Economic Impact Assessment of Climate Change-A Multi-gas Investigation with WIAGEM-GTAPEL-ICM

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Climate change is a long-term issue due to the long lifespan of greenhouse gases and the delayed response of the climate system. This paper investigates the long-term economic consequences of both climate change impacts and mitigation efforts by applying the multi-regional, multi-sectoral integrated assessment model WIAGEM based on GTAP-EL coupled with the reduced-form multi-gas climate model ICM. We investigate emissions reduction paths to reach a radiative forcing target of 4.5 w /m^2. Economic impacts are studied and compared with and without the inclusion of all GHG gases. We find that multi-gas emissions reduction causes less economic losses compared with a case where only CO2 emissions reductions would be considered.

INTRODUCTION

A continued accumulation of anthropogenic greenhouse gases (GHGs) will have severe consequences on our climate, ecological and social systems. Irreversible climate changes are expected to induce significant costs, and no future efforts can nullify the resulting damage. Climate change is a long-term issue because of the lifespan of greenhouse gases. In order to assess the total impacts of climate changes, short and long-term costs and benefits need to be assessed and compared. Increasing atmospheric concentrations of greenhouse gases have a substantial impact on global temperature change and sea-level rise, which might create extensive

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economic, ecological and climatic impacts. The threat of climate change makes economic development strategies as well as energy and environmental policies increasingly important. Climate change is a global problem requiring a global solution.

Because of the long-term time horizon of climate change, climate policy involves a trade-off between short-term costs and long-term benefits. Greenhouse gas emissions reductions induced by environmentally friendly technologies require direct investments in clean technologies and abatement equipment. The benefits of climate change mitigation, however, is not restricted to the lifespan of the physical capital but linked to the lifespan of greenhouse gases. Due to this, it is often argued that investments in emissions reduction technologies should be postponed because the benefits of GHG emissions reduction can be only be detected in the distant future. For this reason, climate change policy has to determine a proper balance between future benefits and present day costs.

The most influential greenhouse gas causing negative impacts on the climate is CO_2. However, methane (CH_4) and nitrous oxide (N_2O) also have strong impacts on climate change. Furthermore, a group of industrial gases covering perfluorocarbons (PFCs), hydrofluorocarbons (HFCs) and sulfur hexafluoride (SF_6) together with the already banned chlorofluorocarbons (CFCs) have a very significant influence on the climate. Most studies investigating the economic impacts of climate change cover only CO_2 (McKibbin and Wilcoxen, 1999; Bernstein, Montgomery *et al.*, 1999; Weyant and Hill, 1999; Edmonds, Scott *et al.*, 1999; Kemfert, 2002a; Böhringer and Rutherford, 1999; Babiker, Reilly *et al.*, 2000; Ellerman, 2000; Tietenberg, Grubb *et al.*, 1999; and Zhang, 2001). Previous studies that incorporate a multi-gas reduction strategy find that a cost saving multi-gas emissions reduction strategy reduces abatement costs and welfare losses (see Manne and Richels, 2000; 2001, Reilly *et al.*, 2002, 2003). A cost effective control of climate change requires that climate policy strategies need to cover not only CO_2 but also other greenhouse gases. The reason why most of the studies focus primarily on CO_2 emissions is that this gas can relatively easy be measured and monitored by the use of fossil fuels. As each of the greenhouse gas has different lifetimes and impacts in the atmosphere, a comparison of the different effects of each gas is very challenging. A cost effective approach needs to cover reduction methods and impacts of each greenhouse gas.

In this paper, we shed some light on this issue and investigate and compare the impacts of pure CO_2 emissions versus a multi gas emission control. In order to do so, we have to go beyond traditional CO_2 concentration stabilization exercises. At first sight, investigating the stabilization of global mean temperature might be considered a suitable extension. The results, however, would considerably be dependent on the specific climate sensitivity of the selected climate model. In order to exclude the related additional uncertainty, we have selected to investigate the stabilization of radiative forcing, which is – along the chain of causes and effects – the first indicator that aggregates the influences of the different greenhouse gases. The radiative forcing target selected is 4.5 W/m^2 which corresponds to CO_2 equivalent concentration of 568 ppm, i.e. a concentration which is approximately twice the pre-industrial level.

We apply the multi-regional, multi-sectoral integrated assessment model WIAGEM (Kemfert, 2002a-b) which is also based on a multi regional trade model GTAP-EL (Burniaux and Truong, 2002; Burniaux. 2002) and coupled with a reduced-form climate module that covers all relevant greenhouse gases (ICM, see Bruckner *et al.*, 2003; Hooss *et al.*, 2001; Hooss, 2001; Joos *et al.*, 2001; Meyer *et al.*, 1999). Section two briefly describes the models and section three shows the different scenarios. Section four illustrates the main model outcomes, while the last section concludes.

THE APPLIED MODELLING TOOL

Our analysis is performed using the multi-regional WIAGEM model (**W**orld **I**ntegrated **A**ssessment **G**eneral **E**quilibrium **M**odel). This is an integrated economy-energy-climate model that incorporates economic, energy and climatic modules in an integrated assessment approach. The model is based on a multi regional trade model GTAP-EL (Burniaux and Truong, 2002; Burniaux. 2002). To evaluate market and non–market costs and benefits of climate change, WIAGEM combines an economic approach with a special focus on the international energy market and integrates climate interrelations with temperature changes and sea level variations. The design of the model is focused on multilateral trade flows. The representation of the economic relations is based on an intertemporal general equilibrium approach and contains the international markets for oil, coal and gas. The model incorporates all greenhouse gases (GHG) that influence potential global temperature, sea level variation and the assessed probable impacts in terms of costs and benefits of climate change. Market and non-market damages are evaluated according to the damage costs approaches of Tol (2001). Additionally, this model includes net changes in GHG emissions from sources and removals by sinks resulting from land use change and forest activities.

[Insert Figure 1]

WIAGEM is an integrated assessment model combining an economy model based on a dynamic intertemporal general equilibrium approach with an energy market model and a climatic sub-model. The model covers a time horizon of 100 years and solves in five-year time increments.[1] The basic idea behind this modelling approach is the evaluation of market and non-

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[1] See Kemfert (2002b) for a detailed model description.

market impacts induced by climate change. The economy is represented by 25 world regions which are further aggregated into 11 trading regions for this study (see Figure 1).

[Insert Table 1]

The economy of each region is disaggregated into 14 sectors, including five energy sectors: coal, natural gas, crude oil, petroleum and coal products, and electricity. Goods are produced for the domestic and export markets. The output of the non-energy sectors is aggregated into a non-energy macro good. The production function for this macro good incorporates technology through transformation possibilities on the output side and constant elasticity substitution (CES) possibilities on the input side. The CES production structure combines a nested energy composite with a capital-labour-land composite at lower levels. The energy composite is described by a CES function reflecting substitution possibilities for different fossil fuels (i.e. coal, gas, and oil). Fossil fuels are produced from fuel-specific resources. The energy-capital-labour-land composite is combined with material inputs to acquire the total output.

A representative household in each region allocates lifetime income across consumption in different time periods to maximize lifetime utility. In each period, households choose between current consumption and future consumption, which can be purchased via savings. The trade-off between current consumption and savings is given by a constant intertemporal elasticity of substitution. Domestic and imported varieties of the non-energy macro good are imperfect substitutes in each region as specified by a CES Armington aggregation function constrained to constant elasticities of substitution.

Producers invest as long as the marginal return on investment equals the marginal cost of capital formation. The rates of return are determined by a uniform and endogenous world interest rate such that the marginal productivity of a unit of investment and a unit of consumption is equalized within and across regions.

Induced technological change is considered as follows: Energy efficiency is improved endogenously by increased expenditures in R&D. This means that, in the CES (constant elasticity of substitution) production function, energy productivity is endogenously influenced by changes in R&D expenditures. The incentives to invest in technology innovations are market-driven. Because energy efficiency is improved by increased R&D expenditures, emissions reduction targets can be met with fewer production drawbacks. Furthermore, investment in R&D and technological innovation give a comparative advantage. The share of R&D expenditures in the total expenditures is endogenously determined by production changes, implying that investment in R&D expenditures competes with other expenditures (crowding out). Spillover effects of technological innovations are reflected through trade effects and capital flows. That means non-R&D-cooperating countries producing technological innovations can benefit from spillover effects through trade of technological innovations and capital flows that can be used for R&D investments. Model calculations show that capital flows increase to non-cooperating countries because of improved competitiveness effects and terms of trade effects. This consequently triggers spillover effects of technological innovations and energy efficiency improvements through increased R&D investments. Figure 1 graphically explains the interrelations of economic activities, energy consumption, climate and ecological impacts in WIAGEM.

In addition to the non-energy macro good, oil, coal and natural gas are traded internationally. The global oil market is characterized by imperfect competition to reflect the ability of the OPEC regions to use their market power to influence market prices. Coal trades in a competitive global market, while natural gas trades in competitive regional markets with prices determined by global or regional supply and demand.

Energy-related greenhouse gas emissions occur as a result of energy consumption and production activities. WIAGEM includes all greenhouse gases covered under the Kyoto Protocol: carbon dioxide (CO_2), methane (CH_4) and nitrous dioxide (N_2O) are considered to have the greatest impact on climate change over the 100-year period covered by the model. Furthermore, the fluorinated gases (HFCs, PFCs and SF_6) are considered as well, as described in the next section. The emissions limitation commitments of Annex B parties are specified as regional emissions limits to reduced coverage of greenhouse gases by the model.

By coupling the economic and climate impact part of WIAGEM with the detailed climate module ICM, we consider the relationship between man-made emissions and atmospheric concentrations and their resulting impact on temperature and sea level. We cover classes of atmospheric greenhouse gas stocks with different atmospheric lifetimes (modeled by the impulse response function) and reduced forms of the carbon cycle model developed by Maier-Reimer and Hasselmann (1987) and applied by Hooss (2001). Energy and non-energy related emissions of CO_2, CH_4 and N_2O as well as those of halocarbons and SF_6 alter the concentrations of these substances which in turn influence radiative forcing. Energy related emissions are calculated according to the energy development of each period. Energy related CO_2 emissions are considered according to the emissions coefficients of the EMF group[2].

Climatological Context and Concept

Integrated assessment (IA) studies typically evaluate many greenhouse-policy scenarios with their respective time-dependent greenhouse gas emissions, the corresponding changes in

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[2] See Delhotal et al (2004)

climate and global environment, and the resulting impact on human society and economy. This is done either by comparing hundreds to thousands of scenarios directly or - with a similar computational burden - by applying numerical optimization schemes. A climate module designed for IA application must, on the one hand, provide the required climate-change information without prohibitive computational effort. On the other hand, it should desirably approach the reliability of sophisticated circulation models.

Coupled general circulation models (GCMs) are the most reliable instruments currently available for the estimation of anthropogenic climate change. They are, though, extensive in computation time and difficult to handle. For typical climate scenarios of a few hundred to one thousand simulated years, they need roughly half a year of real time even in coarse-resolution experiments. Of the enormous amount of data in GCM simulations, only a few climate variables, such as global-mean temperature change or sea-level rise, are typically required for assessments of economic impacts of anthropogenic climate change.

The theory of impulse-response functions (IRFs) allows us to construct simple models that reproduce the greenhouse response of any given GCM in appropriately selected variables to arbitrary perturbations, consuming CPU time in the order of seconds on a workstation. Once calibrated against the outcome of a single GCM simulation, an IRF model works without further reference to the GCM, and may serve as an accurate substitute for the GCM, as long as the forcing is so small that the system responds linearly.

For a choice of policy-relevant climate variables, the time-dependent response of the climate system to small perturbations, therefore, can be computed to good accuracy through a collection of impulse-response function (IRF) modules. In many contemporary integrated assessment models, the greenhouse gas perturbation is represented as a time series of emission impulses, and the concentration response is computed as a *linear* superposition of the responses to these single impulses (Maier-Reimer and Hasselmann, 1987).

Because of the general nonlinear nature of the climate system, the use of such linearized IRF models is confined to, approximately, a doubling of the atmospheric CO_2 concentration with respect to the pre-industrial value of 280 ppm, or to a corresponding equilibrium warming of about 2.5 degrees C. In order to extend the range of applicability to larger CO_2 concentrations and temperatures, a model has been designed that is still based on the IRF approach but is able to treat the most important nonlinear processes.

Non-linear Impulse-response representation of the coupled Carbon cycle-Climate System (NICCS)

The most critical processes limiting the linear response of the carbon cycle are the following: the oceanic uptake of CO_2 is governed by the non-linear carbon chemistry of seawater; the higher the background concentration the slower the downward transport of additional carbon through the surface layer (see e.g. Maier-Reimer & Hasselmann, 1987, or Maier-Reimer, 1993). The carbon cycle further exhibits a fertilization of the land vegetation, which is often described using a logarithmic dependency. In NICCS, a similar differential analogue to a modified version of the Joos vegetation IRF model (Joos *et al.*, 1996) is applied.

For perturbations beyond doubled pre-industrial carbon dioxide concentrations, the problem of non-linear deformations of the carbon cycle response has been overcome through the basic mathematical concept of a differential analogue that can be tuned to a GCM-calibrated IRF in the linear limit of small CO_2 emissions. Although only a mathematical tool to reproduce the detected impulse-response, the differential equations of the analogue are physically interpretable in a manner that is sufficient for treatment of critical non-linear processes. Thus the model's validity is extended into the non-linear domain, up to the uncertain thresholds of abrupt state transitions in the dynamics of the climate system. In a further extension, the greenhouse warming module of NICCS computes not only the global annual mean of the surface temperature, but also - as a first attempt to include spatial information- the first principal components of the annual-mean change in surface temperature, precipitation, cloudiness, and sea level rise (Hooss *et al.*, 2001). The corresponding empirical orthogonal function (EOF) patterns and the IRFs for the EOF coefficients have been calibrated against a transient 850 year simulation with the periodically-synchronously coupled ECHAM3-LSG (Voss *et al.*, 1998; Voss and Mikolajewicz, 2001).

A common problem of climate impact assessments is the determination of probabilities and thresholds for abrupt shifts in the large scale behaviour of the climate system. Candidates in the current debate are:

- Breakdown of the North-Atlantic thermohaline circulation accompanied by a severe cooling of Northern and Central Europe;
- Destabilization of the West-Antarctic Ice shield with a potential sea level rise by up to 6 meters;
- Large-scale ecosystem disruptions with significant climatic feedbacks, e.g. a climate-accelerated desertification of large parts of the Amazon or African rain forest;

Abrupt climate changes of this kind and magnitude have been reconstructed from the geological records; despite the astonishing relative stability of the climate system throughout the past 10,000 years (after the end of the last glaciation), the system might turn out to be not so stable at all if sufficiently perturbed. Initial efforts (Zickfeld and Bruckner, 2003; Mastrandrea and Schneider, 2001; Keller *et al.*, 2000) to include potential abrupt climate changes into integrated assessments with a simplified treatment of the economic system exist. As a similar inclusion in WIAGEM lies beyond the scope of this paper, we have to emphasize that all results presented here are subject to alterations if the risk of abrupt climate changes is proven to influence climate change decision making in this century significantly.

The ICLIPS Climate Model (ICM)

As part of the ICLIPS (**I**ntegrated Assessment of **Cli**mate **P**rotection **S**trategies) project (cf. Toth *et al.*, 2003, and references therein), the NICCS model has been rewritten and supplemented by modules describing the atmospheric chemistry and radiative forcing contributions of non-CO2 greenhouse gases. (Bruckner *et al.*, 2003).

As a result, the multi-gas climate model ICM was obtained that takes into account all important greenhouse gases (carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, sulphur hexafluoride, tropospheric and stratospheric ozone, and stratospheric water vapour) and aerosols by modelling their dynamic atmospheric behaviour as well as the radiative forcing originating from changes in the concentration of the respective substances.

ICM is driven by time-dependent paths of the anthropogenic emissions of CO_2, CH_4, N_2O, halocarbons, SF_6 and SO_2. In WIAGEM total anthropogenic emissions are determined by:

$$TOTEM_{r,t} = E_{r,t} + NonE_{r,t} - S_{r,t} \qquad (1)$$

with TOTEM indicating the total anthropogenic emissions per region and time period, $E_{r,t}$ as regional emissions per time period. Non-energy related emissions are countered for each greenhouse gas, regional and time period. Sinks ($S_{r,t}$) reduce total emissions.[3]

The atmospheric concentration of greenhouse gases may be altered due to direct emissions, exchange with reservoirs (e.g., ocean, biosphere, pedosphere) and chemical reactions (destruction or formation). The biogeochemical submodules of ICM take into account these different processes in a greenhouse gas-specific manner. In general, the modules are reduced-form models of complex two- or three-dimensional greenhouse gas cycles or atmospheric chemistry models and are calibrated with respect to historical concentration records.

The carbon cycle module (see Appendix I) developed at the Max-Planck Institute for Meteorology in Hamburg consists of (a) a differential impulse-response representation of the 3 dimensional Hamburg Model of the Ocean Carbon Cycle (HAMOCC), extended into the non-linear high-CO_2 domain by explicit treatment of the chemistry governing the CO_2 uptake through the ocean surface, and (b) a simple non-linear impulse response model of the terrestrial biosphere's CO_2 fertilization. Applying an inverse calibration technique, the quantitatively unknown CO_2-fertilization factor has been adjusted in order to give a balanced 1980s mean budget as advised by the IPCC inter- model comparison exercise.

Various components of the MAGICC model (Wigley, 1988; Wigley and Raper, 1992; Wigley, 1994; Osborn and Wigley, 1994; Wigley *et al.*, 1996, Harvey *et al.*, 1997) were adopted in order to simulate the atmospheric chemistry of major non-CO_2 greenhouse gases.

Changes in the concentration of non-CO_2 greenhouse gases (CH_4, N_2O, halocarbons, and SF_6) are calculated by a simple one-box model approach according to

$$\frac{dC(t)}{dt} = \frac{1}{b}\sum_r TOTEM_r - \frac{1}{\tau}(C - C_{pre-industral}) \tag{2}$$

where b is a concentration-to-mass conversion factor and τ is the lifetime of the greenhouse gas. For N_2O, halocarbons and SF_6, the lifetime is assumed to be constant (IPCC, 1996; Harvey *et al.*, 1997). CH_4 is removed from the atmosphere by soil uptake and chemical reactions with OH. The lifetime of CH_4 takes into account both processes and as the OH concentration itself is

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[3] This means also that the emissions reductions targets are reduced.

influenced by CH_4, the lifetime attributed to chemical processes is modeled to be dependent on the CH_4 concentration according to Osborn and Wigley, 1994).

[INSERT Table 2]

The atmospheric concentration of different greenhouse gases has the following impact on radiative forcing (IPCC, 1990):

$$\Delta F_{CO2} = 6.3\ln(\frac{CO2}{CO2_0}) \tag{3}$$

$$\Delta F_{CH4} = 0.036(CH4^{0.5} - CH4_0^{0.5}) - f(CH4, N2O) + f(CH4_0, N2O_0) \tag{4}$$

$$\Delta F_{N2O} = 0.14(N2O^{0.5} - N2O_0^{0.5}) - f(CH4_0, N2O) + f(CH4_0, N2O_0) \tag{5}$$

with ΔF measured in Wm^{-2}, concentrations for CH_4 and N_2O given in ppbv and the subscript 0 used to indicate pre-industrial concentrations. . The CH_4-N_2O interaction term (expressed in Wm^{-2}) is determined by:

$$f(CH4, N2O) = 0.47\ln\left[1 + 2.01\cdot10^{-5}\cdot(CH4\cdot N2O)^{0.75} + 5.31\cdot10^{-15}\cdot CH4\cdot(CH4\cdot N2O)^{1.52}\right] \tag{6}$$

where CH_4 and N_2O have to be replaced by actual CH_4 and N_2O concentrations or alternatively by their respective pre-industrial levels as expressed in equations 3 and 4.

Total radiative forcing F can be approximated (IPCC, 2001, p. 355) by adding each greenhouse gas radiative forcing effect. In addition to the components just described, the radiative forcing description in ICM takes into account the contributions from SF_6, tropospheric ozone and stratospheric water vapour (both dependent on CH_4 concentrations), aerosols, and halocarbons including indirect effects according to stratospheric ozone depletion.

The time evolution of the global annual mean surface air temperature is calculated according to the impulse response function approach used in NICCS. A detailed description of this component can be found in Hooss (2001), Hooss *et al.* (2001), Bruckner *et al*. (2003), Joos *et al*. (2001), and Meyer *et al*. (1999). In order to include the radiative forcing of non CO_2-greenhouse gases, the carbon dioxide concentration used in NICCS is to be replaced by the equivalent carbon dioxide concentration (measured in ppm) defined by IPCC (1996a, p.320):

$$C_{Equiv} = 278\,ppm \cdot Exp\left(\frac{\Delta F}{6.3\frac{W}{m^2}}\right) \qquad (7)$$

ICM estimates the climatic changes due to greenhouse gas emissions and the impact modules estimates the corresponding impacts. Market and non-market damages associated with these impacts, are assessed by coupling the climate module of ICM with WIAGEM. We express impacts as changes to regional and global welfare and GDP.

Scenario Definition

The main aim of this paper is to investigate the economic impacts of the inclusion of all greenhouse gases. Due to this, we compare scenarios where we consider only CO_2 emissions or all greenhouse gases, namely methane (CH_4) and nitrous oxide (N_2O). We additionally include fluorinated gases (HFCs, PFCs and SF_6). Figure 2 demonstrates the total greenhouse gas emissions until 2100 in the so-called “business as usual” or reference scenario where no climate control takes place. In this scenario, carbon emissions follow the IPCC emissions scenario report (IPCC, 2000).[4] Additional to the coverage of multi-gases, namely methane (CH_4) and nitrous oxide (N_2O), we add fluorinated gases (HFCs, PFCs and SF_6) in carbon equivalent amounts.

In order to assess the economic impacts of CO_2 and GHG emissions reduction options, we compare different GHG and CO_2 reduction scenarios:

Reference: no climate control policy takes place, emissions development follows the baseline emissions path.

CO_2 Scenario: this scenario covers a reduction of radiative forcing that should not exceed 4.5 W/m^2 by the end of the model horizon. This should be equivalent to a stabilisation of 3°C by 2100. A reduction of emissions can only be reached by CO_2 emissions reduction.

GHG Scenario: this scenario covers also a reduction of radiative forcing that should not exceed 4.5 W/m^2 by the end of the model horizon. This should be equivalent to a stabilisation of 3°C by 2100. However, a reduction of emissions can be reached by multi gas emissions reduction options.

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[4] IPCC (2000), we follow scenario A1B (1). For non-CO2 gases, we use EMF21 estimates from the Environmental Protection Agency (EPA 2001): "Non-CO2 Greenhouse Gas Emissions from Developed Countries: 1990-2010" available at http://www.epa.gov/ghginfo/reports/index.htm and EPA: "Non-CO2 Greenhouse Gas Emissions from Developing Countries: 1990-2010."

The main reason for differentiating between these different scenarios is to investigate the economic impacts of different emissions reduction strategies. As in a multi gas reduction case more low cost emission reduction option occurs, marginal abatement costs are lower. Previous studies find substantial lower emissions abatement costs in a multi gas context (Manne and Richels, 2000, 2003), and Reilly *et al.*, 2000, 2002).

SCENARIO RESULTS

Emissions and Carbon Taxes

A stabilisation of radiative forcing by 4.5 W/m^2 or a stabilisation of temperature by 3°C by the end of the modelling horizon induce substantial emissions reductions. Figure 2 shows the trajectories of the emissions for all gases, and Figure 3 shows the emission reductions relative to the reference case. It can be seen from these Figures that if the above target of radiative forcing stabilisation is to be achieved by CO_2 emissions mitigation alone, then the overall CO_2 emissions will need to be reduced substantially, by about 67 per cent relative to the reference case by 2100, or an average of 6.7 percent per decade. The figure is improved only slightly if non-CO_2 gases (CH_4 and N_2O) are also to be included, from –67% to –60% (cumulative), or from –6.7% to –6% (per decade). Despite this small impact on the level of CO_2 emission reductions, the impact on marginal abatement cost is substantial (see Figure 4). The MAC reaches a level of about 225 US$ 1995 per ton of carbon equivalent ($/TCe) by the year 2100, for the CO_2 alone scenario, but reduced to only about 100 $/TCe 1995 by the year 2100 if non-CO_2 gases are also included.[5]

Emissions of CH_4 and N_2O are also reduced substantially (by 53% and 39% respectively relative to the reference case by the year 2100) for the CO_2 alone scenario. This is because all

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[5] These figures are quoted for the most optimistic case when all countries participate in emission trading to reduce the cost of emission reductions to a minimum. The opposite (most pessimistic) case when no trading is allowed will increase this cost quite substantially for some regions such as the EU and the USA.

GHGs emissions are linked via production and consumption activities, and hence, the reduction of CO_2 emission reductions will lead to the reductions of CH_4 and N_2O emissions - even if the latter are not subject to a target reduction, i.e. not subject to a carbon tax. If CH_4 and N_2O are now also subject to a carbon tax in the same way as CO_2[6] (the GHG scenario), then the emissions from CH_4 and N_2O will rise slightly, and the emissions from CO_2 will decrease, as expected (see Figures 2 and 3).

[Insert Figures 2, 3, 4 and 5]

Economic Effects

Economic efforts to reduce a higher percentage of emissions are higher if we consider only CO_2 emissions and not all greenhouse gases. The reason for this is that the inclusion of multi gases offers more cost saving opportunities than if we consider only CO_2. A cost minimizing strategy leads to lower permit prices in the case of multi-gas scenario, which in turn also leads to lower production (GDP) losses and lower consumption losses (see Table 3).

[Insert Table 3]

We find higher economic losses in terms of GDP mititgation if we only consider CO_2 emissions abatement. Europe and the USA suffer high economic losses because of high abatement costs. These costs are reduced if we consider multi gas emissions reduction options. A pure CO_2 emissions abatement strategy leads to high GDP losses in 2050 and 2100. This results from the fact that meeting the radiative forcing target of 4.5 w / m^2 leads to significant emissions reductions by 2100. The distribution of regional burden sharing varies over time. Those countries with a very high share of fossil fuel production and consumption have to reduce a substantial amount of CO_2 emissions. Because of substitution and growth assumptions in the

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[6] The tax is to be based on carbon equivalent unit (Ceq), which is derived using the IPCC Global Warming Potential (GWP) indices (CO_2 = 0.27 Ceq, GWP = 1; CH_4 = 5.73 Ceq, GWP = 21; N_2O = 84.55 Ceq, GWP = 310).

model, the share of emissions reduction changes and therefore also economic losses in terms of GDP changes. Some developing countries like Asia and China do suffer, not only because of real production cutbacks, but also because of the negative terms of trade effects. Economic losses will be reduced if we consider multi gas options. This is because the economic costs of emission reduction will be lower in this case.

CONCLUSION

The main aim of this paper has been to investigate and compare the economic consequences of a pure CO_2 and a multi-gas emission reduction strategy. We have applied a multi-sectoral integrated assessment model WIAGEM based on GTAP-EL coupled with a detailed climate model ICM. The main finding is that a multi-gas mitigation option is a lower cost option leading to a less economic burden. Meeting a radiative forcing target of 4.5 w/m^2 by the end of the model horizon requires a substantial reduction of greenhouse gases. A multi gas reduction strategy leads to a considerable reduction of methane emissions. A CO_2 emissions reduction strategy causes production and GDP losses in countries with a high share of fossil fuel emissions.

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Appendix I: Mathematical description of ICM

Mathematically the carbon cycle model containing all differential equations can be described as follows:

$$\dot{c}_1 = D(c_1)\cdot\left\{e - \frac{n_2}{h_s}c_s(c_1) + \frac{n_2}{h_2}c_2 - (b_3+b_4)B(c_1) + \frac{1}{\tau_{B3}}c_{B3} + \frac{1}{\tau_{B4}}c_{B4}\right\} \quad \text{(A1) (A2)}$$

$$\dot{c}_2 = \frac{\eta_2}{h_s}c_s(c_1) - \frac{\eta_2+\eta_3}{h_2}c_2 + \frac{\eta_3}{h_3}c_3 \quad \text{(A3)}$$

$$\dot{c}_3 = \frac{\eta_3}{h_2}c_2 - \frac{\eta_3+\eta_4}{h_3}c_3 + \frac{\eta_4}{h_4}c_4 \quad \text{(A4)}$$

$$\dot{c}_4 = \frac{\eta_4}{h_3}c_3 - \frac{\eta_4}{h_4}c_4 \quad \text{(A5)}$$

$$\dot{c}_{Bc} = A(c_1)\cdot\dot{c}_1 \quad \text{(A6)}$$

$$\dot{c}_{B3} = b_3\cdot B(c_1) - \frac{c_{B3}}{\tau_{B3}} \quad \text{(A7)}$$

$$\dot{c}_{B4} = b_4\cdot B(c_1) - \frac{c_{B4}}{\tau_{B4}} \quad \text{(A8)}$$

with:

t	Simulation time
x	Spatial coordinates
s	Season index
e	Anthropogenic CO_2 emissions
C_{CO2}	Atmospheric CO_2 concentration (by volume)
$C_{CO2,\,equiv}$	Atmospheric equivalent CO_2 concentration
$C_{CO2,\,pre}$	Pre-industrial CO_2 concentration
c_a	Anthropogenic carbon in the atmosphere (in GtC)
c_s	Anthropogenic carbon in the oceanic mixed layer
c_j	Anthropogenic carbon in the j^{th} oceanic layer
c_l	Anthropogenic carbon in the composite layer
q_j	Carbon flux from layer j – l into layer j
c_B	Anthropogenic carbon allocated by the land vegetation
c_{Bi}	Anthropogenic carbon in land biosphere reservoir I
c_{Bc}	Short-term anthropogenic carbon in land biosphere
$B(C_1)$	Nonlinear auxiliary function (= additional NPP)
$A(C_1)$, $D(C_1)$	Nonlinear auxiliary functions
T	Near-surface temperature change (relative to pre-industrial level)
CC	Cloud-cover change (relative to pre-industrial level)
P	Precipitation change (relative to pre-industrial level)
H	Humidity change (relative to pre-industrial level)
SLR	Sea-level rise (relative to pre-industrial level)
PC	Principal component
EOF	Empirical orthogonal function

Table 1: Definitions of Countries and Regions in WIAGEM

	Regions
ASIA	India and other Asia (Republic of Korea, Indonesia, Malaysia, Philippines, Singapore, Thailand, China, Hong Kong, Taiwan)
CHN	China
CNA	Canada, New Zealand and Australia
EU15	European Union
JPN	Japan
LSA	Latin America (Mexico, Argentina, Brazil, Chile, Rest of Latin America)
MIDE	Middle East and North Africa
REC	Russia, Eastern and Central European Countries
ROW	Other Countries
SSA	Sub Saharan Africa
USA	United States of America

Table 2: Summary Key Assumptions greenhouse gases[7]

Trace Gas	CO2	CH4	N20
Atmospheric Concentration			
Pre- Industrial (ppmv)	278	.789	0,275
1992 (ppmv)	353	1.72	0,310
Energy related Emissions			
1992 (billion tons)	6.0	.08	.0001
growth rate, post 1992			
Non-energy related Emissions			
1992 (billion tons)	.2	.454	.0139
growth rate, post 1992	0	.8	.2

Table 3: Regional GDP Changes (%) Compared to Reference Case of Different Scenarios

CON- CO2	2010	2050	2100	GDP- Multi Gas	2010	2050	2100
JPN	-3.01	-3.38	-4.07	JPN	-1.38	-2.14	-2.83
CHN	-2.23	-2.74	-3.72	CHN	-1.20	-1.85	-2.10
USA	-3.15	-3.67	-4.02	USA	-1.83	-2.10	-2.49
SSA	-2.09	-2.78	-3.06	SSA	-1.53	-1.85	-2.09
ROW	-1.21	-2.10	-2.53	ROW	-0.56	-1.10	-1.23
CAN	-3.05	-3.76	-4.04	CAN	-1.79	-2.11	-2.53
EU15	-3.98	-4.70	-5.98	EU15	-2.08	-2.81	-3.12
REC	-0.12	-2.25	-4.02	REC	-0.11	-1.13	-2.53
LSA	-2.10	-2.53	-3.08	LSA	-1.13	-1.85	-2.14
ASIA	-2.10	-2.83	-3.77	ASIA	-1.09	-1.85	-2.10
MIDE	-3.08	-4.10	-4.75	MIDE	-1.83	-2.42	-2.79
MEX	-2.10	-2.80	-3.76	MEX	-1.09	-1.85	-2.40

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[7] Source: IPCC (90) and IPCC (92)

Figure 1: Interrelations in WIAGEM

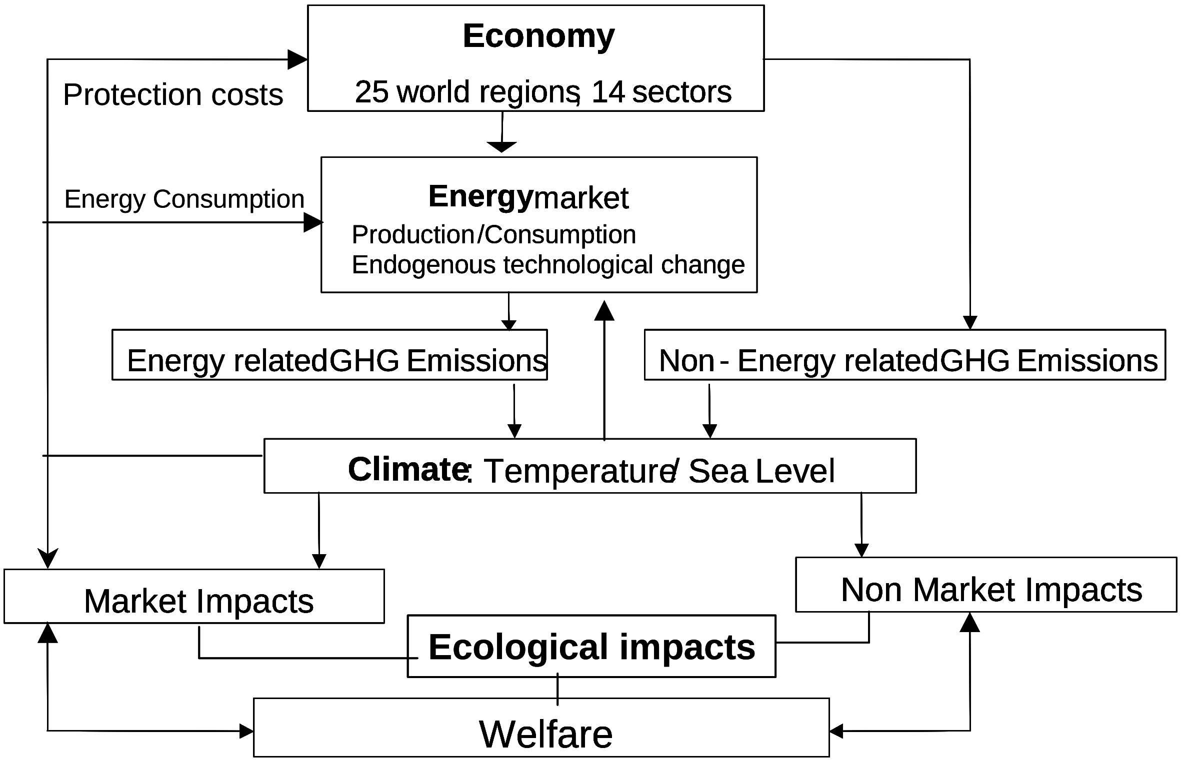
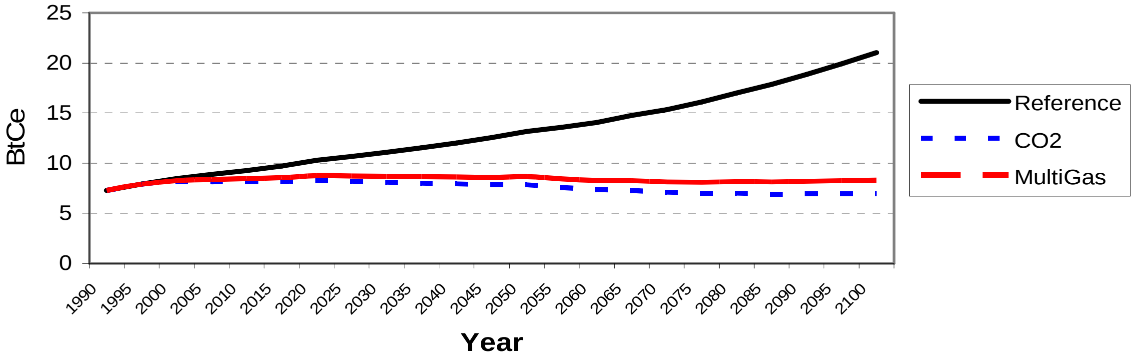
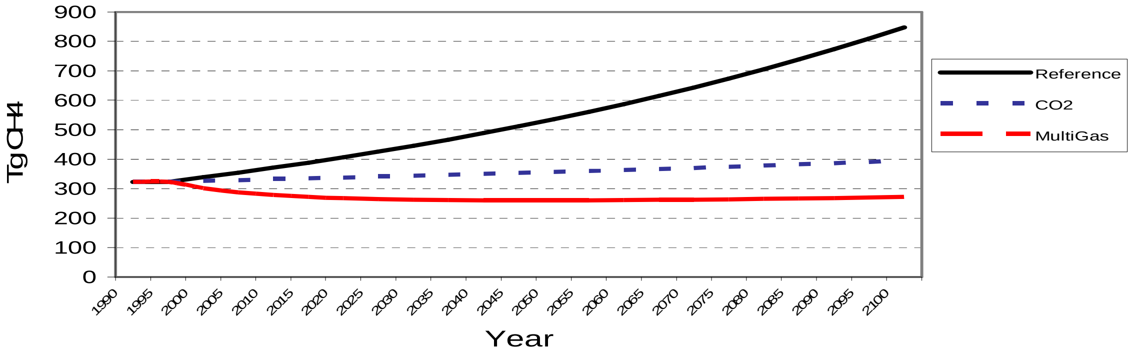


Figure 2: Emissions Trajectories of different Scenarios

a) CO_2 Emissions



a) CH_4 Emissions



c) N_2O Emissions

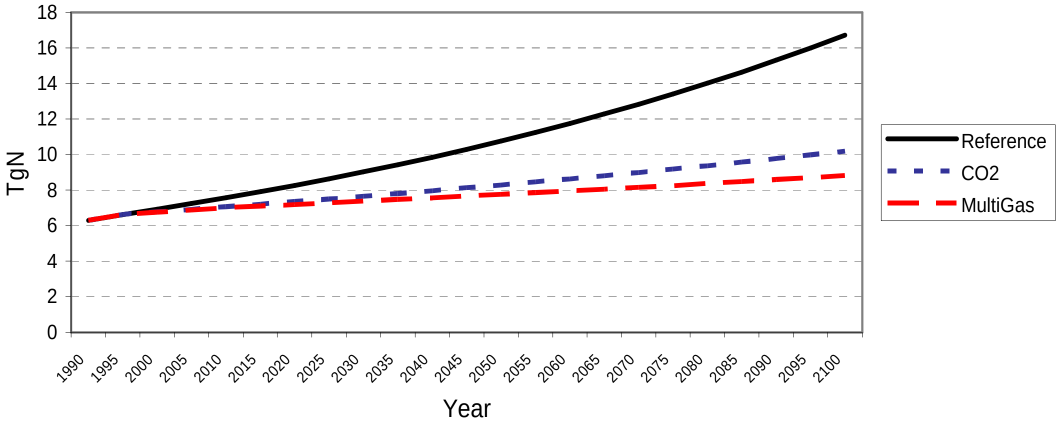
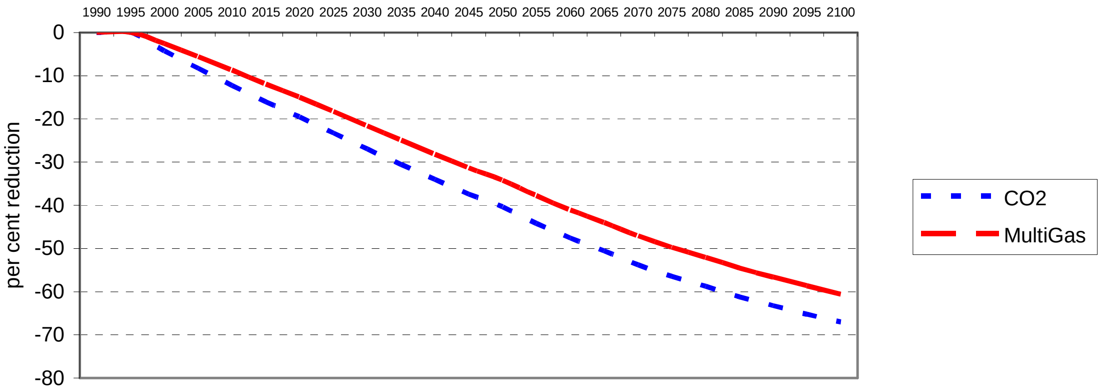
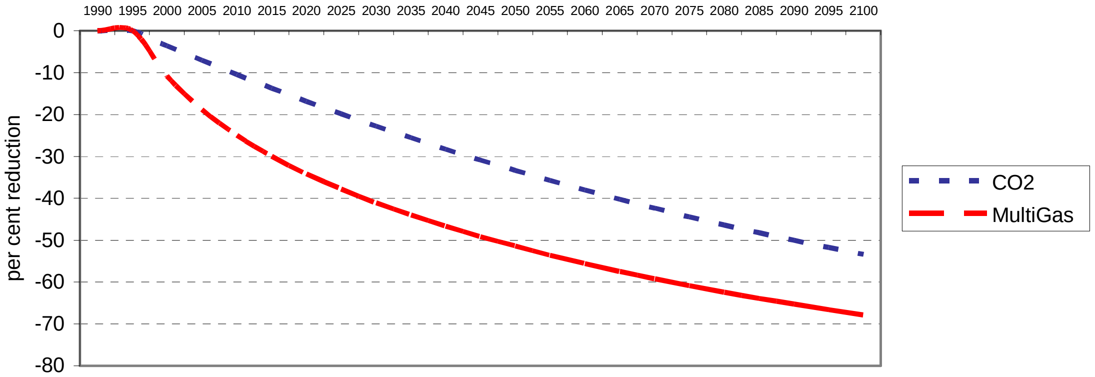


Figure 3: Cumulative Emissions Reductions relative to Reference Case

a) CO_2 Emissions



b) CH_4 Emissions



c) N_2O Emissions

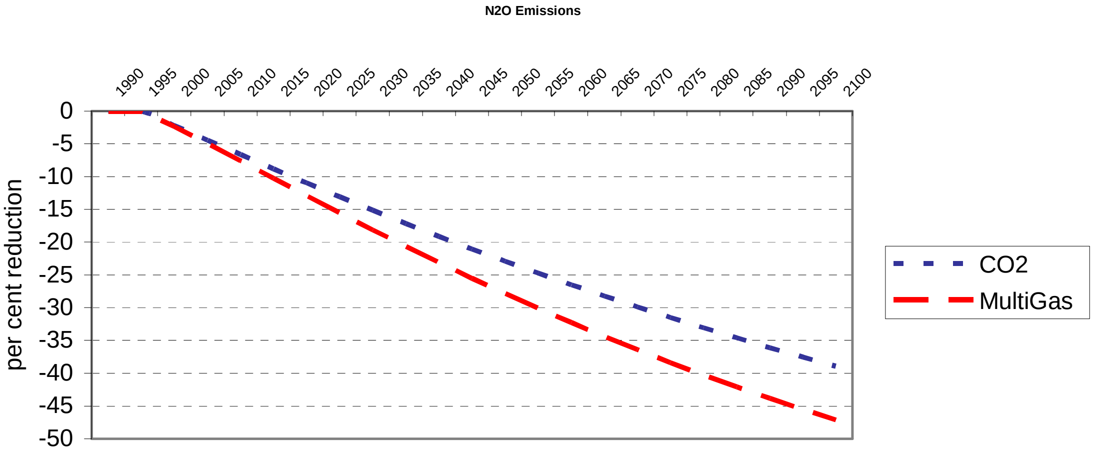


Figure 4: Cumulative MACs/Carbon Price in US$ 1995 Per Ton Carbon

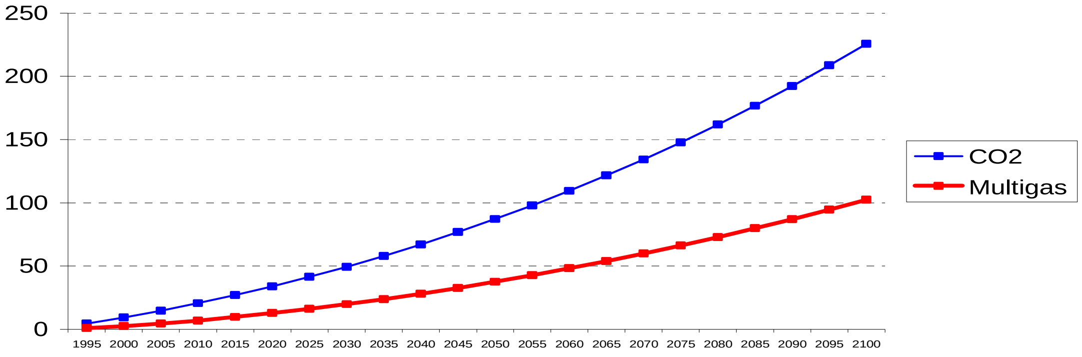


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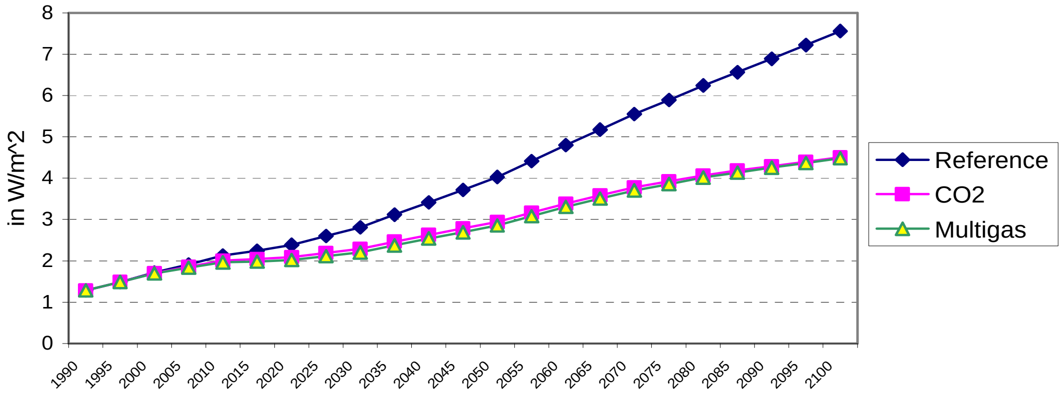
Figure 5: Radiative Forcing and Temperature of different Scenarios

a) Radiative Forcing



b) Temperature Development