The effectivity of technological innovation on mitigating the costs of climate change policies

C. Kemfert[a,b], H. Kremers[a], and T. Truong[c]

[a]Department Energy, Transportation, Environment,
German Institute for Economic Research,
Königin-Luise-Straße 5,
D-14195 Berlin,
Germany

[b]Humboldt-Universität zu Berlin,
Spandauer Straße 1,
D-10178 Berlin,
Germany

[c]School of Economics,
Faculty of Commerce and Economics,
The University of New South Wales,
Sydney NSW 2052,
Australia

Abstract: Which conditions should technological change in the energy sectors fulfil in order to accomplish certain emission objectives. Increased emissions cause an increase in mean global temperature which is a major cause for the changes in mortality and birth rates, and increases health risks. This paper considers an objective of limiting the rise in mean global temperature to 0.1 degree Celcius less than under a Business-as-Usual scenario in 2050.

The integrated assessment model WIAGEM explains energy productivity in a production sector as determined by the sector's outlays on research and development in the recent past. The impact of investments in research and development on energy productivity depends on an efficiency parameter and an elasticity parameter. The efficiency parameter and elasticity parameter are calibrated in such a way that a temperature objective is met. We define two counterfactual scenarios. One scenario limits technological innovation to the developed regions where the value of the efficiency parameters in these regions are determined such that the temperature objective is met. Another scenario extends this scenario to the incorporation of the developing world where the elasticity parameter in these regions are determined such that the temperature objective is met.

We use the 'World Integrated Assessment General Equilibrium Model' (WIAGEM) which combines an economic general equilibrium model based on the MultiSector-MultiRegional-Trade (MS-MRT) model with a climate model and a damage assessment model. WIAGEM is an intertemporal recursive dynamic general equilibrium model with a time horizon. The time span is from 1995 until 2050 in time steps of 5 years.

Keywords: Technological innovation, climate change, learning effects

1 Introduction

Current research on the effects of climate change indicates that the large increase in CO_2 emissions in the period following the industrial age will have major consequences for our societies through increased health risks and mortality rates, possibly lower birth rates, and changes in productivity of land. Since many vested interests stand to loose with these changes, serious efforts are being taken to curb these trends.

Governments are trying to implement new policies that provide society with the incentive to decrease their emissions. Taxes are imposed on the use of fossil fuels in order to making these goods relatively expensive to use. International climate agreements such as the Kyoto Protocol propose to let regions trade in emissions. All these measures mean to put a price on the formerly free emissions, and this causes extra costs for the production sectors involved.

The success of implementing such climate policies depends crucially on the costs these policies impose on the production sectors in the economy. The Kyoto Protocol states new options such as emission permit trading, Joint Implementation, and Clean Development Mechnisms to provide sectors and regions with the possibilities to obtain their emission reductions in the most cost effective way possible. On top of this, the international society is putting its hope on the possibilities of technological innovation in reducing the cost of abatement.

Technological innovation is mainly concentrated on the development of cleaner technologies or more energy efficient technologies. One can decrease emissions by developing technologies that emit less such emissions, i.e. they are cleaner, or by developing new technologies that use less energy, i.e. they are more energy efficient. The effectivity of technological innovation on improving energy efficiency or obtaining cleaner technologies depends on the effectivity of investments in improved technologies and on the velocity with which society takes up new technologies.

In this paper, we investigate the effectivity of such technological innovations with respect to mitigating the effects of climate change on our economy. The economy is represented by an integrated assessment model which couples a computable general equilibrium model with a climate model. The computable general equilibrium model computes an equilibrium which provides a certain scenario of emissions in greenhouse gases over time. The climate model uses this scenario of emissions to compute changes in mean global temperature. The economic model includes the possibility of technological innovations in the sense that investments in research and development at certain time will lead to more energy efficient technologies in future periods. The effectivity of these investments depends on the learning capacity of the economy and on the effectivity of investments. This paper considers the assumptions that have to be imposed on these parameters for technological innovation to be effective.

The effectivity of investments in research and development is measured by the extent to which changes in innovation efforts manage to keep the temperature increase under control at the lowest costs to the economy. This paper considers assumptions on these parameters which decrease the mean global temperature due to fossil fuel emissions with 0.1 degree Celcius in 2050 in comparison to a Business-as-Usual scenario. In this way, we consider the integrated assessment model from an inverted viewpoint. The assumptions on the innovation parameters that lead to a 0.1 decrease in mean global temperature are not unique. We consider two combinations that obtain the required result, and compare them with the business-as-usual scenario in terms of the economic costs to the economy. One scenario considers only technological innovation in the developed regions where the effectivity of investments in research and development is improved such that our temperature objective is achieved. The other scenario includes the developing world where the confrontation with newer, cleaner technologies leads to a quicker acceptance and implementation of these technologies.

This paper applies the World Integrated Assessment General Equilibrium Model (WIAGEM) developed in Kemfert (2002). Kemfert (2004) describes the modelling of induced technological change in more detail and applies it to study the impact of CDM investments. WIAGEM is an integrated assessment model that combines a computable general equilibrium model with a climate model and a damage assessment model. Section 2 describes the WIAGEM model. In Section 3, we describe the modelling of technological innovation in WIAGEM. We also describe the assumptions that we made with respect to the parameters determining the impact of R&D investments and define the scenarios. Section 4 extensively analyzes and compares the three different scenarios with respect to the impact on economic development, welfare, and trade. Section 5 draws the conclusions on this paper.

2 The model

WIAGEM combines an intertemporal general equilibrium model, based on the 'Multi-Sector Multi-Regional Trade' (MS-MRT) model, with a climate model, and a damage impact model. For the MS-MRT model, we refer to (Bernstein et al. 1999a) and Bernstein et al. (1999b). Within the scope of this paper, we limit our attention to the economic part of WIAGEM with an extension to the climate model and refer the interested reader to Kemfert (2002) for more information. The time horizon is 50 years, incremented in 5-years time steps. It takes 1992 as its benchmark year but it is calibrated using the GTAP4 database complemented with GTAP5 data. The model considers the period from 2000 to 2050.

2.1 Economy

WIAGEM aggregates the world into 12 trading regions, which we enumerate in Table 1. Within this set, we distinguish the subset $\mathtt{AnnexB} = \{\mathtt{CAN}, \mathtt{EU15}, \mathtt{JPN}, \mathtt{REC}, \mathtt{USA}\}$ referring to the regions that signed the Annex B to the Kyoto Protocol.

WIAGEM extends the originally 9 production sectors in the MS-MRT model in each region to 15 production sectors. These sectors produce 13 tradable goods, which we summarize in Table 2, and another good that refers to investment. The investment good is complemented with another investment good that refers to research and development activities within the region.

The production factors used in WIAGEM are capital and labour. Physical capital is malleable but cannot be transferred across sectors. Capital stocks increase over time due to investments from output produced for domestic sales, and decrease due to depreciation at a constant geometric rate. The MS-MRT model assumes a two year gestation lag for capital investment and a uniform pattern of investment within a given 10-years period. This means that, if $I(t)$ is the rate of investment in period t, then $2I(t)$ units of capital enter the current capital stock and $3I(t)$ units of capital are delivered in the next period. The labour force in each period is determined by population growth and labour-augmenting technical progress. These growth factors are externally given.

For each fossil fuel sector in each region, there exists a resource of this fossil fuel at each time period. The relation between depletion effects on the supply of oil, gas, and coal, and the actual supply of these fuels is ignored. The model does not keep a record of the current stock of each fuel in each time period. This resource therefore represents the demand for this fossil fuel resource in each time period. This demand is assumed to be constant over time.

Each tradable good in Table 2 is produced in each region by one unique production sector using a constant returns to scale production technology with the goods in Table 2 as intermediate goods, and labour and capital as production factors. Under these conditions, the optimal demand for these inputs are given by the cost minimizing amounts to produce one unit of output times the activity level. According to Bernstein et al. (1999a), the competitive firms also undertake investments which arbitrage current investments against future returns. All investments are forward looking and the producer anticipates the effects of announced policies that are to take effect in the future.

We distinguish between non-energy and electricity production sectors on the one hand and fossil fuel production sectors on the other hand. Output of each non-energy sector and the electricity sector is decomposed into the intermediate (non-energy) inputs and in a sector specific 'Energy-

Value-added' composite using a Leontief functional form. The non-energy intermediate inputs are composites of domestically produced goods and their imported equivalents. The 'Energy-Value-added' composite is decomposed into an energy composite and a value-added composite using a Constant Elasticity of Substitution (CES) functional form. WIAGEM decomposes value-added into its constituents capital and labour also using a CES functional form.

For each fossil fuel production sector, the output good is decomposed into a sector specific fossil fuel resource of this fuel, and a sector specific aggregate good which contains labour, capital, and this fossil fuel input itself in fixed proportions. The first decomposition uses a CES-function, while the second layer uses a Leontief production function to represent the fixed proportions.

Final demand in each region is modeled by a representative household, who maximizes its region's discounted utility over the model's time horizon given his income. WIAGEM assumes that the utility function is of a Constant Intertemporal Elasticity of Substitution (CIES) type. The consumer obtains income from its endowments of time which it can sell as labour, from his initial endowment of capital in each production sector, from the rents it obtains on fossil fuel production, and from tax revenue.

The description of the consumer's choice between consumption and investment in each period is derived from growth theoretic models, see Barro and Sala-i-Martin (1995). This model is essentially a so-called Ramsey model. In such models, the consumption-investment decision of an infinitely living consumer is taken under consideration, where consumption and investment ultimately reach a steady state growth rate which is constant. The model here differs in two important aspects from the growth theoretic approach: The CGE model considers a finite horizon, and the CGE model computes a sequence of equilibria which do not imply the existence of a steady state growth rate in consumption and investment. The solution to the first problem is often to split the life time of the infinitely living consumer into two parts. The first part consists of the periods under consideration, while the second part considers all remaining time periods. Utility maximization over the first part starts with an initial endowment of capital in each stock. Utility maximization over the second part starts with a capital endowment in each stock that would result at the beginning of the next period. The latter stocks are taken from the income of the consumer at the first period. We have to choose a value for each of these computed capital stocks, which determines optimal consumption and investment. WIAGEM chooses them by imposing a constant growth rate on investment in the last period. This condition then becomes an extra condition for the utility maximizing problem.

Solving the inter-temporal optimization problem results in an optimal consumption plan for the time span and optimal savings follow indirectly from the remaining income after consumption. Since we assume the utility function of the consumption household to be homogeneous of degree one, we use expenditure minimization to obtain the optimal amounts of each good providing one unit of utility. Total expenditure on consumption equals expenditure per unit of util times the amount of utils. Total expenditure on consumption plus total expenditure on buying the investment good equals the consumer's income in each period.

The model uses a CES function to obtain the aggregate consumption good from a non-energy composite good and an energy composite. The consumer price index of this composite consumption good is then obtained from the minimum expenditure on the non-energy composite and the energy composite to obtain one unit of this aggregate consumption good. The non-energy composite is decomposed into the non-energy goods using a Cobb-Douglas function. The expenditures on the non-energy goods are composites of domestically produced goods and their imported equivalents. CGE modelers often call such composite goods so-called 'Armington goods', referring to Armington (1969).

The consumption and production of non-energy goods contain an energy composite which is decomposed into the output goods of the energy and electricity production sectors. See also Bernstein et al. (1999b) for a clarification of the energy composite. We use a CES function to decompose each aggregate into its constituent parts. The energy composite is decomposed into the electricity good and a fossil fuel aggregate. The electricity goods in these CES functions are again composites of domestically produced goods of the electricity sector and its imported equivalents. The fossil composite is decomposed into a coal good and a non-coal composite. The non-coal composite is decomposed into a gas good and an oil good.

The use of a unit of a fossil fuel will lead to a certain share of emissions in each greenhouse gas. WIAGEM considers emissions in CO_2^a nd considers the other greenhouse gases, CH_4 and N_2O, in CO_2 equivalents. CO_2 emissions are computed proportional to the fossil fuel consumption in each production sector.

Oil is traded internationally as a homogenous good at one price, hence the producer prices of oil in each region are determined by the world market price. The non-oil fossil fuels as well as the non-energy goods are represented as 'Armington goods' to approximate the effects of infrastructure requirements and high transport costs between some regions. This means that these goods are composites of its domestically produced and its imported equivalent.

The traded non-oil fossil fuel and non-energy goods are supposed to have different prices depending on whether they are produced for domestic use or for export. WIAGEM uses a Constant Elasticity of Transformation (CET) function to decompose the output good of these production sectors. The composite traded non-oil fossil fuel and non-energy goods are decomposed into a good produced for domestic sales and its equivalents produced for exports using a CET function.

WIAGEM assumes that there is perfect competition on the markets. We define an equilibrium in this economy as a set of prices and activity levels such that the economy exhibits

- *market clearing*: the activity levels of each production sector clear the market for the particular output good, while the market for production factors are cleared by the underlying price.
- *zero profits*: the price of each tradable good is determined by the minimum cost to produce one unit of this good.

The market clearing condition depends on whether a tradable good market is considered or a market for production factors. In the case of a market for tradable goods, the market price of this good is determined by the marginal cost to produce this good, while the activity level of the production sector is determined by total demand for this good. The output good of a region's production sector is produced to satisfy domestic sales and exported sales. Domestic sales satisfy the demand for this good as an intermediate good in other domestic production sectors and as final consumption. Furthermore, we assume that part of domestic sales are meant to represent investment costs for this production sector.

The MS-MRT model's main characteric is the modelling of energy use and production. This plays an important role in the model's calibration where the parameters are determined in such a way that available data on energy use and production are reproduced in a 'Business-as-Usual' scenario. The MS-MRT model complements the GTAP4 data with data obtained from sources at DEA and IEA on fossil fuel demand projections. We have added these data in Table 3.

In any period, a region can be running a trade deficit or a trade surplus, but by the terminal year, the debt of a region must have been returned to baseline levels. In any infinite horizon model, this closure rule immediately follows naturally from the budget constraint and prevents the possibility of an infinite accumulation of debt (the literature refers to a 'no-Ponzi games' condition). WIAGEM, as a finite horizon model, approximates this infinite horizon condition by assuming that there be no net change in foreign indebtedness over the finite horizon. Such closure is consistent with neoclassical economics (See Bernstein et al. (1999a)).

The investments of all production sectors are combined into an aggregate investment good particular to the region. The activity level of these investment sectors then satisfies demand for these investment goods. The regional households spend their savings on buying this investment good. WIAGEM adopts a closure on investment and savings, assuming that there is equality between total savings of the consumers, i.e. total demand for the investment good, and the supply of this good by the regional investment sector.

Notice that, in equilibrium, the optimal amount of utils for a representative consumer follows immediately from equating expenditure per unit of util times the optimal amount of utils to this consumer's income. In some sense, the amount of utils of a consumer household plays a role similar to the activity level of a production sector. It follows from the homogeneity of degree zero property of the utility functions that the price of a util equals the expenditure to obtain one unit of it. This util price can be interpreted as a consumer price index.

In the case of a market for production factors, the equilibrium market price arises as the price clearing the market for this production factor. The capital market is a production sector specific market. Hence, the price of this sector's capital good is such that the demand for capital by this sector is satisfied by the regional endowment of this capital good. The labour market is a regional market, which makes the wage rate the clearing price between demand for labour by the regional production sectors and the regional endowment of time spent for labour. Due to the homogeneity of degree zero in the excess demand and the supply functions in the equilibrium equations, any positive multiple of an equilibrium price vector will result in an equilibrium. We therefore have to choose a numeraire good. WIAGEM chooses the wage rate as numeraire.

There will be a gap between producer prices and consumer prices due to possible taxes or subsidies imposed by the regional government on this good. Similarly, there will be a gap between export producer price and consumer price due to possible tariffs or export subsidies imposed by a regional government.

The GTAP4 database provides data for the benchmark year 1992, and more data on succeeding period have to be added in order to be able to calibrate the recursive-dynamic MS-MRT model over the period between 2000 and 2050. The data that are available for this objective are often projections of GDP data for all regions in each period during this time span. These projections indicate a growth rate for each region which determines growth of resources. Table 4 depicts the GDP levels for each region in the year 1992 and the assumed growth rates as percentages of GDP in subsequent periods.

2.2 Climate

Global warming is the consequence of the increase in greenhouse gas emissions into the atmosphere. We refer to CO_2 emissions, N_2O emissions, and CH_4 emissions as greenhouse gas emissions. An increase in such emissions results in increased concentrations in the atmosphere, preventing the heat radiated from the earth's surface to be released. Consequentially, the global temperature on Earth rises to levels where significant damages are expected to occur for the current human way of life. With respect to damages, we should think of increased risks for human life in the sense of higher mortality rates, lower birth rates, and health risks. The increase in temperature also increases sealevels due to a melting of polar ice, causing valuable land to be lost. Higher precipitation levels may decrease or increase the productivity in land.

The increase in greenhouse emissions results from human activities as well as natural processes. Such human activities require the use of a significant amount of fossil fuels which are seen to be the major source behind increased CO_2 emissions. The MS-MRT model is then calibrated in such a way that the total emissions for each region as given in Table 5 are generated from the equilibrium. We obtain total emission in each region by adding the emissions of the regional household and all production sectors. We then take CO_2 emissions as a fixed share of the equilibrium fossil fuel demand by producers and regional consumer.

3 The modelling of technological innovation

A possible action to mitigate the consequences of climate change on our society is seen in the reduction of energy use in modern production processes through the introduction of more energy efficient technologies. To be able to obtain such technologies, the computable general equilibrium model should be extended with the possibility for production sectors to lay aside production for investments into more energy efficient technologies. We refer to these investments as investments in research and development.

WIAGEM uses the concept of induced technological change to endogenize technological change. Induced technological change refers primarily to technological changes following changes in policy or economic conditions, in contrast to so-called ’autonomous’ technological changes which are not induced specifically by changes. Induced technological change is implemented via research and development or via ’learning-by-doing’. WIAGEM implements R&D.

The modelling of induced technological change in CGE models like the one contained in WIAGEM often refers to the overview of this material in Buonanno et al. (2000) or earlier, to Nordhaus (2002). The notion of induced technological change however seems to be first introduced in Hicks (1932) who noted that ”changes in relative prices production factors such as labour or capital would spur the development and diffusion of new technologies in order to economize on the usage of the more expensive productionn sector”. As for details on how to model induced technological change in what we call ’top-down’ models as WIAGEM, we refer to Goulder and Mathai (2000) and to Goulder and Schneider (1999).

The total amount of R&D investments results, in due time, in a more efficient use of energy in the production and household sectors of the host regions. It is convenient to follow regular practice in modern endogenous growth theory here, when we want to model improvements in efficiency into the CGE model. We refer to details on endogenous growth theory in Barro and Sala-i-Martin (1995). This literature introduces so-called efficiency units to introduce endogenously determined changes in technology into the model. In our model, this means that we have to consider the input or consumption of the energy composite in efficiency units. Kemfert (2002) takes such an approach, where investments in research and development are related to changes in the AEEI parameter associated with energy use. We follow this approach by stating a relation between total investments in research and development and changes in this AEEI parameter within the production and household sectors. The parameter $\Delta\text{AEEI}(r,t)$ for region r refers to the change in the AEEI parameter following energy efficiency improving investments in research and development in region r. We use the following constant demand elasticity functional form

$$\Delta\text{AEEI}(r,t) = \delta_{t,r} \cdot \Delta\text{R\&D}(r,t)^{\epsilon_r}, \tag{1}$$

for this relationship. The parameter $\delta_{t,r}$ can be seen as an efficiency parameter while the parameter ϵ_r can be seen as the elasticity parameter in equation (1). A relatively high value of the efficiency parameter $\delta_{t,r}$ indicates a relatively high influence of the investments on the energy efficiency. An increase in investments by one percent, causes an increase in energy efficiency by ϵ_r. A relatively high value of ϵ_r indicates a high effectivity of investments in region r on energy use efficiency. WIAGEM takes the elasticity parameter ϵ_r equal to 0.2 for each region, while Table 6 presents the value of the efficiency parameter in each period in each region.

Business-as-Usual. WIAGEM follows the MS-MRT model by calibrating the economic submodel on the GTAP4 database. This calibration provides values for the share parameters of the model in the year of calibration, 1992. For the subsequent time periods, these share parameters are updated in such a way that the MS-MRT model reproduces the scenarios predicted by other models or data from scientific institutions. The MS-MRT model is calibrated to the development of GDP (Table 4), fossil fuel demand (Table 3), and emission levels (Table 5) over time.

The international society expects a lot from the possibilities of technological innovation in reducing the costs of emission reduction. But, whether technological innovation manages to reduce the costs of emissions on our society and meanwhile enables society to reach the goal of limiting a global temperature increase to only 0.1 degree less than the ’Business-as-Usual’ in 2050 depends among others on the efficiency with which new technologies can be implemented into the economy and the speed of learning in this economy. We define two possible scenarios to study the impact of different values for $\delta_{t,r}$ and ϵ_r on these goals. In the ”Business-as-Usual” scenario, mean global temperature is assumed to rise according to Table 7. We can conclude from the latter table that, in 2050 mean global temperature has risen with 3.809 degrees Celcius compared to the benchmark in 1992.

Developed regions. This scenario assumes that only the developed regions are actively engaged in technological innovation. Technological innovations in the developed world lead to improvements in the efficiency parameter $\delta_{t,r}$ and the elasticity parameter ϵ_r for all developed regions r. We assume that continuous improvements and communication results in a technological innovation that improves these parameters with the same percentages for each developed region r. This means that we have to determine a value δ such that the efficiency parameters $\delta_{t,r}(1+\delta)$ for all developed regions r manages to keep the global temperature rise limited to 3.709 degree Celcius in 2050. Computational experiments on the value of δ indicate a value of 0.325. We do not assume any effects on the developing regions to take place, hence $\epsilon = 0$ in this scenario.

Developing regions. This scenario extends the ’Developed regions’ scenario to an involvement of the developing regions. We assume that technological innovation in the developing world takes place through a learning effect. The developing regions are assumed to learn from the technology in the developed world causing an improvement of the elasticity parameter ϵ_r for all developing regions r. This means that we have to determine a value ϵ such that the learning elasticity $\epsilon_r(1+\epsilon)$

for all developing regions r manages to keep the global temperature rise limited to 3.709 degree Celcius in 2050. The possibility for the developed regions to obtain part of their emission reductions in the developing regions would indicate that the value δ referred to in the 'Developed regions' scenario can be closer to zero or even dissappear causing lower costs to the developed regions.

In Figure 1, we depict the combinations of values for ϵ and δ that will result in a temperature increase of 3.709 in 2050, i.e. a limitation of the temperature increase with 0.1 degrees less than the BaU situation. In this figure, δ represents the change in efficiency necessary in the developed regions and ϵ represents the change in learning capacity necessary in the developing world to allow an efficiency increase equal to δ in the developed world. We assume an extreme case to be occurring here. Let us take $\epsilon = -0.1430$. Figure 1 then indicates that no efficiency gain must be taken in the developed world, hence $\delta = 0$.

4 Simulations

In this section, we calculate the costs of the scenarios that we defined in the previous section. We refer to the opportunity costs of the Annex I regions as given by their marginal costs of emissions which, in our model equals the price of emission permits on the market. Figure 2 illustrates the development of the value of the permit price on the market for emission permits under three different scenarios. We distinguish the Business-as-Usual scenario to which also the model has been calibrated. This scenario corresponds to a value of δ and of ϵ equal to zero. In the first counterfactual scenario defined in the previous section, the 'Developed regions' scenario, we ask what kind of change in efficiency in the developed regions only is necessary to reduce the temperature rise with 0.1 degrees Celcius compared to the Business-as-Usual. We computed a value for δ equal to 0.325, under the assumption that no learning takes place in the developing regions. Hence, the

’Developed regions’ scenario refers to a value of δ equal to 0.325 and a value of 0 of ϵ. In the second counterfactual scenario, we allow the developed regions to export their modern technology to the developing regions. In our scenarios, this results in a change in the learning capacity of the developing regions corresponding to lower values for the ’learning elasticity’ ϵ_r for developing regions r. In Figure 2, we illustrate the extreme case where the temperature change can only be reached by extra learning capacity in the developing regions, i.e. this line corresponds to the situation where $\delta = 0$ and $\epsilon = -0.143$.

In Figure 2, we see that improvements in the efficiency of R&D investments decreases the price of emission permits. Equation (1) indicates that improved efficiency results in a higher value of the AEEI parameter for the production sectors in the developed world. This improved efficiency in energy use indicates a lower energy use, thereby less emissions, hence less demand for emission permits per unit of output. The decreased demand lowers the price for emission permits necessary to clear the underlying market.

The other scenario, the ’Developing countries’ scenario, is depicted in one of its extremes, by assuming $\delta = 0$. If no efficiency gain takes place in the Annex I regions, and the reduction in temperature increase can only be obtained with a decrease in the elasticity ϵ_r for the developing regions r, then we see that the price of emission permits decreases significantly with respect to the Business-as-Usual scenario but not as much as in the previously addressed scenario. A decrease in this elasticity implies that the AEEI factor in the developing regions’ production technologies increases significantly. The production sectors in these regions therefore need less investments in R&D to obtain the same effect on the AEEI as under the Business-as-Usual scenario. On the other hand, the price of the energy composite in these technologies will be decreased, causing energy intensive products to become relatively cheap in the developing world. Here, demand will be shifting from the now relatively expensive imports from the developed world to the cheaper domestically produced goods. The Annex I regions then need to produce less of these energy intensive goods than before, with lower emissions as a consequence. This decreases demand for the emission permits required for production hence leading to a lower permit price to clear the market. This decrease is less than in the ’developed regions’ scenario since it is caused by an indirect effect.

In Figure 3, we illustrated the consequences of implementing our scenarios on total emissions, on the emissions of the Annex I regions, and the emissions of the non Annex I regions. This leads to three figures, each one corresponding to one of the scenarios defined in the previous section. The top figure depicts the total global emissions. These emissions contain total emissions for the Annex I regions, depicted in the left figure, and the total emissions for the non Annex I regions, depicted in the right figure on the lower level of Figure 3.

The figure referring to the emissions of the Annex I regions shows that both counterfactuals significantly reduce emissions as expected, from 2005 on. Since WIAGEM is an intertemporal model, producers and consumers take account of the future in their decisions, and this sudden decrease in emissions in 2005 is in anticipation of the increased prices for emissions in the near future. Notice also that emissions rise at the end of the total period, towards 2050, since WIAGEM considers only a finite time and, as described in Section 2, the last period also takes account of what happens after 2050. The ’Developing regions’ scenario also has more influence on Annex I emissions than the ’Developed regions’ scenario. The reduction of imports of energy intensive goods from the Annex I regions obviously reduces emissions here to a large extent.

The figure referring to the emissions of the non Annex I regions provides a mixed view. Emissions of the non Annex I regions lie above the Business-as-Usual levels for a long time, but on the longer term emissions under this counterfactual will decrease sufficiently. The ’developed regions’ scenario works out more efficiently on emissions in non Annex I regions than the ’developed regions’ scenario. Total emissions, depicted in the top figure, contains all influences on the emissions of Annex I and non Annex I regions.

5 Conclusions

The international society has great expectations about the possibilities of technological change in reducing the costs of implementing climate change policies on the economies of the developed world. In this paper, we investigated the conditions that should be imposed on technological change in order to limit the increase in mean global temperature in 2050 to 0.1 degree less than under a Business-as-Usual scenario. We use the 'World Integrated Assessment General Equilibrium Model' (WIAGEM), an integrated assessment model that combines an intertemporal computable general equilibrium model with a climate model. WIAGEM endogenizes technological change into the CGE model in the form of induced technological change where investments in research and development result in an improved AEEI parameter attached to the use of energy in the production sectors. The relation between the change in the AEEI parameter and the investments in research and development depends on an efficiency parameter and a 'learning' elasticity, the latter elasticity giving some indication on how easy new technological knowledge can be assimilated into the production technologies of an economy.

We defined two counterfactual scenarios to be compared to the Business-as-Usual to which WIAGEM has been calibrated. In one counterfactual, we only let changes in the efficiency parameter of the developed regions be responsible for improvements in the AEEI parameters. No contribution is expected from the developing world. We referred to this counterfactual as the 'Developed regions' counterfactual. We then take another extreme, by defining a counterfactual scenario 'Developing regions' where we only let changes in the 'learning elasticity' of the developing regions be responsible for changes in the AEEI parameters. Both scenarios have a significant impact on the price of emission permits on the Annex I permit trading market. This price, in our model, equals the marginal cost of emissions in the regions that participate on this market. Hence, technological change significantly reduces these costs. As for total global emission, even under these conditions, technological change following investments in research and development, is not able to curb emissions. Emissions will be generally lower as compared to the Business-as-Usual scenario, but they still increase over time, indicating only a postponement of the consequences of climate change to a later date.

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ASIA:	India and other Asian countries
CHN:	China
CAN:	Canada, New Zealand, and Australia
EU15:	European Union
JPN:	Japan
LSA:	Latin America
MEX:	Mexico
MIDE:	Middle East and North Africa
REC:	Russia, Eastern and Central European Countries
ROW:	Rest of the World
SSA:	Sub Saharan Africa
USA:	United States of America

Table 1: The regional aggregation in WIAGEM.

Agriculture
Coal
Chemical rubber and plastics
Crude oil
Electricity
Natural gas
Nonferrous metals
Nonmetal mineral products
Petroleum and coal products
Other manufactures and services
Iron and steel
Pulp and paper
Transport industries

Table 2: The sectoral aggregation of traded goods in WIAGEM.

region	sector	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
JPN	coal	0.09	0.09	0.1	0.11	0.12	0.13	0.13	0.14	0.15	0.15	0.15
	gas	0.27	0.29	0.32	0.35	0.38	0.41	0.43	0.45	0.45	0.48	0.48
	oil	0.24	0.24	0.25	0.25	0.26	0.26	0.26	0.27	0.27	0.28	0.28
CHN	coal	32.02	38.12	44.56	51.59	59.02	66.69	75.12	80.97	81.85	87.27	89.39
	gas	0.77	0.98	1.26	1.6	2.01	2.47	3.02	3.19	3.22	3.38	3.36
	oil	6.27	6.68	7.05	7.27	7.45	7.57	7.7	7.94	7.93	8.28	8.21
USA	coal	21.3	22.09	23.79	25.87	27.79	29.47	31.14	33.39	34.68	37.45	37.03
	gas	19.26	20.77	22.7	24.93	27.01	28.86	30.7	32.06	32.61	34.1	34.19
	oil	17.45	17.1	17.6	18.12	18.45	18.58	18.67	19.22	19.24	20.16	20.07
SSA	coal	4.82	5.2	5.44	5.66	5.85	5.99	6.14	6.43	6.51	6.9	6.84
	gas	0.22	0.27	0.35	0.44	0.55	0.68	0.84	0.87	0.9	0.98	0.99
	oil	7.9	8.47	9.01	9.31	9.62	9.91	10.26	10.6	10.66	11.11	11.04
ROW	coal	15.05	16.23	16.97	17.67	18.25	18.68	19.15	19.74	19.88	20.77	20.7
	gas	3.07	3.84	4.91	6.24	7.78	9.66	11.83	12.7	12.94	13.6	13.58
	oil	14.28	15.3	16.29	16.84	17.38	17.91	18.55	19.23	19.24	20.04	19.85
CNA	coal	6.42	6.66	7.17	7.8	8.38	8.89	9.39	9.68	9.67	10.1	10.01
	gas	5.87	6.33	6.92	7.6	8.23	8.8	9.36	9.68	9.68	10.1	10.01
	oil	5.53	5.43	5.58	5.75	5.85	5.89	5.92	6.1	6.1	6.36	6.29
EU15	coal	6.79	7.04	7.58	8.25	8.86	9.4	9.93	10.23	10.24	10.72	10.63
	gas	6.66	7.18	7.85	8.62	9.34	9.98	10.61	10.95	10.97	11.41	11.3
	oil	6.62	6.49	6.68	6.87	7	7.05	7.08	7.3	7.3	7.6	7.52
REC	coal	9.23	9.31	9.62	9.95	10.14	10.18	10.16	10.48	10.47	10.92	10.88
	gas	26.79	29.14	31.09	32.51	33.59	34.19	34.61	36.07	36.2	49.18	54.24
	oil	13.83	16.19	19.02	22.03	25.15	28.29	31.65	32.63	32.74	34.21	33.94
LSA	coal	0.98	1.05	1.1	1.15	1.18	1.21	1.24	1.3	1.31	1.37	1.36
	gas	3.45	4.33	5.54	7.03	8.77	10.88	13.33	13.72	14.3	15	15.15
	oil	19.18	20.56	21.89	22.62	23.36	24.06	24.92	25.79	25.89	27.35	27.18
ASIA	coal	8.06	9.6	11.22	12.99	14.86	16.79	18.91	19.53	20.58	21.55	21.59
	gas	5.04	6.37	8.18	10.43	13.05	16.07	19.65	20.24	21.21	23.46	24.57
	oil	6.31	6.72	7.09	7.32	7.49	7.62	7.75	8.02	8.05	8.38	8.31
MIDE	coal	0.03	0.03	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
	gas	8.19	9.34	11.22	13.3	15.63	18.13	20.89	22.57	22.71	23.9	24.56
	oil	49.45	57.95	66.33	73.98	81.47	88.57	95.93	99.82	100.01	105.41	105.6

Table 3: Projections of fossil fuel demand (in ExaJoule) obtained from sources at DEA and IEA. See Bernstein et al. (1999a).

region	GDPlevel1992	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
`JPN`	356.33	2.3	2.2	2.1	2	1.9	1.8	1.7	1.7	1.7	1.7	1.7
`CHN`	39.93	6	5.5	5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	3.5
`USA`	581.76	2.3	2.2	2.1	3	2.5	2.3	2	1.9	1.9	2	1.7
`SSA`	31.18	4	4	4	4	4	4	4	4	4	4	4
`ROW`	96.56	4	4	4	4	4	4	4	4	4	4	4
`CNA`	89.91	2.3	2.2	2.1	2	1.9	1.8	1.7	1.7	1.7	1.7	1.7
`EU15`	745.56	2.3	2.2	2.1	2.3	1.9	2	2	1.9	1.9	1.9	1.9
`REC`	55.08	4	1.5	1.5	2.5	1	1	1	1	3	1	2
`LSA`	124.91	4	4	4	4	4	4	4	4	4	4	4
`ASIA`	125.11	6	5.5	5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
`MIDE`	58.75	4	4	4	4	4	4	4	2	2	4	2

Table 4: Business-as-Usual levels of GDP for each region in 1992.
See Bernstein et al. (1999a).

region	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
`JPN`	0.32	0.33	0.34	0.35	0.35	0.35	0.35	0.37	0.41	0.44	0.49
`CHN`	0.71	0.63	0.59	0.58	0.57	0.57	0.57	0.60	0.67	0.48	0.56
`USA`	1.33	1.38	1.39	1.40	1.40	1.40	1.42	1.22	0.87	0.94	1.04
`SSA`	0.11	0.11	0.11	0.11	0.11	0.08	0.03	0.03	0.03	0.03	0.04
`ROW`	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71
`CNA`	0.20	0.20	0.21	0.21	0.21	0.21	0.21	0.22	0.20	0.13	0.14
`EU15`	0.93	0.98	0.99	1.00	1.00	1.00	1.01	1.06	1.16	1.26	1.03
`REC`	0.77	0.75	0.74	0.73	0.72	0.72	0.73	0.76	0.83	0.90	0.99
`LSA`	0.26	0.28	0.29	0.29	0.30	0.30	0.31	0.33	0.36	0.39	0.44
`ASIA`	0.48	0.46	0.46	0.47	0.47	0.48	0.49	0.52	0.58	0.54	0.40
`MIDE`	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19

Table 5: Business-as-Usual levels of carbon emissions for each region in billions of ton Carbon.

region	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
`JPN`	1.00	0.98	0.95	0.93	0.91	0.89	0.87	0.85	0.84	0.82	0.80
`CHN`	0.63	0.69	0.68	0.66	0.65	0.64	0.63	0.61	0.57	0.61	0.60
`USA`	1.06	1.04	1.01	0.99	0.97	0.95	0.92	0.90	0.89	0.87	0.85
`SSA`	0.64	0.65	0.63	0.62	0.60	0.59	0.59	0.57	0.56	0.55	0.54
`ROW`	0.77	0.78	0.77	0.76	0.74	0.73	0.72	0.71	0.69	0.68	0.66
`CNA`	0.77	0.75	0.74	0.72	0.70	0.69	0.67	0.65	0.64	0.63	0.62
`EU15`	1.16	1.13	1.11	1.09	1.06	1.04	1.02	0.99	0.97	0.94	0.92
`REC`	0.69	0.70	0.70	0.69	0.68	0.67	0.67	0.66	0.65	0.64	0.62
`LSA`	0.86	0.86	0.84	0.83	0.81	0.79	0.78	0.76	0.75	0.73	0.72
`ASIA`	0.83	0.86	0.85	0.83	0.81	0.79	0.78	0.76	0.73	0.72	0.70
`MIDE`	0.73	0.74	0.73	0.71	0.70	0.68	0.67	0.66	0.64	0.63	0.62

Table 6: The values for the efficiency parameter $\delta_{t,r}$ of R&D investments.

2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
2.171	1.934	0.018	0.002	−0.012	−0.025	−0.038	−0.048	−0.056	−0.066	−0.072

Table 7: The rise in mean global temperature in degrees Celcius.

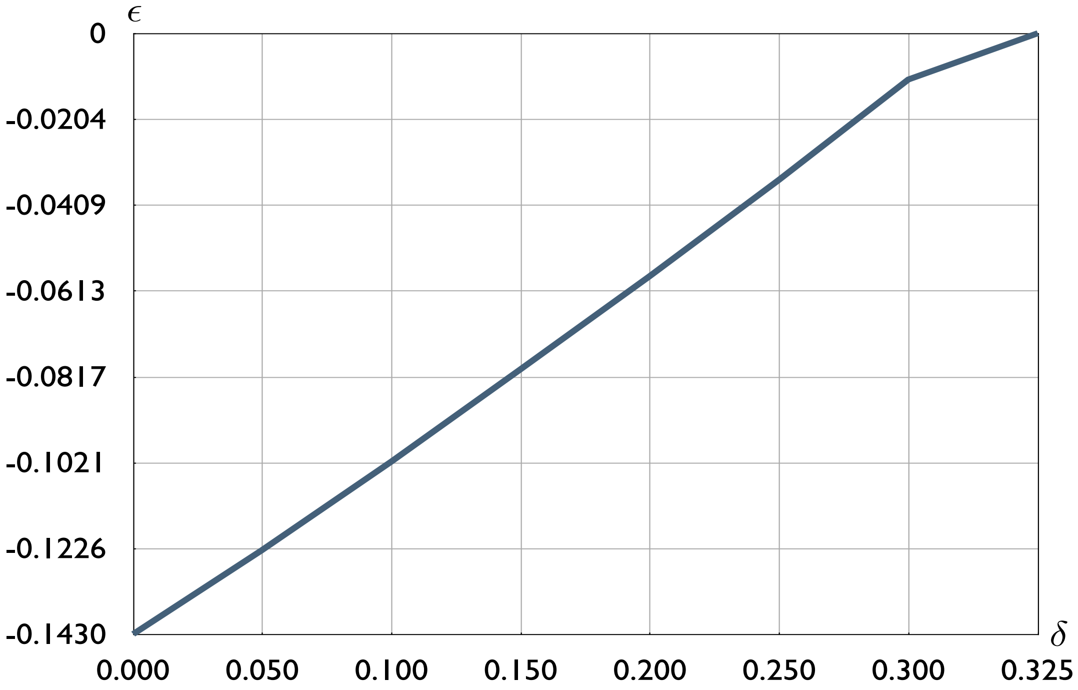


Figure 1: The combination of values for ϵ and δ that keep the temperature rise in 2050 equal to 3.709.

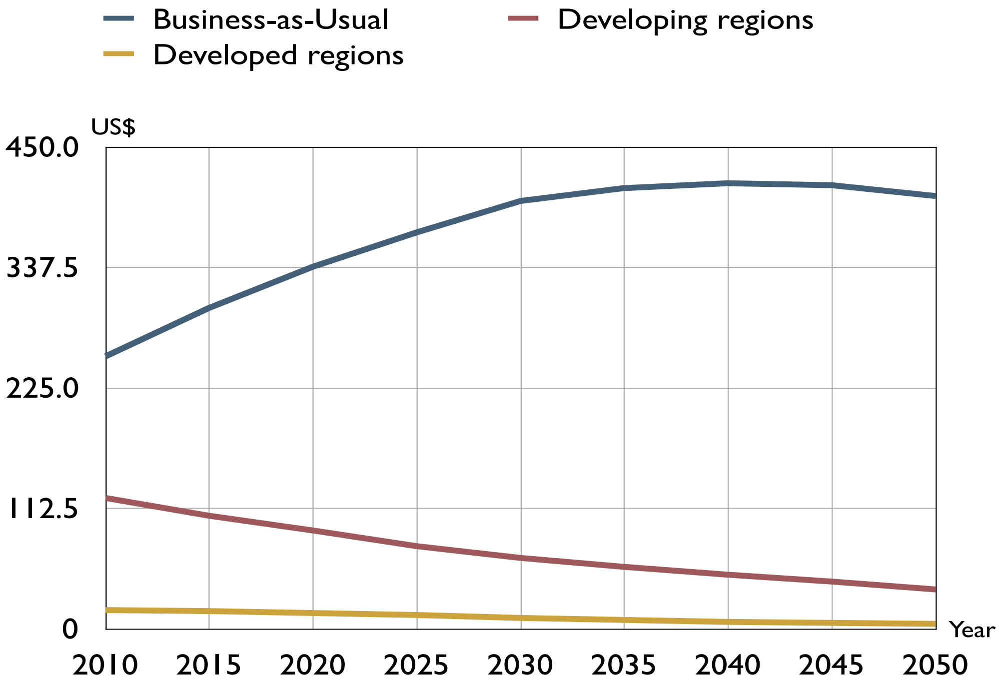
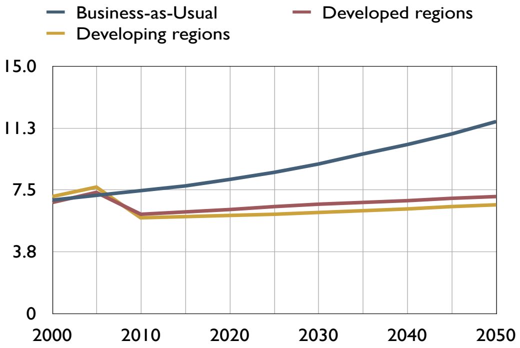
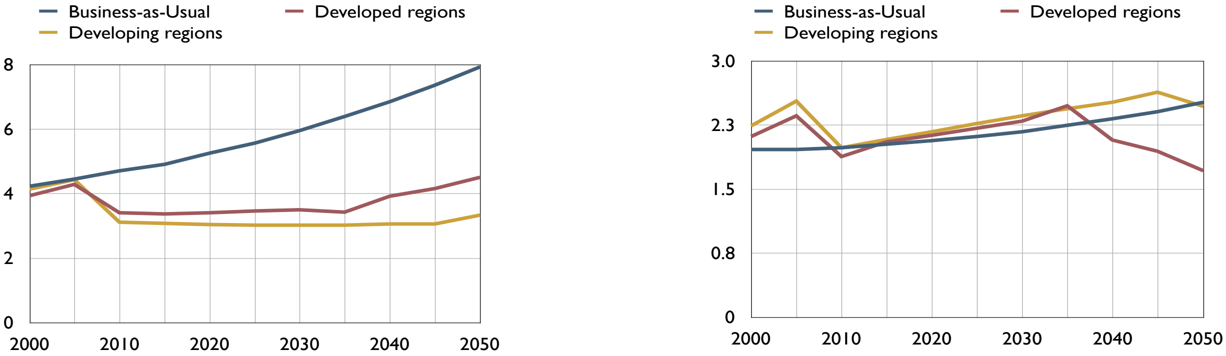


Figure 2: The development of emission permit prices for three scenarios.



Total emissions



Annex I

non Annex I

Figure 3: The development of CO_2 emissions for three scenarios. The top figure represents the total global emissions. On the second level, the left figure represents total Annex I emissions, and the right figure represents the total non Annex I emissions under the three scenarios.