15.5% in 2040. As previously explained, CHI relies on large coal reserves to produce energy, which emits a lot of carbon. Emissions in IND are reduced by -5.5% in 2040; this is the second biggest relative emissions reduction after CHI. The welfare impact is less than 1% negative for CHI and FSU (the latter being a large exporter of fossil energy). We

Table 42: CO_2 Emissions change in — Scenario World Carbon Tax for Climate Change Adaptation

	2010	2020	2030	2040
EUR	-0.2%	-0.4%	-0.6%	-0.7%
XEU	-0.3%	-0.6%	-0.9%	-1.1%
FSU	-0.5%	-0.9%	-1.4%	-2.0%
USA	-0.4%	-0.6%	-1.0%	-1.2%
CAN	-0.2%	-0.3%	-0.5%	-0.6%
AUZ	-0.3%	-0.6%	-0.9%	-1.2%
JAP	-0.1%	-0.3%	-0.4%	-0.5%
MEX	-0.2%	-0.3%	-0.4%	-0.5%
CHI	-3.7%	-6.7%	-11.0%	-15.5%
IND	-0.9%	-2.0%	-3.5%	-5.1%
ASI	-0.2%	-0.5%	-0.9%	-1.2%
LAT	-0.2%	-0.3%	-0.5%	-0.6%
MID	-0.2%	-0.3%	-0.4%	-0.6%
AFR	-0.4%	-0.7%	-1.2%	-1.7%
World	-0.9%	-2.1%	-3.8%	-5.9%

propose that this pattern of results should be broadly acceptable in the framework of an international environmental agreement. For OECD countries, the impact is so small that it is quite negligible.

Table 43: Welfare impact in percent of household consumption — Scenario World Carbon Tax for Climate Change Adaptation

	2010	2020	2030	2040
EUR	-0.03%	-0.03%	-0.04%	-0.04%
XEU	-0.06%	-0.06%	-0.08%	-0.08%
FSU	-0.29%	-0.39%	-0.52%	-0.58%
USA	-0.03%	-0.05%	-0.06%	-0.07%
CAN	-0.06%	-0.08%	-0.11%	-0.12%
AUZ	-0.11%	-0.13%	-0.16%	-0.18%
JAP	-0.01%	-0.02%	-0.02%	-0.02%
MEX	0.05%	0.07%	0.09%	0.09%
CHI	-0.26%	-0.39%	-0.54%	-0.63%
IND	0.48%	0.74%	1.08%	1.32%
ASI	0.38%	0.48%	0.54%	0.53%
LAT	0.06%	0.08%	0.09%	0.10%
MID	0.13%	0.15%	0.23%	0.28%
AFR	0.15%	0.17%	0.23%	0.28%
WORLD	0.00%	0.00%	0.00%	-0.01%

6.3 World GHG Tax for Climate Change Adaptation

In this scenario, we apply a world GHG tax and the tax level is set endogenously to match the adaptation costs occuring in DC. The tax revenue is then redistributed to DC according to the estimated adaptation costs. Table 44 presents the main results. Since taxing all GHG emissions increases effectiveness and efficiency, the tax level is slightly lower and its impact is improved with respect to the previous scenario. The temperature indicator increase is slowed down by -0.3°C.

Table 44: GHG Tax and World GHG Emissions — Scenario World GHG Tax for Climate Change Adaptation

	2010	2020	2030	2040
Carbon tax in USD	1	2	2	3
Carbon tax revenue	10	17	31	45
GHG Emissions variation	-3.0%	-3.9%	-4.9%	-6.2%
CO2 Emissions variation	-0.7%	-1.6%	-2.9%	-4.6%
Temperature increase in °C	0.71	0.88	1.10	1.35
Difference w.r.t. baseline in °C	-0.00	-0.00	-0.01	-0.03

Table 45 summarizes the CO_2 emissions variations per region. Since the tax base includes all GHG, the impact on CO_2 emissions is slightly reduced with respect to the tax on carbon emissions. However we do still see a big impact on CHI's emissions (-12.0%).

Table 46 shows that the impact on CHI and FSU welfare is, once again, relatively the most important, despite being reduced with respect to the scenario *World Carbon Tax with Climate Change Adaptation*. the variations with respect to the

Table 45: CO_2 Emissions variation in — Scenario World GHG Tax for Climate Change Adaptation

	2010	2020	2030	2040
EUR	-0.2%	-0.3%	-0.4%	-0.5%
XEU	-0.2%	-0.5%	-0.7%	-0.9%
FSU	-0.4%	-0.7%	-1.1%	-1.5%
USA	-0.3%	-0.5%	-0.7%	-0.9%
CAN	-0.2%	-0.3%	-0.4%	-0.4%
AUZ	-0.2%	-0.4%	-0.7%	-0.9%
JAP	-0.1%	-0.2%	-0.3%	-0.4%
MEX	-0.2%	-0.2%	-0.3%	-0.4%
CHI	-2.8%	-5.0%	-8.4%	-12.0%
IND	-0.6%	-1.5%	-2.6%	-3.8%
ASI	-0.2%	-0.4%	-0.6%	-0.9%
LAT	-0.1%	-0.2%	-0.4%	-0.5%
MID	-0.1%	-0.2%	-0.3%	-0.4%
AFR	-0.3%	-0.5%	-0.9%	-1.3%
World	-0.7%	-1.6%	-2.9%	-4.6%

Table 46: Welfare impact in percent of household consumption — Scenario World GHG Tax with Climate Change Adaptation

	2010	2020	2030	2040
EUR	-0.03%	-0.03%	-0.04%	-0.04%
XEU	-0.05%	-0.06%	-0.07%	-0.07%
FSU	-0.25%	-0.35%	-0.47%	-0.51%
USA	-0.03%	-0.04%	-0.05%	-0.06%
CAN	-0.06%	-0.08%	-0.10%	-0.11%
AUZ	-0.10%	-0.12%	-0.15%	-0.17%
JAP	-0.01%	-0.02%	-0.02%	-0.02%
MEX	0.04%	0.06%	0.08%	0.09%
CHI	-0.25%	-0.35%	-0.49%	-0.58%
IND	0.47%	0.74%	1.07%	1.31%
ASI	0.37%	0.46%	0.51%	0.50%
LAT	0.03%	0.03%	0.04%	0.05%
MID	0.14%	0.16%	0.25%	0.31%
AFR	0.09%	0.10%	0.14%	0.16%
WORLD	0.00%	0.00%	0.00%	-0.01%

baseline are, however, not so large as to be inacceptable.

To summarize, a world GHG tax has only a slightly more important impact on the temperature change by comparison to a world carbon tax, since all other variations are extremely similar. From a pure economic perspective, a world GHG tax is a first best policy (that is, the defined goal is achieved at the lowest cost).

7 Conclusions

The figures 5 and 6 summarize the scenarios simulated in this study[5]. We can draw several lessons.

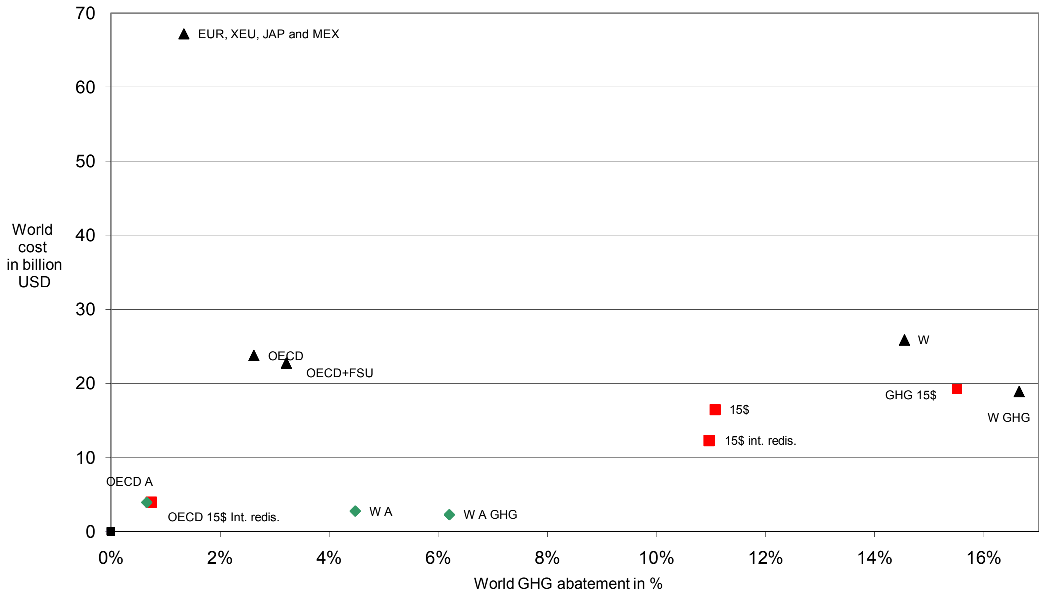

Figure 5: World Cost *versus* GHG Abatement in 2040

Concerning a tax revenue set to compensate DC from climate change damages, we can observe:

- One could consider not taxing DC for the reason that their economies would suffer and the counterbalanced effort for the OECD would be acceptable. Indeed, taxing developing countries will not encourage them to participate. If all countries are taxed, China and FSU are clearly the least interested in participating. FSU is a big polluter and receives nothing. Note that in all simulations USA is an important contributor to the international money transfer, and its participation is therefore crucial.

[5]The black triangles represent the simulations with climate change compensation, the squares represents the uniforms 15 USD tax simulations, and finally the green diamonds represent the simulations with climate change adaptation

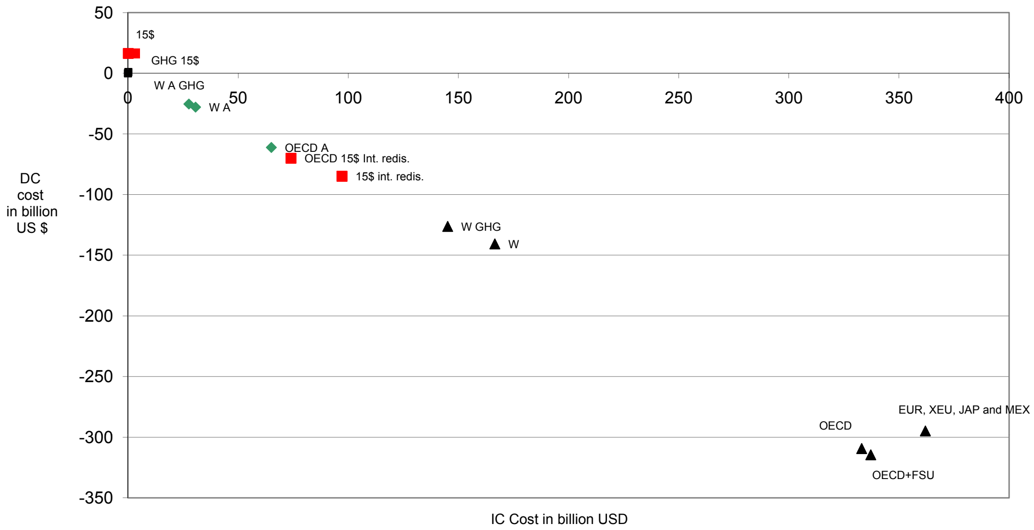

Figure 6: IC Welfare Cost *versus* DC Welfare Costs in 2040

- In all simulations, the USA is an important contributor to the international money transfert, and its participation is therefore crucial.
- Taxing only OECD countries would be an ineffective policy in respect to emissions and participation incentives. Indeed world GHG emissions reduction would be very limited and emissions would actually increase in DC. The economic burden supported by the OECD countries could be perceived as too high and therefore the risk of withdrawal from any international environmental agreement would be significant. We have shown that if USA, CAN and AUZ decide not to implement a such tax, the cost for other industrialized countries could be multiplied at least by two (compare Tables 23 and 27), jeopardizing the implementation of such a policy.
- On the contrary, a flat low carbon tax (e.g. 15 USD) applied to all carbon emissions worldwide could induce significant CO_2 reduction with a limited overall cost. GHG emissions would decrease by 11%, but the carbon tax revenue is too small to compensate DC for the estimated damage costs of climate change.
- If we want to compensate those damage costs, obtain significant carbon emissions reduction, and not penalize severely the OECD, the only solution is to tax all countries. The scenario performed on this assumption, shows that carbon emission abatement would be substantial (more than 19%, see Table 29), but that gains or losses stemming from changes in terms of trade could induce pernicious effects on welfare. Notably, FSU would suffer from loss of terms of trade (its welfare loss is estimated to 3.44% of household

consumption). By contrast, Indian welfare gain is estimated to 6.09% of household consumption (see Table 31).

- Finally, taxing all GHG emissions and not only carbon emissions generates two gains: an environmental gain, GHG emissions abatement would be more important (-16.6% w.r.t. -14.5% for the same tax revenue, compare Tables 29 and 33); and an economic gain, the global cost would decrease by 30%. However, this solution appears difficult to implement.

- In general, the policies simulated affect China and India quite differently. This is important, given that these are two countries that are often mentioned in one breath. China is a loser with nearly any form of carbon tax, including those that target only the industrialized countries. On the other hand, India is a large winner when there is revenue redistribution, and even the world carbon tax without redistribution affects it only moderately. The divergence between these two countries is related to the facts that China holds large reserves of fossil energy and its revenue per capita is much higher and growing faster than that of India. In addition, India is predicted to suffer greatly from climate change while China is not. Thus it may well be much easier to convince India to participate in global efforts than China.

Concerning a tax revenue for an adaptation fund, we can observe:

- The overall cost is reduced and this might foster the acceptance of such a policy. Even countries like CHI or FSU, which, once again, must bear the greatest losses in terms of welfare with respect to their baseline, should be willing to participate if economic compensations (like a free trade agreement) are offered to them in order to reduce their loss. The above remark on China and India is also valid when it comes to the adaptation fund issue.

- The carbon tax would reach only 4 USD per ton in 2040. Once expressed in units per ton of CO_2, the tax rate is about 1 USD per ton. We can note again the relative efficiency of the GHG tax over the carbon dioxide tax, as shown in Figure 5, since for about the same world cost we obtain about 2% more in world GHG abatement.

- The overall impact on climate change is negligible.

Finally, Figure 7 compares different scenarios of tax revenue with climate change compensation with respect to the expected CO_2 concentration until 2040.

Implementing self-enforcing international agreements on GHG emission abatement is a difficult task. One effective way could be to link technology R&D with climate change negotiations. Because of free-riding problems in the climate change negotiations (Barrett, 1990, 1994; Carraro and Siniscalco, 1992; Hoel, 1994), international environmental agreements must be self-enforcing. It is thus necessary to create incentives for broad participation and full compliance.

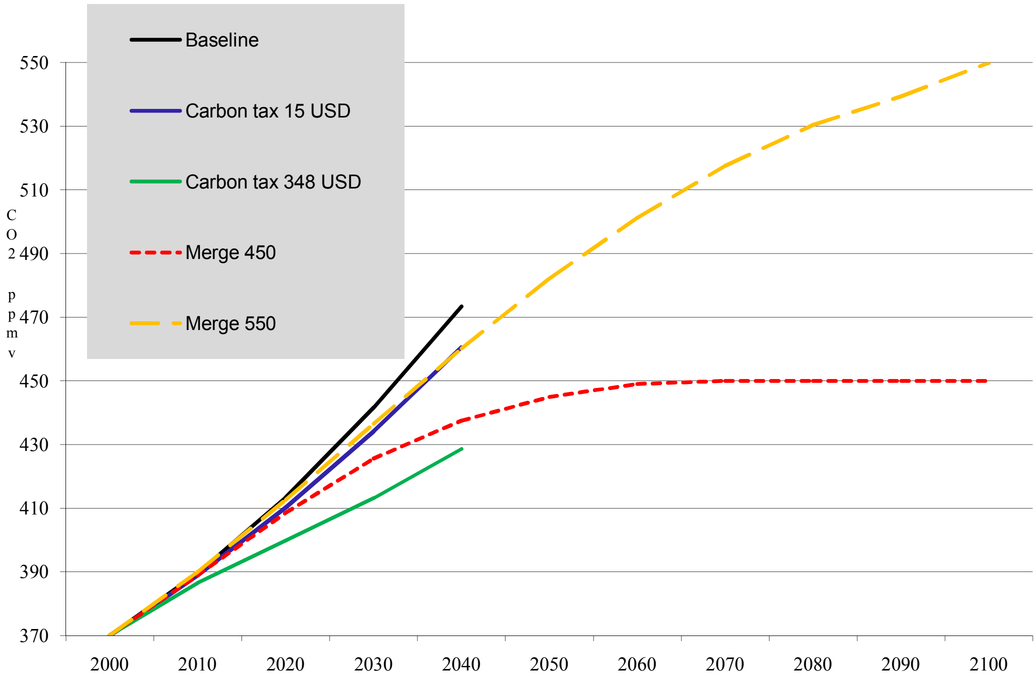

Figure 7: Comparison of different CO_2 concentrations

Based on insights provided by game theory, some economists have proposed to restructure incentives through "issues linkages" consisting in exchanging concessions across different policy dimensions. Multilateral cooperation across different issues gives the possibility to form agreements and to enforce them. Several authors have proposed to link international environmental agreements to international trade (e.g. (Barrett, 1997, 1999)), technology R&D and technology diffusion (e.g. (Carraro and Siniscalco, 1996; Katsoulacos, 1996; Tol et al., 2000)), sustainable development and greening development assistance (Beg et al., 2002; Toman, 2002), international emission trading and the CDM (Viguier, 2004). It is noteworthy that REME has recently started a wide-ranging research project (financed by the European Union) on international post-Kyoto climate policy, with special emphasis on India and China and on technology transfer.

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8 Appendix: Sensitivity Analysis

8.1 OECD Carbon Tax with Climate Change Adaptation

8.1.1 Adaptations Amounts 10% of the Estimated Damage Costs (Low)

In this scenario, the adaption costs are assumed to amount to 10% of the estimated damage costs and only OECD countries pay a carbon tax.

Table 47: Carbon Tax and World GHG Emissions — Scenario OECD Carbon Tax with Climate Change Adaptation (Low)

	2010	2020	2030	2040
Carbon tax in USD	1	3	4	6
Carbon tax revenue	5	9	15	22
GHG Emissions variation	-0.1%	-0.2%	-0.3%	-0.3%
CO2 Emissions variation	-0.1%	-0.3%	-0.4%	-0.5%
Temperature increase in °C	0.71	0.89	1.12	1.38
Difference w.r.t. baseline in °C	0.00	0.00	0.00	0.00

Table 48: CO_2 Emissions change in — Scenario OECD Carbon Tax with Climate Change Adaptation (Low)

	2010	2020	2030	2040
EUR	-0.3%	-0.6%	-0.9%	-1.3%
XEU	-0.4%	-0.8%	-1.4%	-1.9%
FSU	0.1%	0.0%	0.1%	0.1%
USA	-0.4%	-0.8%	-1.4%	-1.9%
CAN	-0.3%	-0.5%	-0.8%	-1.0%
AUZ	-0.5%	-1.0%	-1.7%	-2.5%
JAP	-0.3%	-0.6%	-1.0%	-1.4%
MEX	-0.2%	-0.4%	-0.6%	-0.9%
CHI	0.0%	0.0%	0.1%	0.1%
IND	0.1%	0.1%	0.2%	0.2%
ASI	0.1%	0.1%	0.2%	0.2%
LAT	0.1%	0.1%	0.1%	0.2%
MID	0.1%	0.1%	0.1%	0.2%
AFR	0.1%	0.1%	0.2%	0.2%
World	-0.1%	-0.3%	-0.4%	-0.5%

8.1.2 Adaptations Amounts 30% of the Estimated Damage Costs (High)

In this scenario, the adaption costs are assumed to amount to 30% of the estimated damage costs and only OECD countries pay a carbon tax.

Table 49: Welfare impact in percent of household consumption — Scenario OECD Carbon Tax with Climate Change Adaptation (Low)

	2010	2020	2030	2040
EUR	-0.03%	-0.05%	-0.06%	-0.07%
XEU	-0.05%	-0.07%	-0.10%	-0.12%
FSU	0.05%	-0.01%	-0.04%	-0.05%
USA	-0.03%	-0.05%	-0.06%	-0.07%
CAN	-0.07%	-0.10%	-0.13%	-0.16%
AUZ	-0.09%	-0.13%	-0.17%	-0.20%
JAP	-0.02%	-0.03%	-0.04%	-0.04%
MEX	0.00%	0.00%	-0.01%	-0.02%
CHI	-0.01%	-0.01%	-0.01%	-0.01%
IND	0.34%	0.53%	0.76%	0.92%
ASI	0.23%	0.28%	0.33%	0.33%
LAT	0.05%	0.06%	0.08%	0.09%
MID	0.12%	0.13%	0.18%	0.20%
AFR	0.12%	0.14%	0.18%	0.21%
WORLD	0.00%	0.00%	0.00%	-0.01%

Table 50: Carbon Tax and World GHG Emissions — Scenario OECD Carbon Tax with Climate Change Adaptation (High)

	2010	2020	2030	2040
Carbon tax in USD	5	8	14	20
Carbon tax revenue	14	26	46	67
GHG Emissions Variation	-0.3%	-0.5%	-0.8%	-1.0%
CO2 Emissions Variation	-0.4%	-0.7%	-1.1%	-1.3%
Temperature increase in °C	0.71	0.89	1.12	1.38
Difference w.r.t. baseline in °C	0.00	0.00	0.00	0.00

Table 51: CO_2 Emissions change in — Scenario OECD Carbon Tax with Climate Change Adaptation (High)

	2010	2020	2030	2040
EUR	-0.9%	-1.7%	-2.7%	-3.6%
XEU	-1.3%	-2.4%	-3.9%	-5.3%
FSU	0.1%	0.1%	0.2%	0.2%
USA	-1.3%	-2.4%	-3.9%	-5.3%
CAN	-0.9%	-1.4%	-2.2%	-2.9%
AUZ	-1.6%	-3.0%	-5.0%	-6.9%
JAP	-0.9%	-1.7%	-2.8%	-3.9%
MEX	-0.7%	-1.1%	-1.8%	-2.6%
CHI	0.1%	0.1%	0.2%	0.2%
IND	0.4%	0.3%	0.4%	0.7%
ASI	0.3%	0.4%	0.5%	0.7%
LAT	0.2%	0.3%	0.4%	0.6%
MID	0.2%	0.3%	0.4%	0.6%
AFR	0.2%	0.3%	0.5%	0.6%
World	-0.4%	-0.7%	-1.1%	-1.3%

Table 52: Welfare impact in percent of household consumption — Scenario OECD Carbon Tax with Climate Change Adaptation (High)

	2010	2020	2030	2040
EUR	-0.10%	-0.14%	-0.19%	-0.23%
XEU	-0.16%	-0.21%	-0.30%	-0.36%
FSU	0.01%	-0.06%	-0.13%	-0.17%
USA	-0.10%	-0.14%	-0.19%	-0.22%
CAN	-0.21%	-0.30%	-0.41%	-0.48%
AUZ	-0.28%	-0.38%	-0.50%	-0.57%
JAP	-0.06%	-0.08%	-0.11%	-0.13%
MEX	0.01%	0.00%	-0.04%	-0.08%
CHI	-0.03%	-0.03%	-0.03%	-0.03%
IND	1.02%	1.55%	2.23%	2.69%
ASI	0.67%	0.85%	0.97%	0.97%
LAT	0.16%	0.19%	0.24%	0.26%
MID	0.37%	0.39%	0.53%	0.60%
AFR	0.36%	0.41%	0.54%	0.62%
WORLD	0.00%	-0.01%	-0.01%	-0.02%

8.2 World Carbon Tax with Climate Change Adaptation

8.2.1 Adaptations Amounts 10% of the Estimated Damage Costs (Low)

In this scenario, the adaption costs are assumed to amount to 10% of the estimated damage costs and all countries pay a carbon tax.

Table 53: Carbon Tax and World GHG Emissions — Scenario World Carbon Tax with Climate Change Adaptation (Low)

	2010	2020	2030	2040
Carbon tax in USD	1	1	2	2
Carbon tax revenue	5	9	15	22
GHG Emissions variation	-0.3%	-0.8%	-1.5%	-2.4%
CO2 Emissions variation	-0.5%	-1.1%	-2.0%	-3.1%
Temperature increase in °C	0.71	0.89	1.12	1.38
Difference w.r.t. baseline in °C	0.00	0.00	0.00	-0.00

Table 54: CO_2 Emissions change in — Scenario World Carbon Tax with Climate Change Adaptation (Low)

	2010	2020	2030	2040
EUR	-0.1%	-0.2%	-0.3%	-0.3%
XEU	-0.1%	-0.3%	-0.4%	-0.6%
FSU	-0.2%	-0.4%	-0.7%	-1.0%
USA	-0.2%	-0.3%	-0.5%	-0.6%
CAN	-0.1%	-0.2%	-0.2%	-0.3%
AUZ	-0.1%	-0.3%	-0.5%	-0.6%
JAP	-0.1%	-0.1%	-0.2%	-0.2%
MEX	-0.1%	-0.1%	-0.2%	-0.3%
CHI	-1.9%	-3.4%	-5.8%	-8.3%
IND	-0.4%	-1.0%	-1.8%	-2.6%
ASI	-0.1%	-0.3%	-0.4%	-0.5%
LAT	-0.1%	-0.1%	-0.2%	-0.3%
MID	-0.1%	-0.1%	-0.2%	-0.3%
AFR	-0.2%	-0.3%	-0.6%	-0.8%
World	-0.5%	-1.1%	-2.0%	-3.1%

Table 55: Welfare impact in percent of household consumption — Scenario World Carbon Tax with Climate Change Adaptation (Low)

	2010	2020	2030	2040
EUR	-0.01%	-0.02%	-0.02%	-0.02%
XEU	-0.03%	-0.03%	-0.04%	-0.04%
FSU	-0.11%	-0.18%	-0.25%	-0.28%
USA	-0.02%	-0.02%	-0.03%	-0.04%
CAN	-0.03%	-0.04%	-0.05%	-0.06%
AUZ	-0.05%	-0.07%	-0.08%	-0.09%
JAP	-0.01%	-0.01%	-0.01%	-0.01%
MEX	0.02%	0.04%	0.04%	0.05%
CHI	-0.13%	-0.20%	-0.27%	-0.32%
IND	0.24%	0.37%	0.55%	0.67%
ASI	0.19%	0.24%	0.27%	0.26%
LAT	0.03%	0.04%	0.05%	0.05%
MID	0.06%	0.08%	0.12%	0.15%
AFR	0.08%	0.09%	0.12%	0.14%
WORLD	0.00%	0.00%	0.00%	0.00%

8.2.2 Adaptations Amounts 30% of the Estimated Damage Costs (High)

In this scenario, the adaption costs are assumed to amount to 30% of the estimated damage costs and all countries pay a carbon tax.

Table 56: Carbon Tax and World GHG Emissions — Scenario World Carbon Tax with Climate Change Adaptation (High)

	2010	2020	2030	2040
Carbon tax in USD	2	3	5	7
Carbon tax revenue	15	26	46	67
GHG Emissions Variation	-1.0%	-2.3%	-4.2%	-6.3%
CO2 Emissions Variation	-1.4%	-3.0%	-5.5%	-8.4%
Temperature increase in °	0.71	0.89	1.11	1.37
Difference w.r.t. baseline in °C	0.00	-0.00	-0.00	-0.01

Table 57: CO_2 Emissions change in — Scenario World Carbon Tax with Climate Change Adaptation (High)

	2010	2020	2030	2040
EUR	-0.3%	-0.6%	-0.9%	-1.1%
XEU	-0.5%	-0.9%	-1.3%	-1.7%
FSU	-0.7%	-1.3%	-2.1%	-3.1%
USA	-0.6%	-1.0%	-1.5%	-1.9%
CAN	-0.3%	-0.5%	-0.8%	-0.9%
AUZ	-0.5%	-0.9%	-1.5%	-1.9%
JAP	-0.2%	-0.4%	-0.6%	-0.9%
MEX	-0.3%	-0.4%	-0.6%	-0.8%
CHI	-5.4%	-9.7%	-15.6%	-21.6%
IND	-1.3%	-3.0%	-5.2%	-7.5%
ASI	-0.4%	-0.8%	-1.4%	-2.0%
LAT	-0.2%	-0.4%	-0.7%	-1.0%
MID	-0.2%	-0.4%	-0.7%	-0.9%
AFR	-0.6%	-1.0%	-1.8%	-2.6%
World	-1.4%	-3.0%	-5.5%	-8.4%

Table 58: Welfare impact in percent of household consumption — Scenario World Carbon Tax with Climate Change Adaptation (High)

	2010	2020	2030	2040
EUR	-0.04%	-0.05%	-0.06%	-0.07%
XEU	-0.08%	-0.10%	-0.12%	-0.13%
FSU	-0.47%	-0.60%	-0.80%	-0.90%
USA	-0.05%	-0.07%	-0.09%	-0.11%
CAN	-0.10%	-0.13%	-0.16%	-0.18%
AUZ	-0.16%	-0.20%	-0.24%	-0.27%
JAP	-0.02%	-0.02%	-0.03%	-0.03%
MEX	0.07%	0.11%	0.13%	0.14%
CHI	-0.39%	-0.58%	-0.80%	-0.93%
IND	0.72%	1.10%	1.60%	1.96%
ASI	0.57%	0.71%	0.80%	0.78%
LAT	0.10%	0.11%	0.14%	0.15%
MID	0.20%	0.23%	0.34%	0.41%
AFR	0.22%	0.25%	0.35%	0.41%
WORLD	0.00%	0.00%	-0.01%	-0.02%

8.3 OECD and FSU Carbon Tax with Climate Change Compensation

In this scenario, we assume the participation of FSU and OECD countries to a carbon tax. The tax revenue is redistributed according to damage costs occured in the DC.

Table 59: Carbon Tax and World GHG Emissions — Scenario OECD and FSU Carbon Tax with Climate Change Compensation

	2010	2020	2030	2040
Carbon tax in USD	13	22	39	57
Carbon tax revenue in billion USD	48	87	153	223
GHG Emissions variation	-1.2%	-1.9%	-2.7%	-3.2%
CO2 Emissions variation	-1.6%	-2.6%	-3.7%	-4.4%
Temperature increase in °C	0.71	0.89	1.11	1.37
Difference w.r.t. baseline in °C	0.00	0.00	-0.00	-0.01

Table 60: CO_2 Emissions change in % — Scenario OECD and FSU Carbon Tax with Climate Change Compensation

	2010	2020	2030	2040
EUR	-2.4%	-4.2%	-6.3%	-8.0%
XEU	-3.4%	-5.8%	-8.8%	-11.3%
FSU	-4.7%	-8.1%	-13.1%	-17.8%
USA	-3.6%	-6.3%	-9.7%	-12.6%
CAN	-2.4%	-3.8%	-5.8%	-7.3%
AUZ	-4.4%	-7.6%	-11.8%	-15.3%
JAP	-2.4%	-4.3%	-6.6%	-8.6%
MEX	-1.8%	-2.8%	-4.7%	-6.6%
CHI	0.3%	0.3%	0.4%	0.4%
IND	1.1%	0.9%	1.3%	1.9%
ASI	0.9%	1.1%	1.5%	1.9%
LAT	0.6%	0.8%	1.2%	1.6%
MID	0.8%	1.2%	1.8%	2.5%
AFR	0.7%	0.9%	1.3%	1.7%
World	-1.6%	-2.6%	-3.7%	-4.4%

Table 61: Welfare impact in percent of household consumption — Scenario OECD and FSU Carbon Tax with Climate Change Compensation

	2010	2020	2030	2040
EUR	-0.28%	-0.37%	-0.50%	-0.60%
XEU	-0.47%	-0.63%	-0.87%	-1.05%
FSU	-3.08%	-4.11%	-6.00%	-7.31%
USA	-0.29%	-0.41%	-0.57%	-0.67%
CAN	-0.62%	-0.85%	-1.17%	-1.38%
AUZ	-0.75%	-0.99%	-1.29%	-1.45%
JAP	-0.17%	-0.22%	-0.29%	-0.35%
MEX	0.08%	0.09%	0.00%	-0.11%
CHI	-0.07%	-0.07%	-0.07%	-0.06%
IND	3.29%	4.93%	6.92%	8.16%
ASI	2.23%	2.81%	3.23%	3.23%
LAT	0.53%	0.62%	0.79%	0.86%
MID	1.18%	1.24%	1.71%	1.94%
AFR	1.13%	1.29%	1.73%	1.98%
WORLD	-0.01%	-0.02%	-0.03%	-0.09%

8.4 OECD and FSU Carbon Tax with Climate Change Adaptation

In this scenario, we assume the participation of FSU and OECD countries to a carbon tax. The tax revenue is redistributed according to adaptation costs (20% of damage costs estimates) occured in the DC.

Table 62: Carbon Tax and World GHG Emissions — Scenario OECD and FSU Carbon Tax with Climate Change Adaptation

	2010	2020	2030	2040
Carbon tax in USD	2	4	7	10
Carbon tax revenue in billion USD	10	17	31	45
GHG Emissions variation	-0.2%	-0.4%	-0.6%	-0.8%
CO2 Emissions variation	-0.3%	-0.6%	-0.8%	-1.1%
Temperature increase in °C	0.71	0.89	1.12	1.38
Difference w.r.t. baseline in °C	0.00	0.00	0.00	0.00

Table 63: CO_2 Emissions change in — Scenario OECD and FSU Carbon Tax with Climate Change Adaptation

	2010	2020	2030	2040
EUR	-0.5%	-0.9%	-1.4%	-1.9%
XEU	-0.7%	-1.3%	-2.0%	-2.8%
FSU	-0.9%	-1.8%	-3.1%	-4.7%
USA	-0.7%	-1.3%	-2.2%	-3.0%
CAN	-0.5%	-0.8%	-1.2%	-1.6%
AUZ	-0.9%	-1.7%	-2.8%	-3.9%
JAP	-0.5%	-0.9%	-1.6%	-2.2%
MEX	-0.4%	-0.6%	-1.0%	-1.4%
CHI	0.1%	0.1%	0.1%	0.1%
IND	0.2%	0.2%	0.3%	0.4%
ASI	0.2%	0.2%	0.3%	0.4%
LAT	0.1%	0.2%	0.3%	0.4%
MID	0.2%	0.3%	0.4%	0.5%
AFR	0.2%	0.2%	0.3%	0.4%
World	-0.3%	-0.6%	-0.8%	-1.1%

Table 64: Welfare impact in percent of household consumption — Scenario OECD and FSU Carbon Tax with Climate Change Adaptation

	2010	2020	2030	2040
EUR	-0.06%	-0.07%	-0.10%	-0.12%
XEU	-0.09%	-0.12%	-0.17%	-0.20%
FSU	-0.55%	-0.77%	-1.13%	-1.37%
USA	-0.06%	-0.08%	-0.11%	-0.13%
CAN	-0.12%	-0.16%	-0.22%	-0.26%
AUZ	-0.15%	-0.20%	-0.27%	-0.31%
JAP	-0.03%	-0.04%	-0.06%	-0.07%
MEX	0.02%	0.02%	0.01%	-0.01%
CHI	-0.02%	-0.02%	-0.02%	-0.02%
IND	0.68%	1.05%	1.51%	1.82%
ASI	0.45%	0.57%	0.66%	0.66%
LAT	0.11%	0.13%	0.16%	0.17%
MID	0.23%	0.25%	0.35%	0.40%
AFR	0.23%	0.26%	0.36%	0.41%
WORLD	0.00%	0.00%	-0.01%	-0.01%