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Kemfert, Claudia and Zhang, ZhongXiang

University of Oldenburg, Germany, East-West Center, USA

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Claudia Kemfert[a] **and ZhongXiang Zhang**[b,*]

[a] Department of Economics
University of Oldenburg
D- 26111 Oldenburg
Germany
Tel: +49 441 798 4106
Fax: +49 441 798 4101
Email: kemfert@uni-oldenburg.de

[b] Research Program
East-West Center
1601 East-West Road
Honolulu, HI 96848-1601
USA
Tel: +1-808-944 7265
Fax: +1-808-944 7298
Email: ZhangZ@EastWestCenter.org

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[*] Corresponding author.

Abstract

Using a world multi-sectoral, multi-regional trade model, this paper has investigated the economic and environmental implications of climate control coalitions cooperating on R&D investment that triggers low cost environmentally friendly technologies. We start with the Kyoto scenario where all Annex B industrialized countries (including the US) are assumed to individually meet their mandatory Kyoto greenhouse gas emissions reduction targets. Next, we consider industrialized country's cooperating on climate control and R&D-induced technological innovations. We then expand climate control coalition to include developing countries. Finally, we investigate the implications of additional R&D investment from industrialized countries to developing countries. Our results clearly demonstrate that cooperation on climate control and R&D among industrialized countries induces technological innovations, lowers their compliance costs and thus places less strong economic burden on these countries. But without developing countries getting involved in climate control and R&D investment, such a cooperation alone is unable to completely offset negative economic effects of the emissions reduction commitments on both industrialized countries themselves and developing countries. Recognizing the importance of developing countries' participation and their legitimate demand for adequate technology transfer and financing, the paper concludes that linking developing country's cooperation on climate control with industrialized country's R&D and technology transfer would produce win-win-win outcomes for both developing countries and industrialized countries and for the global environment.

Keywords: Kyoto Protocol, climate change mitigation, R&D, CGE analysis

JEL classification: Q43, Q48, Q54, Q55, O13, O32, O44, F18, C68, C7

1. Introduction

March 2001, the President Bush changed his mind about a campaign pledge to regulate carbon dioxide. Soon after, he thought the Kyoto Protocol "fatally flawed", and decided the US withdrawal from the Protocol on the grounds that it would be harmful to the nation and does not impose any restrictions on emission of greenhouse gases by developing nations. Nevertheless, he insisted last June that climate change was a serious problem, and promised to propose an alternative. Nearly one year after pulling out of the Kyoto Protocol, he finally announced his long-awaited, domestic climate plan on February 14, 2002.

The Bush plan represents a welcome step forward, because it signals that the U.S. recognizes the importance to take action against climate change. This is particularly significant, given the President decision to reject the Protocol. Moreover, by explicitly putting forward an intensity target, it provides a reference against which to measure the U.S. has made progress in controlling the growth of emissions. However, the plan does not offer a credible reply to the Bush administration's critique that Kyoto Protocol failed to require developing countries' participation, which led the administration to pull out of the Protocol. What are alternatives?

Is it possible to offer a framework in such a way that can provide incentive for cooperation between industrialized countries and developing countries on climate control? To address this question, we have to know what is the most challenging issue in international climate change negotiations. On the one hand, given that developing countries represent rapidly growing greenhouse gas emissions sources in line with their industrialization and urbanization, industrialized countries insist that developing countries should take on commitments. On the other hand, developing countries argue that industrialized countries are responsible for the majority of both historical and current greenhouse gas emissions. They insist on legitimate demand for industrialized countries to provide adequate technology transfer and financing, if curbing greenhouse gas emissions requires special action on their part.

In this paper, we aim to examine the linkage between R&D in industrialized countries and climate mitigation in developing countries to ascertain whether such a linkage provides incentives for cooperation between industrialized and developing countries on climate control. We assess the linkage using a world multi-sectoral, multi-regional trade model WIAGEM. Technical innovation is induced by knowledge accumulation. We assume that part of the technological benefits are a global public good. Not only the innovating country but all other countries enjoy positive spillover effects through international trade and capital flows. On the other hand, we treat part of them as a club good that is only appropriated by the members. Non-members are only able to attain such benefits if they are willing to cooperate with the members on climate control. In our context, if developing countries cooperate on climate control, they can attain the R&D cooperation benefits. As such, developing countries are able to cut their baseline greenhouse gas emissions, and industrialized countries can count these reductions credits towards their emissions targets under the Kyoto Protocol. Linking developing country's cooperation on climate control with industrialized country's R&D and technology transfer could prove to be win-win outcomes for both developing countries and industrialized countries. The former get increased access to more advanced energy efficiency and pollution control technologies, thus accelerating their future development along a more sustainable path, while the latter are able to meet their Kyoto commitments at a lower overall cost than would otherwise have been the case.

This study differs from earlier economic studies in two important aspects. First, no global multi-regional trade (MRT) models have incorporated R&D-induced technological changes as our model has done. Second, our scenarios examined are unique, and to our knowledge this is the first study to examine implications of industrialized countries investing in developing countries via R&D. This will allow us to investigate the contribution of enhanced R&D in developing countries to increasing GDP growth in developing countries and lowering Annex B country's compliance costs.

The paper is organized as follows. The second section discusses international climate control coalitions, pointing out that R&D cooperation could be an effective strategy for inducing climate change cooperation. The third section illustrates the applied modeling concept WIAGEM, with the mathematical description of endogenous technological change given in Appendix. The fourth section describes the policy scenarios examined, whereas the fifth section discusses all the simulation outcomes. The paper ends with the main conclusions.

2. International Climate Control Coalitions

The greatest success of international climate control policy was the establishment of the Kyoto Protocol. It is one of the leading and most important international environmental agreements in the history of global negotiation and bargaining policies. However, recent climate change negotiation processes confirm that the initial climate change control coalition was not stable: the United States, the world's largest economy and emitter of greenhouse gases (GHG) left the coalition and now acts as a free rider. The reason for this behavior can be explained by game theoretic validation. Economic payoffs to free ride are higher than joining coalitions.[1]

Cooperation to reduce greenhouse gas emissions must be voluntary, as there is no international authority to enforce action. Extensive economic literature on game-theoretic approaches to international cooperation that address climate change has been produced since the early nineties (Barrett, 1992, 1995; Carraro, 1999, 2000; Carraro and Siniscalco, 1992, 1993; Cesar, 1994; Chander, Parkash and Tulkens, 2001; Chander et al., 1999; Courtois, et al., 2001; Endres and Finus, 1998; Finus, 2000; Finus and Rundshagen, 2001; Hoel, 1994; Kemfert, 2001a, 2002b; Kemfert et al., 2002).

Unfortunately, cooperation can also increase the incentive for each country to free ride when not fulfilling its commitment. If the marginal benefits of additional emissions reductions decline, each country gains the benefits of emissions reduction implemented by others and reaps fewer benefits from its own actions. Although the rules adopted for the Kyoto Protocol include penalties for non-compliance, they may be difficult to enforce.[2] From the aforementioned game-theoretic literature, the following conclusions can be derived:

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[1] The recent announcement (February 14th, 2002) by the US administration proposes a voluntary environmental program avoiding huge economic losses resulting from economic growth reductions.

[2] An Annex B Party not meeting its commitment can be penalized 1.3 permits from its allocation for the next commitment period for each ton of excess emissions. However, a penalized country can threaten to withdraw from the protocol. In practice, the penalties, if any, are likely to be negotiated.

- A global, self-enforcing agreement that is stable and profitable[3] to all signatories[4] is highly unlikely.
- Self-enforcing international environmental agreements are likely to include a limited number of countries.
- An equilibrium is likely to consist of multiple agreements of different size and with different commitments.
- Equity and efficiency cannot be separated because the number of signatories affects the compliance costs each member bears. Compliance costs, in turn, affect the number of signatories (Carraro, 2000).
- The existence of stable agreements depends on leakage, i.e. increased economic activity and emissions by non-members resulting from emissions reduction action by members. Leakage reduces the environmental benefits due to cooperation, creating an increased incentive to free ride.[5]

Based on the game theory literature, the US withdrawal from the Kyoto Protocol is not surprising, especially since it considered the cost of participation to be high. The adoption of low-cost unilateral action or formation of a separate agreement (e.g. NAFTA) would be consistent with the game theory literature.

A variety of incentives exist for free riders or unstable coalition partners to join or remain in the game. These include *transfers* (Carraro and Siniscalco, 1993; Hoel, 1994), *issue linkage* (Folmer and van Mouche, 1993; Folmer, van Mouche and Ragland, 1993; Gil and Folmer, 1998; Barrett, 1995; Carraro and Siniscalco, 1995; Mohr, 1995), *legal enforcement* through *third-party arbitration* (Barrett, 1992), *matching* (Barrett, 1995; Guttman, 1978, 1987), *self-enforcing strategies* (Barrett, 1994b; Endres and Finus, 1998), *social norms* (Hoel and Schneider, 1997), *tit-for-tat* (Cesar, 1994), *trigger strategies* (Barrett, 1994a; Cesar, 1994), and *unilateral action* (Barrett, 1995; Hoel, 1991).

Comparing different incentive approaches, the best strategy for increasing the number of participants and/or emissions reductions and ensuring compliance with commitments appears to be transfers and issue linkage. Unilateral action does not prevent free riding and may lead to increased levels of emissions. With trigger strategies, penalties must be effective and hence are not suitable for a self-enforcing agreement; they are furthermore not renegotiation-proof. Legal enforcement is not feasible where the participants are sovereign nations. Matching, over time, leads all countries to behave in the same manner as the country making the least effort in reducing emissions. Tit-for-tat has been shown to be highly effective, especially if participants in a game are likely to meet again (Axelrod, 1984). But governments may not maintain tit-for-tat strategies for climate policy if other policy priorities arise. While social norms may reduce free riding, they differ across countries and may not be effective in ensuring compliance.

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[3] An agreement is profitable if welfare is higher with the agreement than without the agreement.

[4] An agreement is stable if none of the members has an incentive to leave and no non-member has an incentive to join. An agreement must be profitable to be stable (Bosello et al., 2001).

[5] Paltsev (2001, p. 55) reports leakage of 5% to 15% depending upon assumptions about fossil fuel supply elasticities and trade substitution possibilities. This compares with leakage rates of 5% for GREEN, 8% for G-Cubed, 9% for GTEM, 11% for Gemini-E3, 14% for Worldscan, 26% for MS-MRT and 34% for MERGE when each country, including the United States, must meet its Kyoto Protocol target domestically. International emissions trading reduces the leakage rate approximately by half. The US withdrawal from the Kyoto Protocol would decrease leakage by reducing the marginal cost of compliance.

If an agreement is profitable, there is a net gain to the members. In principle, this net gain can be distributed so that each adherent is a net beneficiary and thus attracts new members. Transfers can take the form of differential emissions reduction commitments with emissions trading mechanisms, such as those established by the Kyoto Protocol. A stable global agreement requires a policy mix that couples global emissions trading with a transfer mechanism designed to offset ex-post incentives to free ride (Bosello et al., 2001). Transfers to the United States to induce it to adopt more stringent emissions targets are not considered by Kyoto Protocol parties, since this would require renegotiation of the Protocol to accommodate the United States.

If countries that do not benefit from an environmental agreement benefit from agreements on another issue and vice versa, linking agreements on two or more issues may enable countries to advance their joint interests on multiple issues at the same time, thus creating more room for mutual consensus than what would be possible on any single issue. In principle, issue linkage can improve both profitability and stability. Suggested links to climate change include *trade* (Barrett, 1992, 1995, 1997; Cesar, 1994; Conconi and Perroni, 2000; Kemfert, 2002b; Whalley, 1991), *research and development* (Carraro and Siniscalco, 1995, 1997; Katsoulacos, 1997; Kemfert, 2002b; Tol et al., 2000; Buchner et al., 2002), *international debt* (Mohr, 1995), and other environmental problems such as *biodiversity* (Barrett, 1994a), and *trade sanctions* (Batyabal, 1995; Heister, 1993).[6] Linkage is more likely to be successful when the benefits of the linked issue can be limited to the agreement participants, unlike environmental agreements which benefit all countries regardless of their participation.

As links with other issues merely increase the possible set of solutions (Gil and Folmer, 1998), linkage does not necessarily lead to better outcomes. Accordingly, studies examining potential links between climate change and international trade agreements conclude that such a link may or may not lead to participation by a larger number of countries. Implementing trade sanctions on non-cooperating countries does not guarantee greater cooperation (Courtois et al., 2001). Kemfert (2002b) finds that, with one exception, trade sanctions against non-members do not provide a significant incentive to join an agreement. Conconi and Perroni (2000) find that the effect of linking trade and environmental agreements is ambiguous.[7] Linking trade and environmental agreements helps if the environmental policy stakes are small relative to the welfare effects of trade policies.

Moreover, imposing trade restrictions faces methodological and implementation challenge and legal uncertainty. Barrett (1994, 2001) states that trade restrictions are the most obvious enforcement mechanism for an international climate change agreement, but are difficult to apply for climate change due to the very large number of goods affected, the difficulty of calculating the appropriate border tax for each product, and likely inconsistency with international trade agreements.[8] Aldy, Orszag and Stiglitz (2001) suggest tariffs or trade restrictions based emissions associated with production, including standards that place the production of non-members at a disadvantage. Measure of this sort boils down to the whole processes and production methods

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[6] A strategy that links climate change to international debt is not considered. It is assumed that debt concessions by climate negotiating parties to the United States would be politically unacceptable even in return for more aggressive climate change targets given the high per capita income of the United States relative to the Kyoto Protocol parties.

[7] They distinguish between issue linkage, where a country is free to participate in none, either, or both agreements, and issue tie-in, where a country must be a party to both or none of the agreements.

[8] Barrett, 2000.

(PPMs) controversy.[9] Under WTO rules, an imported product is not allowed to be treated differently to a “like product” (i.e., a product with the same physical characteristics) produced domestically, only on the ground of PPMs employed to produce the product, although recent WTO Appellate Body decisions on the Shrimp-Turtle dispute have cast doubt on these interpretations.[10]

In searching for potential issues to be linked, a growing literature suggests that cooperation on research and development appears to be a more promising way of expanding cooperation on climate change. Tol et al. (2000) find that technology and capital transfers increase the incentives to cooperate. Kemfert (2002b) finds that full cooperation on climate change and technological innovation benefits all countries relative to unilateral action, although technological spill over effects reduce the effectiveness of this strategy. Buchner et al. (2002) find that linking R&D cooperation with cooperation on climate change control is profitable and guarantees the stability of the linked agreement.[11] In summary, the literature suggests that R&D cooperation could be an effective strategy for inducing climate change cooperation. Trade measures are less likely to be effective.

However, recent studies indicate that, despite the high profile of the climate change issue, most industrialized countries have scaled back their spending in mitigation-related R&D. This is not that surprising, because, given the nature of a public good, the knowledge obtained from basic research is likely to be under-provided if undertaken unilaterally. Thus, Barrett (2001) suggests that basic R&D is best supplied cooperatively. International commitments to provide R&D funding are not unprecedented. A good example is multilateral cooperation and funding for the international space station.

The climate control coalition might want to induce the United States to adopt a more stringent greenhouse gas target. The US withdrawal and adoption of a unilateral target reduces the environmental benefits anticipated by the climate control coalition when they negotiated their commitments. The US action also reduces the costs of meeting their commitments and raises concerns about adverse competitiveness impacts.

World Trade Organization (WTO) rules allow border tax adjustments for environmental taxes or charges on products (ozone-depleting substances) or physically incorporated inputs (chemicals in plastic products), but not on production processes (CO_2 emissions) or non-physical incorporated inputs (energy used in production). This means that border tax adjustments are not allowed for production processes or methods (PPMs) used in exporting countries. However, the Shrimp/Turtle case seems to signal an development of the WTO towards dealing with the issue of PPMs.[12]

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[9] In dealing with the whole PPMs controversy, a distinction is drawn between product-related PPMs and non-product related PPMs. Product-related PPMs refer to the characteristics of the final product, for example, the environmental impact of a product when it is used or disposed, whereas non-product related PPMs refer to the characteristics of the processes or methods in manufacturing a product or providing a service (OECD, 1997).

[10] See Zhang (2004) and Zhang and Assunção (2002) for further discussions on the Shrimp-Turtle dispute and interactions between climate policies and trade policy.

[11] These results are sensitive to the level of technological spillover assumed.

[12] Vikhlyaev, 2001.

Some multilateral environmental agreements (MEAs) including CITES, the Montreal Protocol and the Basel Convention, define "specific" trade measures, usually against non-coalition countries. The Montreal Protocol imposes trade restrictions on goods made with, but not containing, ozone-depleting substances.[13] So far, no trade measure taken pursuant to an MEA has been challenged in the WTO by a non-party. The legal ambiguity surrounding the possibility of such a challenge raises questions about the effectiveness of such measures.[14] Buck and Verheyen (2001) conclude that trade sanctions which discriminate against goods or services from non-coalition nations are very likely to be incompatible with WTO law.[15] However, the economic effects of measures allowed under WTO law taken by countries willing to act on climate change will exert economic pressure on those falling behind on climate change. Buck and Verheyen (2001) conclude that:

- product (e.g. energy efficiency) standards applied in a non-discriminatory way on imported and domestic products would be compatible with WTO law;
- eco-labeling schemes which consider non-product-related environmental impacts of products would most likely violate WTO provisions;
- procurement programs developed and implemented in the context of an MEA will not violate WTO law even if they include PPM-based technical specifications; and
- trade restrictive environmental measures – including PPM-based measures – can be justified under the provisions of the GATT if such measures have been agreed to and negotiated on a multilateral basis. Trade disputes are more likely to arise from such national measures undertaken to fulfill obligations under an MEA rather than from the provisions of the MEA.[16]

De Moor et al. (2002) note that President Bush has proposed $ 4.5 billion in research, suggesting that joint efforts in technology development could be a promising option for cooperation.[17] Barrett proposes:

- collectively funded R&D (including developing countries based on UN assessment) and
- coordinated adoption of national standards to drive adoption of lower emitting technologies.[18]

In summary, there are several precedents for multilateral environmental agreements that specify trade measures to be taken against non-coalition countries. At least one agreement imposes trade restrictions based on production processes or methods. The WTO may be moving to greater acceptance of trade restrictions based on PPMs. However, considerable legal uncertainty remains in all of these areas. It appears that the Kyoto Protocol parties could make amendments to include

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[13] In other words, the Montreal Protocol imposes trade restrictions based on PPMs despite the fact that WTO rules do not allow border tax adjustments based on PPMs.

[14] Vikhlyaev, 2001, p. 18.

[16] Zhang and Assunçâo, 2002.

[17] De Moor et al., 2002.

[18] Barrett, 2000.

specific trade measures to be taken against non-coalition countries such as the United States, provided that they are related to climate change. Those measures could include trade restrictions on specified products based on their method of production.

3. The Model WIAGEM

The analysis is performed using the WIAGEM model. The multi regional model WIAGEM (**W**orld **I**ntegrated **A**ssessment **G**eneral **E**quilibrium **M**odel) is an integrated economy-energy-climate model that incorporates economic, energetic and climatic modules in an integrated assessment approach. In order 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. That is why we think that the model is best suited for an investigation of cost and benefits through climate-related trade policies. 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) which influence the 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.

Induced technological change is considered as follows (see Appendix for the mathematical description). 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 effect and terms of trade effect. 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, and climate and ecological impacts in WIAGEM.

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 submodel. The model covers a time horizon of 50 years and solves in five-year time increments.[19] The basic idea behind this modeling approach is the evaluation of market and non-market impacts

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

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

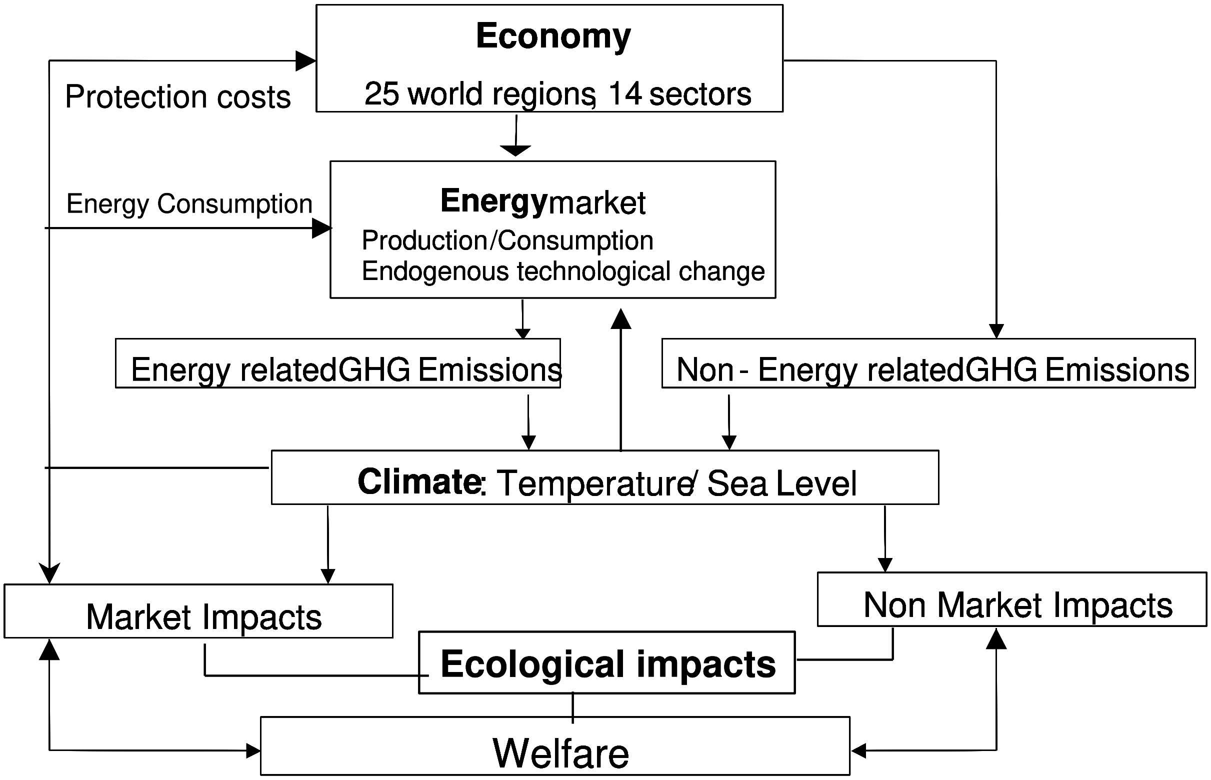

Figure 1 Interrelations in WIAGEM

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

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 get 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.

In addition to the non-energy macro good, oil, coal and 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 the market price. Coal trades in a competitive global market and 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. The model includes three of the six greenhouse gases covered under the Kyoto Protocol: carbon dioxide (CO_2), methane (CH_4) and nitrous dioxide (N_2O). These gases are considered to have the most influence on climate change over 50 year period covered by the model, so exclusion of the remaining three gases is not believed to alter the general insights from this analysis.

The emissions limitation commitments of Annex B Parties are specified as regional emission limits for 2010 adjusted to reduced coverage of greenhouse gases by the model. Sink enhancement actions are assumed to have zero cost and to have a global potential of 464 MtC in 2010.

The climate submodel estimates the climatic changes due to the greenhouse gas emissions and estimates the associated market and non-market damages. The atmospheric concentrations of CO_2, CH_4 and N_2O are based on the first atmospheric lifetime of each gas because of the 50 year time horizon of the model. This means that the emissions remaining in the atmosphere are assumed to have an infinite lifetime. The atmospheric concentrations affect radiative forcing, which influences the potential and actual surface temperature and the sea level. Market and non-market damages associated with these impacts, expressed as changes to regional and global welfare, are calculated as a function of the potential temperature change, the change in regional GDP, and regional coastal protection costs.

4. Formation of Policy Scenarios

The main purpose of this paper is to investigate whether developing countries would economically benefit from cooperation on climate control and R&D-induced technological innovations either by Annex B countries or by themselves. To that end, we examine the following one baseline scenario and four main policy scenarios using the WIAGEM model.

Business-as-usual (or baseline) scenario: This scenario assumes no specific intervention to limit the rate of greenhouse gas emissions but does allow for anticipated changes in demographic, economic, industrial and technological developments as well as environmental policies not directly aimed at limiting greenhouse gas emissions. As such, emissions both for Annex B countries and non-Annex B countries are expected to continue to rise unconstrainedly.

The Kyoto scenario: All Annex B countries (including the US) are assumed to individually meet their mandatory Kyoto GHG emissions reduction targets without any trading of emissions permits. No emissions targets are set for developing countries.

The R&D scenario: All Annex B countries (including the US) are still required to meet the same commitments as under the Kyoto scenario, but we assume that these countries cooperate on R&D investments to maximize their joint welfare. This scenario is to examine the contribution of R&D to lowering Annex B country's compliance cost, given that investments in R&D induce technological innovations and changes that offer potentials to reduce emissions at lower costs.

The DEV&R&D scenario: We assume that developing countries also cooperate with Annex B countries on climate control and R&D measures. All countries both Annex B and non-Annex B developing countries maximize their joint welfare.

The R&D ITOD scenario: We assume that industrialized Annex B countries invest R&D, which would have otherwise been spent on their territories, in non-Annex B developing countries (DCs) via R&D investments. This will trigger improved energy efficiencies and low cost emissions reduction options in developing countries where there is great potential of emissions reductions but abatement costs are low in comparison with Annex B countries, thus leading to further emissions reductions in developing countries. The resulting emissions reductions in developing countries are in turn counted towards Annex B country's targets so that the global emissions remain the same levels as that under the Kyoto scenario. This would spur the incentives for Annex B countries to invest in R&D in DCs.

In the last four policy scenarios, we assume that no trading across countries is allowed. This treatment allows us to examine the effectiveness of R&D-induced technology innovations.

Table 2 Definition of policy scenarios

Policy scenario	Features
Kyoto	Kyoto Emissions reduction targets are imposed on all Annex B countries including the US
R&D	Annex B countries Cooperate on R&D-induced technological progress
DEV & R&D	Developing nations cooperate with Annex B countries on climate control and on R&D
R&D ITOD	Annex B countries invest in non-Annex B developing countries via R&D investments, with the resulting emissions reductions accounted in Annex B country's emissions balance

5. Simulation Results

Table 3 and Figures 2-7 present the main simulation results. They speak themselves. Thus, in what follows, we just provide some brief explanation to help readers better understand these results.

Under the Kyoto scenario, all Annex B countries are required to meet mandatory emissions reduction targets. Given that these countries have high marginal abatement costs, complying with the targets places economic burden on these countries. Table 3 shows the regional Hicksian equivalent[20] decomposed into the domestic, terms of trade and spillover effects. It can be seen that these Annex B countries experience losses of production, welfare and the terms of trade. This also leads to negative terms of trade and spillover effects on those developing countries which have no mandatory emissions reduction targets, such as the main developing regions Asia and

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[20] We use the Hicksian equivalent measured in real income changes as utility and welfare measure.

China modeled in WIAGEM. These negative effects lead to production losses in these regions which in turn lower their emissions in comparison with the baseline scenario. The emissions reductions in developing countries combined with mandatory reductions in Annex B countries lead to global emissions reduction of 6% below the baseline levels. However, this environmental effectiveness in terms of higher global emissions reduction is improved under this scenario at considerable economic costs. There are two reasons. First, because no emission trading is allowed, lower cost options are not taken into account by countries with high marginal emissions abatement costs. Second, Russia emissions fall below the baseline emissions path as a result of economic disruptions, implying that its emissions reductions targets are not binding. This could lead to less economic losses, provided that Russia could sell surplus emissions permits on a global emissions permits market. However, because emissions trading is not allowed in our scenario, Russia cannot benefit from otherwise increased revenues from such a sale.

Under the R&D scenario, Annex B nations, such as the US, the EU, Japan and Russia cooperate on climate control and R&D. As would be expected, R&D cooperation induce technological innovations that offer low cost emission abatement options in these countries. Thus, this will lower the compliance costs of Annex B countries and place less strong economic burden on these countries. This leads to an increase of GDP and a decrease in emissions for each cooperating Annex B country in comparison with the Kyoto scenario. As shown in Table 3, thanks to much improved domestic production effects, the welfare loss of cooperating Annex B nations is much lower under the R&D scenario than under the Kyoto scenario. However, because marginal abatement costs of Annex B countries are still high even with R&D cooperation and options for these nations to trade emissions permits are not allowed, no positive economic benefits are observed. It is also seen that developing countries can benefit from improved trade effects and spillover effects of Annex B country's technological innovations. In the mean time, the overall environmental effectiveness, measured in the global emissions, is increased markedly in comparison with the Kyoto scenario.

When climate control coalition expands to include also developing countries, a full global cooperation on climate control and R&D investments under the DEV&R&D scenario triggers environmental friendly technologies both in Annex B and non-Annex B developing countries that offer low cost options to reduce emissions, thus further lowering compliance costs of Annex B countries in comparison with the R&D scenario. This will place even less economic burden on developed nations and enhance economic benefits in developing nations. However, for developing countries the positive domestic economic effect is not dominating their economic gain, but still the trade and spill over effects of developed nations are. This is because the self-induced growth and production effects in developing countries cannot reach that large extent. Clearly, international trade and spillover effects are more important for developing countries. It is these effects that lead to an increase of welfare and GDP and a substantial reduction of GHG emissions in developing countries under the DEV&R&D scenario in comparison with the R&D scenario.

R&D expenditure in the OECD countries in 2001, on average, accounts for 2.3% of GDP, with Sweden, Finland, Japan and Iceland being the only four countries whose the R&D-to-GDP ratio exceeds 3% (OECD, 2003). Instead of investing R&D that would have otherwise been spent on their turfs, we assume that Annex B countries would invest 2.5 % of their GDP in developing countries (DCs) via R&D under the R&D ITOD scenario. The additional R&D investment in developing countries triggers improved energy efficiencies and low cost emissions abatement options in developing countries. This leads to further emissions reductions in DCs. The resulting emissions reductions in DCs are accounted in Annex B country's emissions balance so that the global emissions remain the same levels as that under the Kyoto scenario.[21] This assumption indicates that Annex B countries do not have binding emissions reductions but DCs have in order to meet the global Kyoto emissions reduction target. These binding emissions reduction targets lead to slightly less economic gains in DCs under the R&D ITOD scenario than under the DEV&R&D scenario because emissions reductions need to be met in the former scenario. On the other hand, these binding emissions reduction targets do not result in economic losses in DCs because they benefit from low cost and investment effects of Annex B countries. Furthermore, Annex B countries do not have binding emissions reduction targets under the R&D ITOD scenario as they face under the DEV&R&D scenario so that they do not suffer huge economic losses. This explains why DCs experience less economic gains and Annex B countries less economic losses in comparison with the DEV&R&D scenario. Because Annex B countries contribute to large part of the world wealth, the world as a whole experiences more economic gain under the R&D ITOD scenario than under the DEV&R&D scenario.

6. Conclusions

Climate change is a global problem requiring a global response. This paper has aimed to investigate whether linking developing country's cooperation on climate control with industrialized country's R&D and technology transfer provides incentives for cooperation between industrialized and developing countries on climate control. To that end, we have examined the four policy scenarios using a world multi-sectoral, multi-regional trade model WIAGEM. The following main conclusions emerge from this analysis.

First, cooperation on climate control and R&D among Annex B countries induces technological innovations, lowers their compliance costs and thus places less strong economic burden on these countries. Developing countries also benefit from improved trade effects and spillover effects of Annex B country's technological innovations. Moreover, the overall global environmental effectiveness is increased markedly in comparison with the Kyoto scenario.

Second, when climate control coalition expands to include also developing countries, a full global cooperation on climate control and R&D investments under the DEV&R&D scenario further lowers compliance costs of Annex B countries and places even less economic burden on developed countries. The trade and spillover effects of developed countries also lead to an increase of welfare and GDP and a substantial reduction of GHG emissions in developing countries in comparison with the R&D scenario. This further improves the overall global environmental effectiveness.

Finally, our paper has examined economic and environmental implications of Annex B countries investing 2.5 % of their GDP, which would have otherwise been spent on their turfs, in developing countries via R&D under the R&D ITOD scenario, with the resulting emissions reductions in DCs accounted in Annex B country's emissions balance so that the global emissions remain the same levels as that under the Kyoto scenario. Our results show that the additional R&D investment leads to further emissions reductions in DCs. Although DCs experience slightly less economic gains under the R&D ITOD scenario than under the DEV&R&D scenario, they

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[21] Otherwise it would be difficult to explain why Annex B countries have any incentives to invest in R&D in DCs.

benefit from low cost and investment effects of Annex B countries. In the mean time, with the emissions constraints relaxed for Annex B countries, they gain even more. Because Annex B countries contribute to large part of the world wealth, the world as a whole experiences more economic gain under the R&D ITOD scenario than under the DEV&R&D scenario.

All in all, linking developing country's cooperation on climate control with industrialized country's R&D and technology transfer would be win-win-win outcomes for both developing countries and industrialized countries and for the global environment.

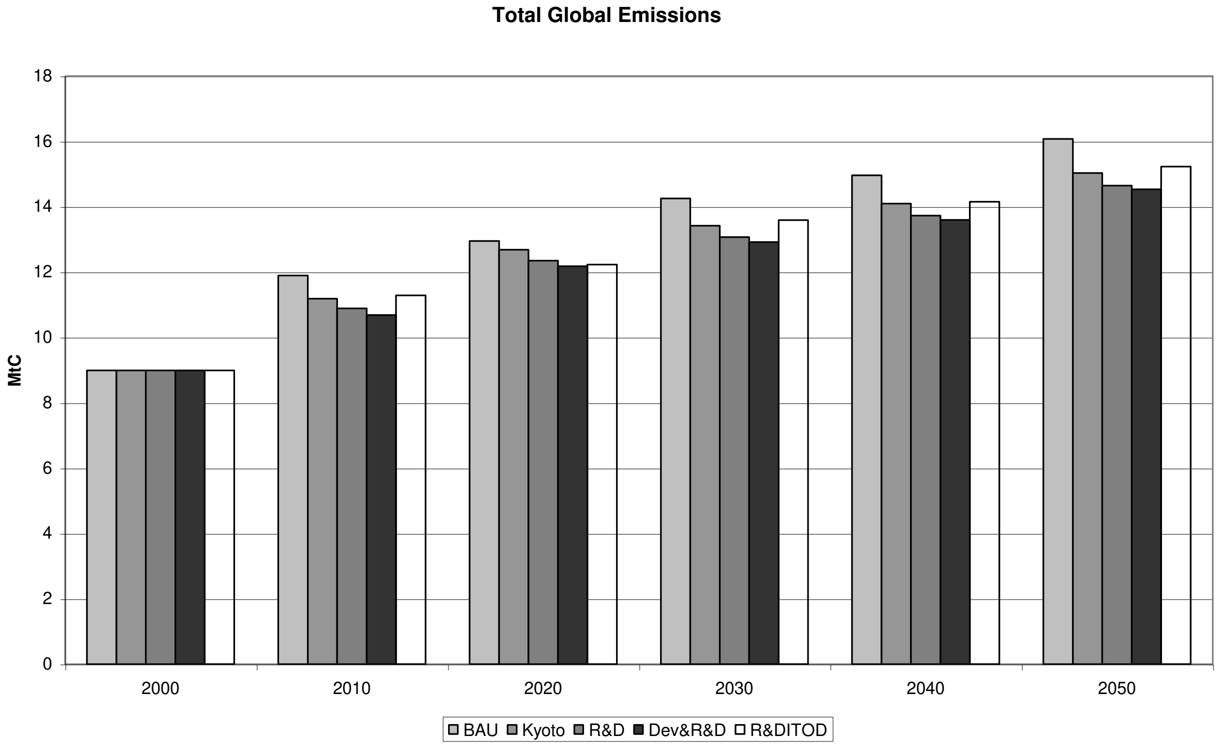

Figure 2 Global emissions (million tons of carbon)

Kyoto

	HEV	Domestic	ToT	Spillover
JPN	-0,0874	-0,0624	-0,0128	-0,0121
CHN	-0,0147	0,0000	-0,0044	-0,0103
USA	-0,0874	-0,0685	-0,0129	-0,0060
SSA	-0,0314	0,0000	-0,0005	-0,0309
ROW	-0,0412	0,0000	-0,0186	-0,0226
CAN	-0,0547	-0,0444	-0,0081	-0,0022
EU15	-0,1247	-0,0805	-0,0392	-0,0049
REC	0,0047	0,0006	0,0012	0,0030
LSA	-0,0412	0,0000	-0,0283	-0,0129
ASIA	-0,0612	0,0000	-0,0480	-0,0132
MIDE	-0,0145	0,0000	-0,0114	-0,0031
MEX	-0,0314	0,0000	-0,0215	-0,0099

R&D

	HEV	Domestic	ToT	Spillover
JPN	-0,0660	-0,0338	-0,0141	-0,0181
CHN	-0,0054	0,0000	-0,0017	-0,0037
USA	-0,0614	-0,0412	-0,0142	-0,0060
SSA	-0,0287	0,0000	-0,0004	-0,0283
ROW	-0,0384	0,0000	-0,0158	-0,0226
CAN	-0,0247	-0,0176	-0,0031	-0,0040
EU15	-0,0260	-0,0133	-0,0107	-0,0020
REC	0,0125	0,0002	0,0027	0,0096
LSA	-0,0152	0,0000	-0,0114	-0,0038
ASIA	-0,0372	0,0000	-0,0313	-0,0059
MIDE	-0,0057	0,0000	-0,0047	-0,0011
MEX	-0,0125	0,0000	-0,0089	-0,0036

DEV+R&D

	HEV	Domestic	ToT	Spillover
JPN	-0,0515	-0,0264	-0,0110	-0,0141
CHN	0,0841	0,0104	0,0347	0,0390
USA	-0,0212	-0,0143	-0,0049	-0,0021
SSA	0,0125	0,0002	0,0005	0,0118
ROW	0,0115	0,0002	0,0044	0,0069
CAN	-0,0127	-0,0091	-0,0016	-0,0021
EU15	-0,0184	-0,0094	-0,0076	-0,0014
REC	0,0115	0,0001	0,0025	0,0089
LSA	0,0708	0,0013	0,0492	0,0203
ASIA	0,0528	0,0130	0,0165	0,0233
MIDE	0,0995	0,0235	0,0538	0,0222
MEX	0,0226	0,0036	0,0118	0,0072

R&DITOD

	HEV	Domestic	ToT	Spillover
JPN	0,0146	0,0031	0,0036	0,0078
CHN	0,0478	0,0059	0,0197	0,0222
USA	0,0275	0,0068	0,0064	0,0144
SSA	0,0174	0,0002	0,0007	0,0165
ROW	0,0159	0,0003	0,0061	0,0095
CAN	-0,0084	-0,0043	-0,0010	-0,0031
EU15	0,0125	0,0034	0,0051	0,0039
REC	0,0112	0,0001	0,0024	0,0087
LSA	0,0841	0,0016	0,0585	0,0241
ASIA	0,0852	0,0126	0,0266	0,0460
MIDE	0,0985	0,0181	0,0533	0,0271
MEX	0,0584	0,0073	0,0306	0,0206

Table 3 Changes in regional Hicksian equivalent decomposed into domestic, terms of trade (ToT) and spillover effects relative to baseline levels

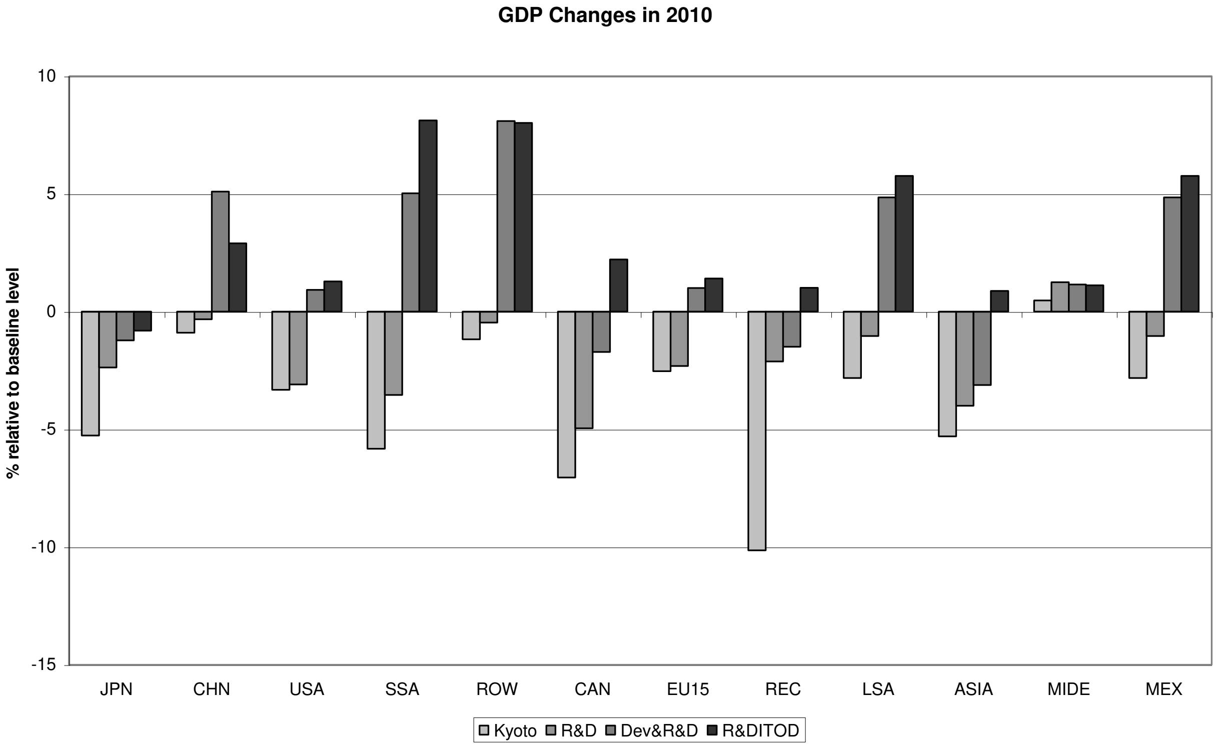

Figure 3 Percentage changes in GDP relative to baseline levels in 2010

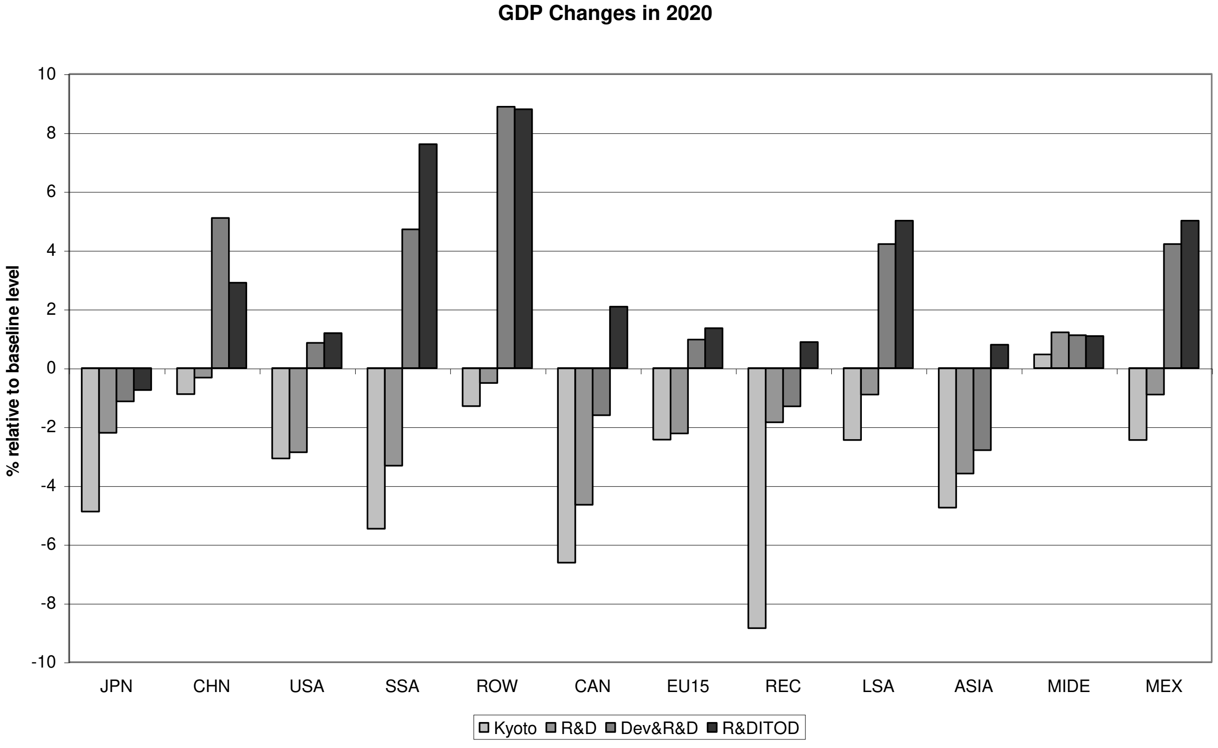

Figure 4 Percentage changes in GDP relative to baseline levels in 2020

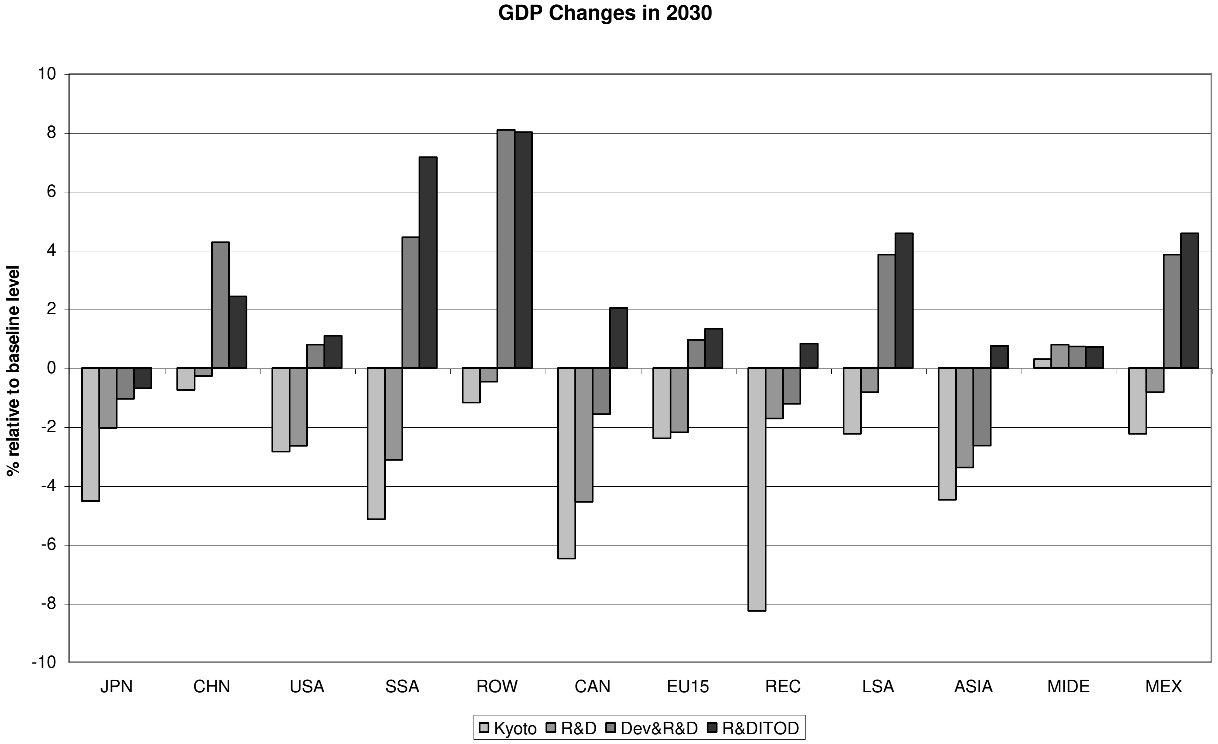

Figure 5 Percentage changes in GDP relative to baseline levels in 2030

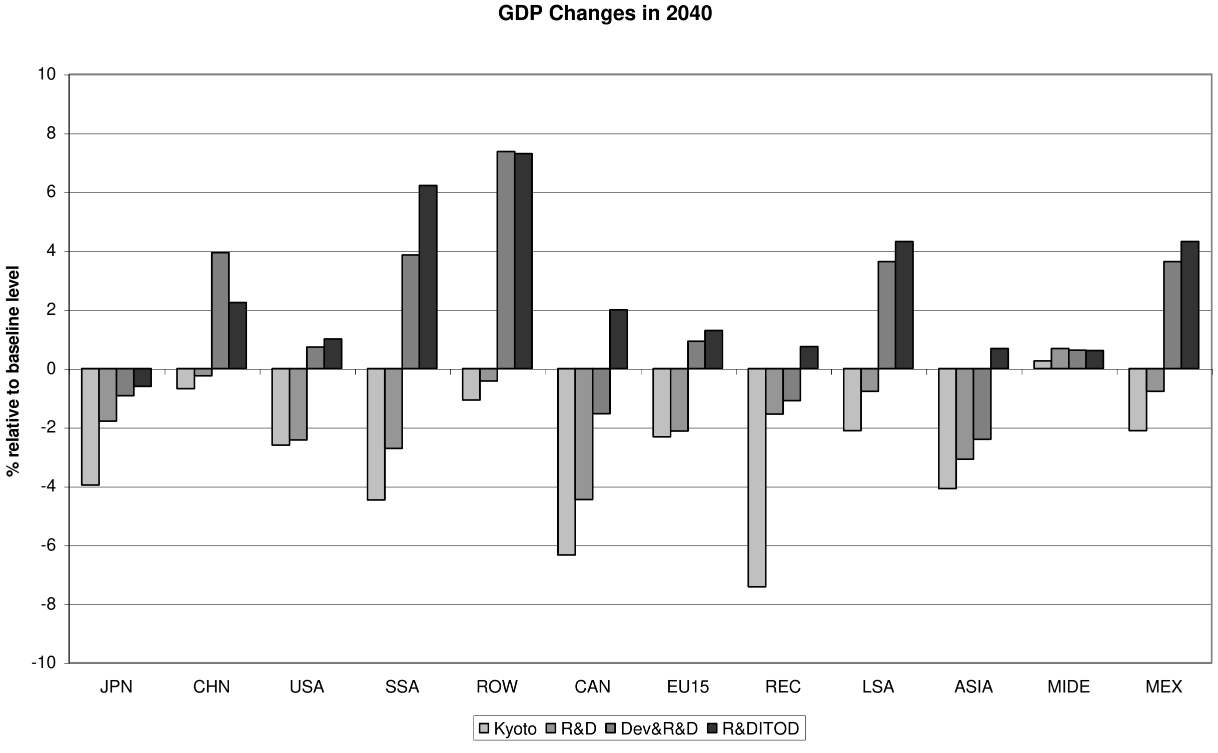

Figure 6 Percentage changes in GDP relative to baseline level in 2040

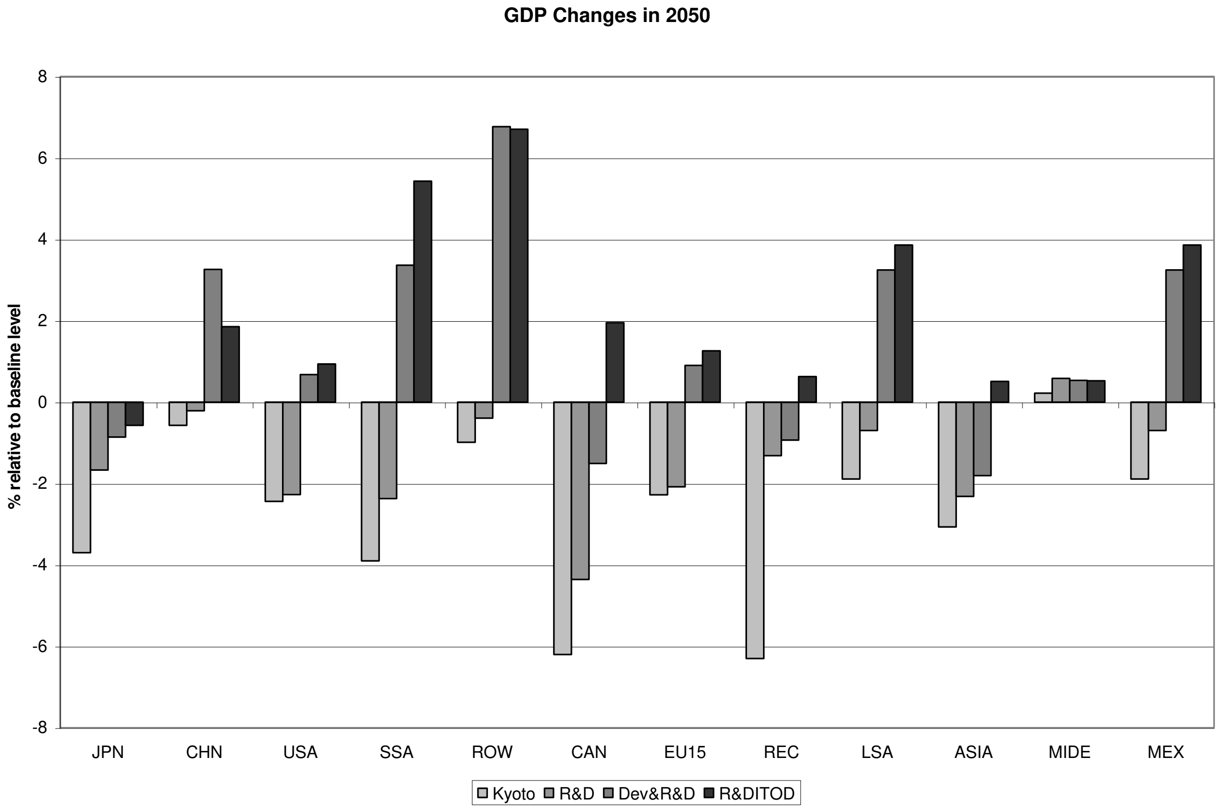

Figure 7 Percentage changes in GDP relative to baseline levels in 2050

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Appendix: Mathematical Description of Endogenous Technological Change

This section briefly describes the mathematical formulation of endogenous technological change. Goods are produced for the domestic and export market. Production of the energy aggregate is described by a CES function reflecting substitution possibilities for different fossil fuels (i.e., coal, gas, and oil), capital, and labor representing trade off effects with a constant substitution elasticity. Fossil fuels are produced from fuel-specific resources and the non-energy macro good subject to a CES technology. Energy efficiency is improved endogenously by increased expenditures on R&D. That means (in the CES production function) energy productivity is endogenously influenced by changes in R&D expenditures.
The CES production structure follows the concept of ETA-MACRO combining nested capital and labor at lower levels. Energy is treated as a substitute of a capital labor composite determining (together with material inputs) overall output. Energy productivity is increased endogenously by increased R&D expenditures.
The representative producer of sector j ascertains the CES *profit function*

$$\Pi_j^Y(p) = \left[a_j^{DX} (p_j{}^{1-\sigma_{DX}} + (1-a_j^{DX}) p^{FX\,1-\sigma_{DX}} \right]^{\frac{1}{1-\sigma_{DX}}}$$

$$- \left[a_j^M p_j^{M\,1-\sigma_{KEM}} + (1-a_j^M) \left[EP_j^E p_j^{E\,1-\sigma_{KLE}} + (1-a_j^E) \left[a_j^K (p^{RK})^{1-\sigma_{KL}} + (1-a_j^K)(p_j^L)^{1-\sigma_{KL}} \right]^{\frac{1-\sigma_{KLE}}{1-\sigma_{KL}}} \right]^{\frac{1-\sigma_{KLEM}}{1-\sigma_{KLKE}}} \right]^{\frac{1}{1-\sigma_{KLEM}}} \qquad (1.1)$$

with:

a_j^{DM} : Domestic production share of total production by sector j

a_j^K : Value share of capital within capital-energy composite

a_j^L: Value share of labor within capital-energy-labor aggregate

a_j^M : Value share of material within capital-energy-labor material aggregate

p_j : Price of domestic good j

p^{FX}: Price of foreign exchange (exchange rate)

p^{RK}: Price of capital

p_j^E : Price of energy

p_j^M : Price of material/land

p^L: Price of labor

σ_{KE}: Substitution elasticity between capital and energy

σ_{KEL}: Substitution elasticity between labor, capital, and energy composite

σ_{KLEM}: Substitution elasticity between material and labor, capital, and energy composite

Y: Activity level of production sector j

CET: Constant elasticity of transformation τ

CES: Constant elasticity of substitution σ

$EP^{E}_{j,t}$: Endogenous energy productivity

With $EP_{j,t}{}^{E} = \delta^{E}_{j,t} \cdot KR\&D_{j,t}{}^{\theta}$ as increase of energy productivity. R&D expenditures (*KR&D*) improve innovations in more energy efficient technologies.[22] δ determines the efficiency of research and development. This share is endogenously determined by production changes of cooperating countries: $\delta^{E}_{coopj,t} = \partial Y^{E}_{coopj,t}$. Knowledge spillover effects from cooperating to non cooperating countries are considered by capital flows: $\delta^{E}_{non-coopj,t} = \partial Y^{E}_{non-coopj,t} \cdot CAPFLOW^{E}_{non-coop,t}$.

Capital is used for production with a capital price p^{K}_{t} and a utility price of p^{RK}_{t}, and is depreciated by rate δ:

$$\Pi^{K}_{t}(p) = (1-\delta)p^{K}_{t+1} + p^{RK}_{t} - p^{K}_{t} - ptc^{r}_{t} \text{-} pR\&D_{t} \tag{1.2}$$

with:

p^{K}_{t} : Price of capital in period t

p^{RK}_{t} : Price of capital services in period t

ptc^{r}_{t} : Price of regional protection costs

$pR\&D_t$:Price of regional R&D investments

K_t: Activity level of capital in period t

Investments are produced by Leontief technology:

$$\Pi^{I}_{t+1}(p) = P \quad p^{K}_{t+1} - \sum_{j} a^{I}_{j} p^{A}_{j,t} \tag{1.3}$$

a^{I}_{j} Value share investment of good j

I_t: Activity level of investments in period t

P: Time period

R&D investments follow the same determination

$$\begin{aligned} &\Pi^{R\&DI}_{t+1}(p) = P \quad p^{K}_{t+1} - \sum_{j} a^{R\&DI}_{j} p^{R\&DA}_{j,t} \\ &ITOT = \sum_{j} I_{t} + R\&D_{t} \end{aligned} \tag{1.4}$$

WIAGEM includes four energy production sectors, one non-energy sector and three fossil fuel sectors traded internationally for oil, gas and coal. Coal production in the OECD and gas production in Russia grow with energy demand at constant prices. The elasticity of

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[22] We follow the theoretic and applied approaches of Goulder and Mathai (2000), Buonanno, Carraro et al. (2000) and Nordhaus (1997).

substitution between the resource input and non-energy inputs is calibrated to meet a given price elasticity of supply. Exhaustion leads to rising fossil fuel prices at constant demand quantities. The carbon-free backstop technology establishes an upper boundary on the world oil price; this backstop fuel is a perfect substitute for the three fossil fuels and is available in infinite supply at one price calculated to be a multiple of the world oil price in the benchmark year. Demand elasticities depend on backstop technologies when low backstop cost demand elasticities are high and vice versa.

A composite energy good is produced by either conventional fossil fuels - oil, gas, and coal – represented by a nested CES technology (with an elasticity of interfuel substitution σ_{fuel}) or from a backstop source with Leontief technology structures. Oil and gas can be substituted by an elasticity of substitution twice as large as the elasticity between their aggregate and coal. The energy good production is determined by industry and household final demand.

$$\begin{aligned}\Pi_j^E(p) = p_j^E - EP_{j,t}^E \Big[a_j^{ELE} p_j^{ELE1-\sigma_{ELE}} + (1-a_j^{ELE}) \cdot a_j^{OIL} (p_j^{OIL})^{1-\sigma_{FOSSIL}} \Big] \\ + a_j^{GAS} (p_j^{GAS})^{1-\sigma_{FOSSIL}} + a_j^{COA} \Big[a_j^{HCO} (p_j^{HCO})^{1-\sigma_{COA}} \Big] \qquad (2.1) \\ + a_j^{SCO} (p_j^{SCO})^{1-\sigma_{COA}} \quad \Big]^{\frac{1-\sigma_{FOSSIL}}{1-\sigma_{COA}}} \quad \Big]^{\frac{1-\sigma_{ELE}}{1-\sigma_{FOSSIL}}} \quad \Big]^{\frac{1}{1-\sigma_{ELE}}} - p^{ET} CARBLIM_j\end{aligned}$$

With:

a_j^{ELE}	Electricity value share of energy aggregate by sector j
a_j^{OIL}	Oil value share of fossil energy aggregate by sector j
a_j^{GAS}	Gas value share of fossil energy aggregate by sector j
a_j^{HCO}	Hard coal value share of coal aggregate by sector j
a_j^{SCO}	Soft coal value share of coal aggregate by sector j
σ_{ELE}	Substitution elasticity between electricity and fossil energy
σ_{FOSSIL}	Substitution elasticity between fossil energy inputs
σ_{COA}:	Substitution elasticity between hard and soft coal
p^{ET}	Price emissions permits
E_j	Activity level of energy production
$CARBLIM_j$	Sectoral GHG emissions