Endogenous Technological Change in Strategies for Mitigating Climate Change

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Summary

This thesis suggests that induced technological change has potential to reduce the burden that climate change mitigation puts on the economy. Furthermore, international cooperation on climate policy, which may trigger this induced technological change, may be achieved by linking climate negotiations to other issues. The starting point of the research presented here are the following two assumptions: first, action to mitigate climate change is necessary, and second, technologies will play a key role in this effort because technology and technological change facilitate the reduction of anthropogenic greenhouse gas emissions. As a consequence, the way technological change is described in integrated assessment models of climate change is of great importance, and a sound understanding of such endogenous technological change and its interaction with climate policies is needed.

There is empirical evidence that technological change is induced by policies. However, previous assessments of such induced technological change (ITC), i.e. technological progress triggered by policy, have been ambiguous about its responsiveness to climate policies and its potential to reduce the costs of mitigating climate change. On the other hand, a clear climate policy is required in order to induce the technological progress that might facilitate emission abatement at low costs. Ideally, climate policy ought to be global in order to prevent carbon leakage and to achieve efficiency. However, the literature on international environmental agreements suggest that the prospect for global climate policy is not bright. This raises two broad research questions: First, what is the role of ITC for climate change mitigation? And second, if there is a desirable contribution of ITC to mitigation, how can we achieve a global policy that triggers this technological change? The four papers presented in this thesis make contributions to these two questions.

The first paper focuses on the impact of ITC on the costs and strategies of mitigating climate change within a single integrated assessment model. I find that the impact of ITC is significant. The analysis reveals two “directions” of technological change. First, there is technological change that permeates the entire economy—this is reflected in a strong impact on the overall macro-economic costs of mitigation. Second, there is technological change whose impact is specific to the energy sector, as evident from strong changes in the composition of mitigation options. ITC therefore proves to be an influential determinant of mitigation costs and strategies. Costs may rise or fall due to ITC depending on whether progress in low carbon energy or progress in the resource sectors prevails. The effect of ITC on the competitiveness of mitigation options influences their contributions to overall mitigation. Moreover, this stresses the importance of models that resolve important technological options, including their potential of ITC, and account for the economy-wide impact of ITC.

The first paper used a single model with one specific formulation of ITC—but the question how to incorporate ITC in models is far from trivial. On the contrary, among models that include ITC there is a wide variety of approaches taken to describe ITC.

The second paper of this thesis compares ten state-of-the-art models that implement ITC. It explores the resulting differences in their assessment of ITC, identifies the underlying reasons for the differences, and draws conclusions that are robust across models. At the heart of this comparison are *ceteris paribus* scenarios that aim to isolate and expose the impact of ITC in the various models. The analysis reveals that ITC has potential to reduce costs, in many models substantially. However, the magnitude of the impact of ITC differs greatly among the models, ranging from 90 percent reduction of mitigation costs to almost no effect. Numerous reasons for this were identified, including business-as-usual emissions, differences in mitigation strategies, and modeling assumptions.

Business-as-usual emissions have a strong impact on mitigation costs because they determine the necessary emission reductions. Although an effort was made to harmonize the business-as-usual scenarios of the different models, considerable differences remained and need to be taken into account.

Mitigation strategies are explored on two levels of aggregation. First, abatement is decomposed into the contributions of reductions of economic output, energy intensity of output, and carbon intensity of energy. The analysis reveals that macro-economic models without explicit representation of the energy sector tend to focus their abatement strategy on reductions of energy intensity, whereas energy system models and models that feature an energy sector achieve the majority of their abatement through decarbonization. Decarbonization becomes particularly important for large reductions of emissions. Second, abating emissions through change in the composition of energy supply is considered. The composition of the energy supply mirrors the trends of the decomposition analysis. Models that focus their abatement strategy on reducing energy intensity and economic output are those that lack options to decarbonize the energy system, or that simply did not resolve the energy sector explicitly. Conversely, large reductions of carbon intensity are implemented through large shares of carbon free energy.

Three key modeling assumptions were identified that explain some of the major differences in model results: first, when models include additional market distortions, i.e. they describe a second-best world, climate policy may remove these distortions causing not costs but a benefit of climate policy. Second, the choice of the model type is influential because it often implies an equilibrium concept, which in turn implies different degrees of flexibility to react to climate policy. Third, different assumptions about foresight of economic agents determines their long-term investment behavior, which strongly influences mitigation strategies and costs.

The first two papers looked at climate policies implemented as global policy targets taking for granted that policies are agreed upon and implemented to achieve the targets, although this is known to be difficult. The remaining papers look at the potential of issue linking to help to build such agreements. To address issue linking, I develop a model of coalition formation, which incorporates international trade and sanctions as well as knowledge spillovers from research cooperation and international standards.

In the third paper, I show in numerical experiments that introducing trade sanctions positively affects international cooperation. Participation rises with the tariff rate, up to full cooperation. How quickly participation rises depends on the ease with which taxed goods are substituted with alternatives. Global welfare rises with participation despite the distortions caused by trade restriction. Tariffs therefore seem to be a feasible means of increasing participation.

In the forth paper, I apply an extended version of the coalition model to issue linking of environmental agreements and technology oriented agreements. It turns out that linking the environmental agreement to cooperative research changes the incentive structure such that more actors sign the agreement. The type of technological knowledge that spills over makes a difference for the effectiveness of this type of issue linking: research cooperation focusing on productivity is unambiguously more effective than cooperation on mitigation technology in raising participation in the agreement, global welfare, and environmental quality. International technology standards are also shown to have a positive effect on coalition formation. While the existence of a separate standards agreement alone has very little impact on environmental cooperation, it significantly increases participation in a linked agreement on environmental and technological cooperation.

Overall, the studies reported in this thesis suggest that there is indeed potential that ITC may reduce the burden that mitigation requirements will put on the economy. And while there is no final conclusion on the magnitude of the impact of ITC due to the remaining model uncertainty, this thesis advances the understanding of these uncertainties and the underlying reasons for the variability in the results. To exploit a large potential of ITC, a clear carbon price signal is required. This thesis suggests that linking the negotiations on climate policy to trade sanctions or to research cooperations is a feasible way to create incentives that make a cooperative global climate policy more likely. More research is needed to determine the magnitude of the potential of issue linking, but its potential in general has been shown and different issue linking proposals have been characterized with respect to their advantages and disadvantages.

Chapter 1

Introduction

1.1 Motivation

This chapter sets out to motivate the main research questions addressed in this thesis on the role of technological progress in integrated assessment modeling of greenhouse gas mitigation.[1] The necessity to reduce emissions arises from the science of climate change and its impacts. Therefore, the current state of knowledge on climate change and its impacts is briefly summarized in this section before turning to an introduction of the economic themes: first, the consequences of including the economic processes that cause technological progress in models, thus making technological progress susceptible to (climate) policies. Second, building the international coalitions that are willing to implement these policies, therefore setting the incentive for the technological change necessary for mitigating climate change. This chapter closes with the statement of the main research questions and an outline of the remaining chapters of this thesis.

1.1.1 A Sense of Urgency

The Scientific Basis

When describing the climate of the earth, climatologists distinguish the climate system consisting of components such as atmosphere, oceans and land surface, and external factors that drive the dynamics of this system, so-called forcings. The earth's climate will change in response to variation in these forcings, which include solar radiation, the earth's albedo, and the greenhouse effect. The latter describes how a set of chemicals in the atmosphere (the greenhouse gases, GHG) capture radiation from the earth that would otherwise diffuse to outer space. The magnitude of this effect depends on the concentrations of the GHG.

The earth's climate has always been subject to changes due to variations in the natural forcings, for example in solar radiation or volcanic eruptions. In recent earth history, anthropogenic emission of GHG, mainly linked to fossil fuel combustion, have added to the concentration of GHG in the atmosphere causing a trend of global warming.

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[1] *Integrated assessment models* address a problem by combining knowledge across more than one discipline to evaluates its whole cause-effect chain (see, for example, van der Sluijs, 2002).

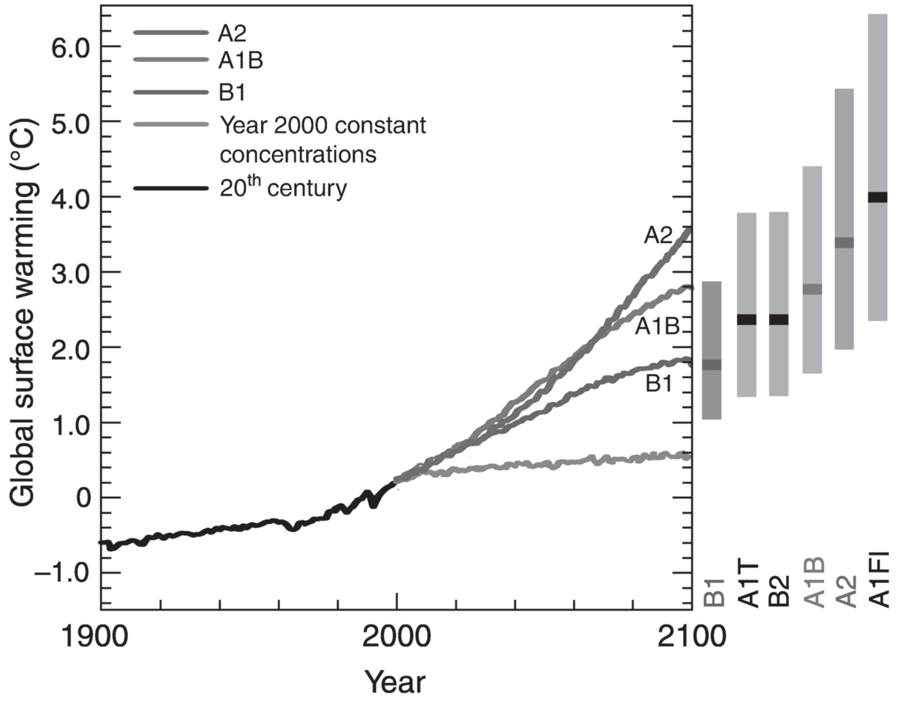

Figure 1.1: Multi-model global averages of surface warming (relative to 1980-1999) for the SRES scenarios A2, A1B and B1, shown as continuations of the 20th century simulations. Adapted from IPCC (2007).

Working Group I of the Intergovernmental Panel on Climate Change (IPCC) has collected the scientific evidence supporting this theory in their contribution to the IPCC assessment reports (IPCC WG1, 2001, 2007). The reports show beyond reasonable doubt that we are witnessing global warming, and that anthropogenic emissions are a major contribution to it (Rahmstorf, 2008). The Fourth Assessment Report (IPCC WG1, 2007) attests that 0.7 °C warming relative to preindustrial levels have already occurred, and that even if GHG concentration were not to increase any further, we are already committed to an additional 0.5 °C of warming due to the inertia in the climate system (Figure 1.1.1). But currently projected unmitigated GHG emissions will cause a much steeper increase in GHG concentrations. If unabated, the projected increase in global mean temperature in 2100 is projected to be in the range of 1.7 °C and 7.0 °C.

Global warming in this order of magnitude is sufficient to disturb the dynamics of the earth system. Due to its complexity and non-linearity, the earth system contains elements that may switch to a qualitatively different behavior when climate change surpasses certain thresholds, so-called tipping elements. Lenton et al. (2008) list 15 such tipping elements, a prime example being Arctic sea ice. Sea ice cover reflects more solar radiation compared to the darker ocean surface. Therefore melting sea ice has a positive feedback on warming, and may be destabilized at low levels of global warming. In fact, the loss of Arctic summer sea ice may already have been triggered. Other tipping elements are the ice sheets of Greenland and West Antarctica, the Indian summer monsoon, the Amazon rainforest, and the Boreal forests.

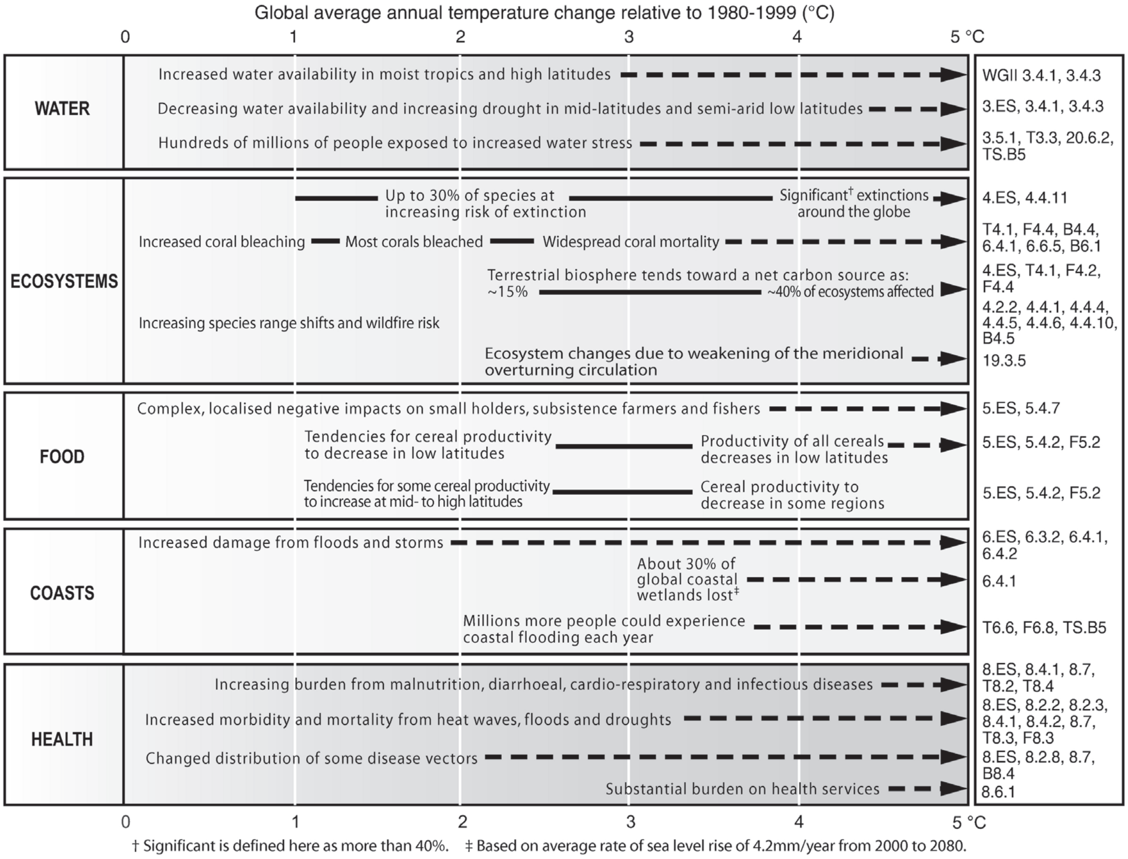

Figure 1.2: Examples of impacts associated with global average temperature change. Adapted from IPCC WG2 (2007).

Impacts

Besides these abrupt changes in the earth system, global warming affects ecosystems and human societies in a variety of ways. Working Group II of the IPCC studies the impacts of climate change. In IPCC WG2 (2007), the expected impacts are for the first time presented scaled against climate change (Figure 1.2). Even at low levels of warming of up to 2 °C relative to 1980-1999, adverse impacts on water availability, ecosystems, food supply, coastal safety, and human health are expected for 2050, and increasingly so for 2100. When climate change proceeds unmitigated, impacts in 2100 at 4 to 5 °C warming include billions of additional people subjected to increased water stress, extinction of species around the world, millions additional people at risk of coastal flooding each year, and increased mortality from heatwaves, floods, and droughts (Parry et al., 2008).

This increased pressure on natural systems and societies may give rise to a list of security risks. The German Advisory Council on Global Change (WBGU) looked at connections between climate change and international conflicts (Schubert et al., 2007). They conclude that the consequences of unmitigated climate change for international conflicts are severe:

> [...] climate change will draw ever-deeper lines of division and conflict in international relations, triggering numerous conflicts between and within countries over the distribution of resources, especially water and land, over the man-

agement of migration, or over compensation payments between the countries mainly responsible for climate change and those countries most affected by its destructive effects.

1.1.2 Economics of Climate Change

Economists have attempted to monetize the impacts of climate change in so-called damage functions (see, for example, Nordhaus and Boyer, 2000). This is a notoriously difficult undertaking as it includes estimating the monetary value of ecosystem services, health, and human life. Stern (2007) estimates the costs of business-as-usual climate change to equate at least an average reduction of 5 percent global per capita consumption, now and forever. When non-market impacts, high climate sensitivity, and the disproportionate burden for poor regions are taken into account, his estimate rises to 20 percent.

A strong case for action against climate change would emerge if the costs of mitigating climate change are comparatively low—low compared to the impacts of unmitigated climate change, and also low compared to adapting to changed climate. Therefore, the economics of climate change need to address mitigation and adaptation.

Mitigation and Adaptation

It is now certain that mitigation and adaptation will have to complement each other. There will be climate change even under the most stringent mitigation policy, and therefore there will be need for at least some adaptation (Figure 1.2). On the other hand, the IPCC deems it very likely that unmitigated climate change would exceed the world's capacity to adapt (IPCC, 2007, Topic 6.2). Hence there is need for at least some mitigation. Exactly where to draw the line between between "avoiding the unmanageable" and "managing the unavoidable" is hard to tell. The aforementioned tipping points offer some guidance: the "short list" of policy-relevant tipping elements in Lenton et al. (2008, Table 1) comprises eight tipping elements for which a critical temperature range is given. The critical value for six of them may be avoided by restraining global warming to 2 °C. Therefore, a policy goal like the European Union's 2 °C target (EU Council, 2007) may serve as an approximation for the division of labor between mitigation and adaptation. The 2 °C target requires an ambitious mitigation effort.

Technology is both part of the problem and part of the solution for the issue of climate change mitigation. A majority of GHG emissions are of technological origins: 56.6 percent of all GHG emissions are CO_2 emissions from fossil fuel combustion. In terms of the corresponding activities, emissions from energy supply, industry, and transport amount to 58.4 percent of the global total. At the same time technology and technological change in particular offer the main possibilities for reducing emissions (IPCC WG3, 2007, Ch. 3.4).

According to IPCC WG3 (2007), some of the main technological mitigation options are:

- Improving energy efficiency and energy conservation
- Reducing the carbon intensity of energy, e.g. by switching fuels like substituting gas for coal

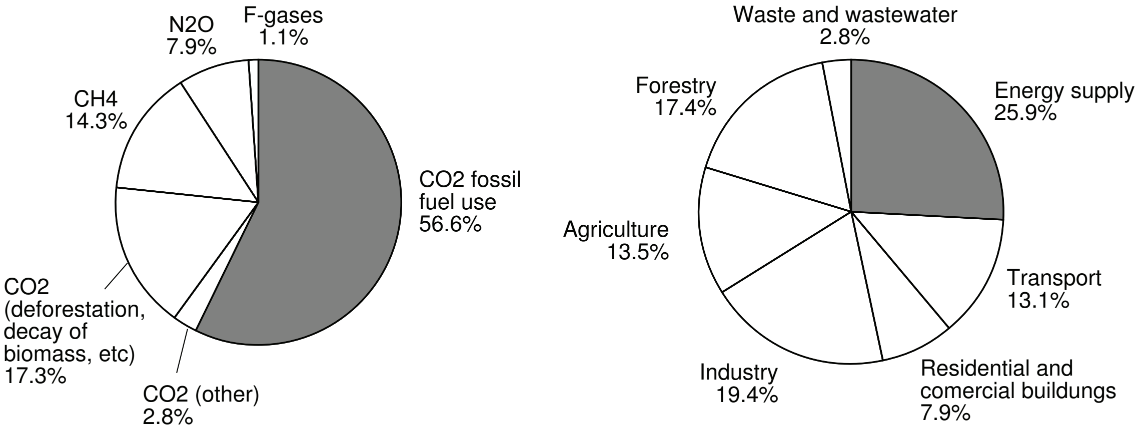

Figure 1.3: Greenhouse gas (GHG) emissions. Share of different anthropogenic GHGs in total emissions in 2004 in terms of CO_2-equivalent (left), and share of different sectors in total anthropogenic GHG emissions in 2004 in terms of CO_2-equivalent (right). Adapted from IPCC (2007).

- Introducing carbon capture and storage technologies
- Energy from renewable energy sources
- Nuclear power
- Develop and diffuse new technologies and practices to reduce GHG from agriculture and land use

Therefore, there is a strong link between mitigation and technological progress, and any policy that aims at mitigating emissions will have to induce technological change, most importantly the decarbonization of the energy sector. Hence, mitigation and technological change are interwoven in at least two ways: first, technological progress is essential for mitigation options. In particular, this refers to low carbon energy technology options, and energy efficiency improvements. Second, mitigation policies need to set incentives for technological progress, for example by establishing a price on GHG emissions. The following sections explore these two aspects.

Mitigation Options: Technological Change

Technological progress does not happen automatically although early economic models resorted to this assumption of so-called *exogenous* technological change (for example Nordhaus, 1994; Nordhaus and Boyer, 2000), i.e. technological change is assumed to happen independently of policy or other economic activities. On the contrary, it is the result of actions of economic agents. The literature distinguishes three channels through which *endogenous* technological change (ETC) occurs (IPCC WG3, 2007, Ch. 2.7):

- Research and Development (R&D), which refers to some entity (for example firms or the government) spending resources on developing new technologies or improving existing technology, for example research spent on improving fuel cell technology.

- Learning by Doing, which refers to advances made through production and use of technologies. Examples include improving labor productivity in production of technologies which ultimately brings down production costs. As a result, unit costs of the technology fall as a function of cumulated capacity.

- Spillovers, referring to the transfer of ideas and knowledge among firms, industries, or other entities. The gas turbine technology transferred to electricity production is one example, spillover of knowledge in-between countries due to foreign direct investment is another.

There is empirical evidence for all three channels of technological change. For example, there are econometric studies linking R&D expenditure to productivity increases (for example Griliches, 1992), as well as statistical analyses on "learning curves" correlating increasing cumulative production volumes and technological advances (IPCC WG3, 2007, Ch. 3.4). These insights were originally taken up by two separate branches in the modeling literature, macro-economic endogenous growth theory and the learning (or experience) curve literature (Köhler et al., 2006).

The endogenous (or "new") growth theory focuses on R&D and spillover effects. In these models, knowledge capital is accumulated through R&D investments, externalities to physical capital accumulation, or other spillovers, leading to productivity improvements (see, for example, Aghion and Howitt, 1998). The empirical evidence of learning curves of individual technologies has been used by bottom-up energy system models. As these models resolve technological detail, they can implement "learning curves" for various energy technologies.

Although present in the literature, ETC was neglected in early policy models of climate change. Even in 2002, Grubb and colleagues find that "most models of energy, economy, and environment" use exogenous assumptions to describe technological change (Grubb et al., 2002). The Third Assessment Report (IPCC WG3, 2001) included some new models that incorporated ETC, but still ETC was not prevalent. Surveying these existing ETC models, Grubb and colleagues find "striking discrepancies in their basic conclusions." While they can cite several models where induced technological change is very responsive to climate policy and hence has large effects, their survey includes models that show only a modest response. Their conclusion is that there is neither agreement on how to model ETC, nor are the results from ETC modeling consistent. Clearly, further research on the impact of ETC is merited. This view is enforced by a subsequent survey (Sijm, 2004) on ETC in climate policy modeling. By this time, the list of models implementing ETC had grown, but discrepancies among macro-economic models as well as between top-down and bottom-up models were still large.

Given the importance of ETC for mitigation scenarios, more research is needed to, first, identify robust conclusions about the likely effects of induced technological change in climate policy models, and second, to understand and learn from the differences in model predictions so far in order to improve this important feature.

Mitigation Incentives: The Carbon Price

There are two sides to modeling *induced* technological change. On the one hand, as discussed in the previous section, an endogenous formulation of technological progress has to be part of the economic model. The model has to allow for technological change to be induced. On the other hand, there has to be a policy (here: a climate policy) to induce this change. In a world without a central authority that can imposes such a policy onto all nations, achieving an efficient global climate policy requires voluntary cooperation of sovereign states. In the climate policy models referred to in the previous section this issue is simply assumed away: most of these models do not specify policies but global policy goals, assuming their efficient implementations by nations. Furthermore, it is assumed that all nations agree on the need to take action and on the extent of climate policy. In a word, there is full cooperation concerning climate protection.

The following section sets the stage for investigating these assumptions. First, the theory of externalities is introduced. In light of this theory, the fact that GHG emissions cause climate change as an externality justifies policy intervention on the global level. More specifically the realization of a global price on GHG emissions is justified—either by means of a price policy such as a tax, or a quantity policy such as emission caps. Second, the theory of international environmental agreements explores which incentive structures qualify to foster international cooperation on such environmental policies.

Theory of externalities The emission of greenhouse gases poses an externality problem. Intuitively, these are situations where the economic decision of one actor directly or indirectly affects a second actor who had no part in this decision. In the case of climate change, GHG emissions are linked to economic decisions of the emitter, for example the decision to burn fossil fuel to generate electricity. Other actors are then affected by climate change damages. Mathematically this means that a variable describing the economic decision (emissions) is part of the utility functions of both players.

The theory of externalities investigates whether the existence of externalities has an adverse effect on economic efficiency, i.e. whether the economy allocates goods and services in a (Pareto-) efficient manner. In the institutional set-up of a competitive equilibrium, achieving efficiency boils down to the existence markets. For example, if all externalities are treated just like other commodities, i.e. there are markets for them, then according to the first fundamental theorem of welfare, the resulting competitive equilibrium will be efficient (see Cornes and Sandler, 1996, Chapter 3).

On the other hand, a rationale for policy intervention arises in the absence of such markets. Then, the emerging allocation can be shown to be inefficient because social and private costs of the externality diverge. In the case of climate change, the private costs of the emitter are only the climate change impacts affecting the emitter herself, while the social cost is the total of all climate change impacts.

An efficient equilibrium may be restored by adjusting the private costs to match the social costs. One way of doing this is to impose a price on the externality, thus internalizing the external costs—a tax in case the externality has a negative effect, or a subsidy in case of a positive externality (Pigou, 1946, as cited in Cornes and Sandler, 1996, Chapter 4).

Alternatively, the conflicting interest of the emitting party and the damaged party could be resolved by bargaining among them. The outcome of such a bargaining process would depend on the initial property rights, but can be shown to be (Pareto-) efficient regardless of the latter (Coase, 1960, as cited in Cornes and Sandler, 1996, Chapter 4). Suppose, for example, that emission of GHG was completely unregulated. Implicitly, this amounts for potential emitters to have the right for unlimited emissions granted to them. Any actors who preferred lower GHG concentration level has an incentive to offer payment to the emitters such that these reduce their emissions, and emitters would have an incentive to accept payment. If, on the contrary, all parties had the right to a clean atmosphere, it would be up to the emitters to offer payment for permission to emit. Coase argued that, if transaction costs were low, such bargaining would take place due to the best interest of all parties, and that this makes policy intervention such as Pigouvian taxes unnecessary. In case of climate change, the considerable transaction costs for bilateral bargaining between all affected parties may be reduced by establishing markets for emission permits.

In an undistorted competitive equilibrium, the price signals from either the emission tax or the permit price will suffice to attain an allocation that is Pareto-efficient. And while introducing additional features (for example uncertainty or an oligopolistic market structure) poses the question of "prices versus quantities" anew (see Hepburn, 2006 for an overview of the extensive literature), it is undisputed that global cooperation to put a price signal on GHG emissions is an approach to mitigating climate change that is, at least potentially, Pareto-efficient.

International Environmental Agreements This is where the literature on international environmental agreements picks up. This branch of the literature shifts the focus from the question which policy instrument is preferable to the issue of how to build self-enforcing coalitions of players that jointly implement a single environmental policy. Often, this includes the application of game theoretic concepts to the question. Applied to climate change, cooperation or non-cooperative behavior translates to abating GHG emissions or not. In a world without central authority, such cooperation can only be voluntary, i.e. by agreement.

A stable climate or a clean atmosphere has the properties of a public good: it is non-rival and non-excludable in its use. When a good is non-rival, its provision has an externality: once provided, it is available to others who were not part of the decision to create this good. Therefore, as discussed previously in the section on externalities, provision of a non-rival good constitutes a positive externality and is prone to undersupply and merits policy intervention.

Non-excludability gives rise to a free-riding incentive. Since nobody can be excluded from consumption of the good regardless of whether one contributed to its provision, there is an incentive to let others provide the good and to enjoy its benefits for free. This gives rise to a situation similar to the well known prisoners' dilemma where two prisoners are charged with a common crime (Table 1.1). Ideally, they would both deny these charges and, in the absence of better evidence, be convicted for lesser crimes. For if both confessed, they would face a more severe punishment. However, if only one remained silent while the other confessed, the former will be incriminated while the latter escapes punishment as a principal witness. The game theoretic analysis reveals that when rational actors face this situation, both will try to incriminate the other. Therefore, in the

Table 1.1: Prisoners' Dilemma. The payoff structure of the Prisoners' Dilemma.

	Deny	Confess
Deny	probation, probation	acquittal, jail
Confess	jail, acquittal	jail, jail

	Deny	Confess
Deny	-2, -2	0, -6
Confess	-6, 0	-4, -4

Table 1.2: Chicken Game. The payoff structure of the Chicken Game.

	Swerve	Straight
Swerve	tie, tie	coward, brave
Straight	brave, coward	crash, crash

	Swerve	Straight
Swerve	0, 0	-2, 1
Straight	1, -2	-10, -10

end, both will lose compared to the socially optimal outcome they could attain if they cooperated.

The good news from early research in international environmental agreements is that transboundary pollution problems do not fall into the category of prisoners' dilemma games (Carraro and Siniscalco, 1993). While players in a prisoners' dilemma will always benefit from non-cooperative behavior, in transboundary pollution players may be better off to abate their emissions even though other players do not. This game structure is known as a chicken game (Table 1.2). It refers to the situation of two cars racing towards each other on a narrow lane. The drivers have a choice of avoiding a crash by swerving but at the price of being a "chicken", or coward. By not swerving, players show bravery and win. But if neither driver swerves and the cars crash, the loss is far greater than being ridiculed as a coward. Unlike in the prisoners' dilemma, partial cooperation is therefore preferable to no cooperation—however, both players prefer their opponent plays "cooperatively." Similarly in climate change, it may be rational to abate emissions and thus prevent the worst from happening even though some nations do not cooperate, i.e. participate in the abatement effort. Nevertheless, the situation where the others cooperate on abatement and oneself belongs to those enjoying the stable climate for free is still preferable. Therefore, a strong incentive to free-ride remains.

Consequently, the bad news from the literature on international environmental agreements is that stable coalitions tend to be small, in particular in cases where cooperation is needed the most. That is, cooperation fails when the difference between cooperative and non-cooperative behavior is large, and therefore much is to be gained by cooperating (for example Barrett, 1994).

The above situation describes the incentives to sign an international environmental agreement that restricts action to abatement or no abatement. But the "rules of the game" (or the incentive structure of the treaty) change with the design of the agreement. Since the early 1990s numerous suggestions have been made how to design international environment agreements in order to set the right incentives for voluntary participation if not by all then at least by as many as possible. Suggestions include side payments or transfers, the introduction of minimum participation clauses, financial penalties for non-participants, trade sanctions, and linking the issue of environmental protection to other issues within one agreement (see, for example, Wagner, 2001; Barrett and Stavins, 2003; Perez, 2005).

From the perspective of endogenous technological change modeling, this literature on international environment agreements raises two fundamental questions. First, as mentioned above, there is no induced technological change without a corresponding policy. For induced technological change to play a key role in mitigating GHG emissions, there needs to be a price on carbon. Thus, the question of how to raise participation in international environmental agreements is an essential prerequisite to induced technological change.

Second, technology itself is a potential incentive to broaden international environmental agreements. Development and diffusion of technology as well as technology transfers work on the international level. Linking technology oriented agreements to international environmental agreements therefore has the potential to raise participation in international environmental agreements (de Coninck et al., 2007).

1.2 Thesis Objective

The objective of this thesis is to explore the role of endogenous technological change (ETC) for strategies to mitigate climate change. I address (a) the role of ETC for mitigation costs and options and (b) international cooperation as a necessary assumption for inducing global technological change and the role of ETC in fostering this international cooperation.

The following chapters of this thesis are guided by two sets of research questions corresponding to these two broad topics. First, existing integrated assessment models of global mitigation options are employed to address the following questions:

- What is the impact of ETC on mitigation policy scenarios? What is the role of economy wide feedbacks concerning ETC? What are the implications of ETC in particular for mitigation costs and mitigation strategies, i.e. the optimal composition of mitigation options?
- How much do integrated assessment models differ in their analysis of ETC? What are the underlying reasons for the differences? What conclusions are robust across models despite the model uncertainty?

Second, a newly developed dynamic model of coalition stability is used to explore some strong assumptions made in the previous chapters. These assumptions include global agreement to take action in mitigating climate change, and to do so in a globally coordinated, cooperative way, such as to yield prices on GHG emissions globally. The following questions guide the research in these chapters:

- What is the prospect for international cooperation on climate change mitigation? How can it be increased by the design of international environmental agreement? What is the potential of trade sanctions to increase participation in international environmental agreements? What are the effects on environmental and global welfare of trade sanctions on the one hand and increased cooperation on the other hand?

How can competitive equilibria be computed in models with emission externality, international trade, and tariffs?

- How can ETC help to promote international cooperation on emission abatement? What are the roles of different technology oriented agreements (TOA)? What is the role of cooperative research and development and technological spillovers? In which ways does the type of technology that spills over matter? What is the role of international technology standards?

1.3 Thesis Outline

The research questions are addressed in four journal publications, which are reproduced as Chapters 2 to 5. Chapter 6 summarizes and draws conclusions.

Chapter 2 explores the impact of endogenous technological change on the costs of climate protection and on mitigation strategies in terms of the optimal mix of mitigation options. I apply the integrated assessment model MIND in a numerical sensitivity analysis to assess the implication of parameter uncertainty for conclusions concerning endogenous technological change. In extensive parameter studies of economic and technological parameters these uncertainties are explored further, and insights are gained into feedbacks between technological progress and macro-economic dynamics. This chapter has been published in the *Energy Journal*.[2]

Chapter 3 compares ten state of the art integrated assessment models incorporating features of endogenous technological change. The aim is to learn from the differences in the effects of endogenous technological change in these models, and to identify conclusions that are robust across models. In preparation of the model comparison exercise, all modeling teams were invited to two workshops on the implementation of endogenous technological change within each model, and the implementation of the numerical scenarios specific to this comparison. In particular, two sets of policy scenarios were run to analyse the impact of technological change being endogenous under *ceteris paribus* conditions, namely CO_2 concentration stabilization in presence and absence of endogenous technological change. The models' business-as-usual projections were harmonized to minimize so-called "baseline effects." The analysis of model results focused on aggregated indices of mitigation costs and strategies that could be obtained from all models despite the large divergence in model design. Costs are evaluated as reductions in gross world product. Mitigation strategies were analysed in two ways: first, by applying a decomposition analysis to carbon dioxide reductions along Kaya's identity using the refined Laspeyres index method, and second, by comparing mitigation strategies in terms of the mix of technological options in the energy sector. Furthermore, the carbon price and usage of carbon sequestration and storage are assessed as indicators of the economies' dependency on fossil fuels and the importance of an end-of-pipe technology for carbon free energy. Close cooperation with the participating modeling teams was necessary to ensure the accurate interpretation of the numerical results. This chapter has been published in the *Energy*

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[2] Edenhofer, O., K. Lessmann, N. Bauer (2006): Mitigation Strategies and Costs of Climate Protection: The Effects of ETC in the Hybrid Model MIND. *Energy Journal* Special Issue Endogenous Technological Change and the Economics of Atmospheric Stabilisation, 207–222.

Journal.[3]

In Chapter 4 I explore incentives to foster participation in an international environmental agreement that aims to mitigate GHG emissions. In particular, the prospect of trade sanctions to stabilize coalitions are addressed. For this purpose, I develop an integrated assessment model in the economic framework of multi-actor optimal growth models. The model accounts for climate change as a stock pollutant (CO_2 concentration and global mean temperature), damages from climate change, and international trade and tariffs. The implementation includes an algorithm to solve for a competitive equilibrium despite multiple externalities in the economy. In addition to the effect of tariffs on participation, I analyse the impact on environmental effectiveness, global welfare, and credibility of imposing the sanctions. This chapter is accepted for publication in *Economic Modelling*.[4]

Chapter 5 considers the scope of technology oriented agreements for fostering international cooperation by examining the impact of cooperative research and development (R & D) on the one hand and international technology standards on the other hand. The basic model from Chapter 4 is extended for this paper to allow for knowledge spillovers in two sectors: R & D aimed at augmenting labor productivity, and R & D targeting mitigation technology. In the analysis, R & D cooperations are compared in terms of their effectiveness to raise participation, sustain environmental protection, and their effect on global welfare. International technology standard are assessed as a complement to research cooperation as well as by themselves. This chapter is submitted to *Resource and Energy Economics*.[5]

Chapter 6 concludes.

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[3] Edenhofer, O., Lessmann, K., Kemfert, C., Grubb, M., and Koehler, J. (2006): Induced Technological Change: Exploring its Implications for the Economics of Atmospheric Stabilization: Synthesis Report from the Innovation Modeling Comparison Project. *Energy Journal* Special Issue Endogenous Technological Change and the Economics of Atmospheric Stabilisation, 57–107.

[4] Lessmann, K., R. Marschinski, and O. Edenhofer: The Effects of Tariffs on Coalition Formation in a Dynamic Global Warming Game. *Economic Modelling* (2009), doi:10.1016/j.econmod.2009.01.005.

[5] Lessmann, K. and O. Edenhofer: Research cooperation and international standards in a model of coalition stability. *Resource and Energy Economics*, submitted.

Chapter 2

Mitigation Strategies and Costs of Climate Protection The Effects of ETC in the Hybrid Model MIND[*]

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Mitigation Strategies and Costs of Climate Protection: The Effects of ETC in the Hybrid Model MIND

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MIND is a hybrid model incorporating several energy related sectors in an endogenous growth model of the world economy. This model structure allows a better understanding of the linkages between the energy sectors and the macro-economic environment. We perform a sensitivity analysis and parameter studies to improve the understanding of the economic mechanisms underlying opportunity costs and the optimal mix of mitigation options. Parameters representing technological change that permeates the entire economy have a strong impact on both the opportunity costs of climate protection and on the optimal mitigation strategies e.g. parameters in the macro-economic environment and in the extraction sector. Sector-specific energy technology parameters change the portfolio of mitigation options but have only modest effects on opportunity costs e.g. learning rate of the renewable energy technologies. We conclude that feedback loops between the macro-economy and the energy sectors are crucial for the determination of opportunity costs and mitigation strategies.

1. SETTING THE SCENE

The Innovation Modeling Comparison Project (IMCP) explores the consequences of endogenous technological change (ETC) for the economics of stabilizing atmospheric carbon dioxide (CO_2) concentration. This paper contributes to the IMCP by presenting an analysis of technological change, both at different levels and in different sectors of the Model of Investment and technological Development (MIND). MIND combines an intertemporal endogenous growth model of the macro-economy with sector-specific and technological details taken

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from the field of energy system modeling. In particular, we explore the impact of endogenous technological change on opportunity costs and mitigation strategies within the framework of a social cost-effectiveness analysis.

We explore the impact of ETC in a social cost-effectiveness framework because we want to understand how technological change is induced by climate policy. Several studies have already incorporated aspects of ETC in this framework (Buonanno et al, 2003; Chakravorty et al, 1997; Goulder and Mathai, 2002; Kypreos and Barreto, 2000; Nordhaus and Boyer, 2000; Nordhaus, 2002; Popp, 2004a; 2004b). The added value of MIND arises mainly from two features. First, we incorporate a wide spectrum of relevant mitigation options, including improvement of energy efficiency, carbon capture and sequestration (CCS), renewable energy technologies, and traditional non-fossil fuels (exogenous time series for large hydropower and nuclear). Second, technological change in MIND has an endogenous formulation with R&D investments in labor and energy productivity, learning-by-doing, and vintage capital in the different energy sectors. We believe that including these features of ETC is essential for the assessment of macro-economic mitigation costs and the portfolio of mitigation options. MIND is a hybrid model merging features from bottom-up and top-down models. It resembles a bottom-up model because it comprises several energy sectors. However, compared to energy system models, the technologies are represented at a more aggregated level. In MIND, these sectors are embedded within a macro-economic environment, in order to evaluate the feedbacks between the macro-economy and the energy sector (see Manne et. al. 1995 for an example of a similar exercise). We will show that these feedbacks are crucial for an understanding of opportunity costs and mitigation strategies in an economy faced with climate policy.

The next section briefly introduces the model and its calibration, highlighting the improved treatment of CCS in MIND 1.1. Section 3 discusses technological change within MIND, forming the main part of this paper. Section 4 draws conclusions.

2. THE MODEL STRUCTURE OF MIND 1.1

The model equations of MIND are introduced and discussed in Edenhofer, Bauer and Kriegler (2005). The model version 1.0 presented therein has been extended by Bauer (2005), to replace exogenous scenarios of Carbon Capture and Sequestration (CCS) with a technologically detailed, endogenous treatment of the CCS option (model version 1.1). This study uses MIND 1.1, adapted slightly to meet the requirements of the IMCP, and enhanced by a more sophisticated carbon cycle (Hoos et al. 2001). The following section provides a summary of the model structure and parameter calibrations. Model equations are restricted to the parameters treated in the sensitivity analysis and parameter studies in this article; for a comprehensive discussion of the model structure we refer to Edenhofer et al. (2005) and Bauer (2005).

MIND is an integrated assessment model comprising a model of the world economy drawing specific focus on the energy sector, and a climate module computing global mean temperature changes. MIND therefore allows us to assess the impacts of constraints to climatic change on the economy in cost-effectiveness analysis.

MIND models economic dynamics by adopting an endogenous growth framework. It calculates time paths of investment and consumption decisions that are intertemporally optimal. The objective is to maximize social welfare, defined as the present value of utility (pure rate of time preferences is 1%), which is a function of per capita consumption exhibiting diminishing marginal utility. Most economic activity is subsumed in an aggregate CES production function (equation 1), the output Y_A of which describes the gross world product (GWP).[1]

$$Y_A = \phi_A[\xi_A^L(A * L_A)^{-\rho_A} + \xi_A^E(B * E)^{-\rho_A} + \xi_A^K \mathrm{K}_A^{-\rho_A}]^{-1/\rho_A} \tag{1}$$

The income share related parameters ξ_A are calibrated so that the actual income shares of labor L_A, energy E, and capital K_A relate to each other at the ratio of 66:4:30. Total factor productivity Φ_A is a fixed scalar calibrated to a value where the historical output of 2000 is reproduced. The elasticity parameter ρ_A determines the elasticity of substitution $\sigma_A = (1+\rho_A)^{-1}$. In some integrated assessment models, the elasticity of substitution between capital and energy is 0.4 for developed countries and 0.3 for developing countries (Manne et al, 1995). We have chosen an overall elasticity of substitution for all three factors of $\sigma_A = 0.4$. Labor L_A is described by an exogenous population scenario adopted from the common POLES/IMAGE baseline (CPI, Vuuren et al. 2003). Capital stock K_A is built up through investments and depreciates at a rate of 5 %. The initial value of K_A is derived from Y_A and an estimated capital coefficient. Capital coefficients were computed from the OECD database and from PWT6.1 for different countries. Their values agglomerate around 2.5. Since energy sector capital is separate from K_A, we assume a lower capital coefficient of 2.0. Variables A and B denote the productivities of labor and energy, respectively, and are stock variables determined by R&D investments according to equation (2):

$$\frac{\dot{A}}{A} = \alpha_A \left(\frac{RD_A}{Y}\right)^{\gamma_A}, \qquad with\ A(t = \tau_1) = A_0 \tag{2}$$

$$\frac{\dot{B}}{B} = \alpha_B \left(\frac{RD_B}{Y}\right)^{\gamma_B}, \qquad with\ B(t = \tau_1) = B_0 \tag{3}$$

RD_A and RD_B are investment flows controlled by the central planner. The parameters γ_A and γ_B (where $0<\gamma_A<1$. $0<\gamma_B<1$) model the decreasing marginal productivity of R&D investments. They are assumed to take the values of 0.05

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[1] MIND is implemented in discrete time steps of 5 years. In the model equations of this text we present the more intuitive continuous formulations, e.g. in case of derivatives.

and 0.1, respectively. Parameters α_A and α_B determine the productivity of R&D investments. They are calibrated at a rate such that spending 1 % of the GWP on energy R&D increases the energy efficiency parameter by 2.25 %; when 2.5 % of GWP is spent on labor R&D, the labor efficiency parameter increases by 2 %.

The energy input to aggregate production, E, is an additive composite of fossil energy, renewable energy, and traditional non-fossil energy, with the latter given exogenously. Fossil energy is produced from energy conversion capital and primary energy input in a CES production function. Fossil resources are converted to primary energy using an exogenous assumption about the carbon/energy ratio of the fossil fuel mix, its availability being described by a model of resource extraction. Resource R is extracted by capital K_{res}, the average productivity of which is subject to a scarcity effect ($\kappa_{res,s}$) and a learning-by-doing effect ($\kappa_{res,l}$):

$$R = \kappa_{res} K_{res} \tag{4}$$

$$\kappa_{res} = \kappa_{res,s}\,\kappa_{res,l} \tag{5}$$

The initial resource extraction is $R = 6.4$ GtC (SRES), assumed to be produced by a capital stock of $K_{res} = 5$ trillion \$US. This determines $\kappa_{res,l}$ because $\kappa_{res,s}$ is normalized to unity.

The scarcity effect $\kappa_{res,s}$ is determined by the marginal costs of resource extraction C_{res}^{mar}:

$$\kappa_{res,s} = \frac{\chi_1}{C_{res}^{mar}} \tag{6}$$

In equation 6, parameter χ_1 as well as the marginal costs in 2000 are set to \$113. During the simulation, marginal costs C_{res}^{mar} increase with cumulative resource extraction CR_{res} according to equations 7 and 8.

$$C_{res}^{mar} = \chi_1 + \chi_2 \left(\frac{CR_{res}}{\chi_3} \right)^{\chi_4} \tag{7}$$

$$CR_{res}(t) = \int_{\tau_1}^{t} R(t')dt', \text{ with } CR_{res}(t = \tau_1) = 0 \tag{8}$$

Parameter χ_1 denotes initial costs of the fossil resource, the exponent χ_4 captures the curvature of the function (i.e. the timing of increasing costs), and χ_2 gives the marginal costs once the amount described by χ_3 has been extracted. We parameterize this function according to Rogner's (1997) empirical assessment of world hydrocarbon resources, and arrive at the values $\chi_2 = 700$, $\chi_3 = 3500$ and $\chi_4 = 2$.

The learning-by-doing effect of capital productivity $\kappa_{res,l}$ depends on the ratio of actual resource extraction $E_{res,l}$ to initial resource extraction $E^0_{res,l}$.

$$\dot{\kappa}_{res,l} = \frac{\kappa_{res,l}}{\tau_{res,l}\,\kappa^{max}_{res,l}} (\kappa^{max}_{res,l} - \kappa_{res,l}) \left(\left[\frac{E_{res,l}}{E^0_{res,l}} \right]^{\beta_{res,l}} - 1 \right) \tag{9}$$

$$with \;\; \kappa_{res,l}\,(t = \tau_1) = \kappa^0_{res,l}$$

The factor $\beta_{res,l} = 0.4$ dampens the learning-by-doing effect: a rapid increase in extraction induces a loss in productivity gains relative to the same increase in extraction spread over a longer time period. Furthermore, productivity gains from learning saturate when productivity approaches its maximum value $\kappa^{max}_{res,l}$ which is set to twice its initial value. Parameter $\tau_{res,l}$ determines the speed of learning and is set to 100 years.

Renewable energy E_{ren} is produced by capital Kap_{ren} which is employed at $FLH_{ren} = 2190$ full load hours per year.

$$E_{ren}\,(t) = FLH_{ren} * Kap_{ren}\,(t) \tag{10}$$

$$Kap_{ren}\,(t) = \int_{t_0}^{t} \omega\,(t - t')\,\kappa_{ren}(t')\,I_{ren}\,(t')dt' \tag{11}$$

The available renewable energy capital stock in each point in time is determined by summing over the investments into renewable energy I_{ren} in preceding time steps multiplied with the productivity of installed capital κ_{ren}. Depreciation is modeled by weights ω which determine the fraction of capital that still remains. ω_1 to ω_7 are set to 1.0, 0.9, 0.8, 0.7, 0.5, 0.15, 0.05, and $\omega_i = 0$ if $i > 7$. This allows to model different capital productivities for different vintages of the capital stock. Capital productivity κ_{ren} indeed changes in time because the costs of renewable energy equipment c_{ren} decrease, subject to learning-by-doing.

$$\kappa_{ren} = \frac{1}{c_{ren}\,(t) + c_{floor}} \tag{12}$$

The inverse of floor costs $c_{floor} = 500$ US\$/kW constrains capital productivity from above, while c_{ren} starts out at $c_{ren} = 700$ US\$/kW and decreases with cumulative installed capital $CKap_{ren}$:

$$CKap_{ren} = \int_{\tau_0}^{t} Kap_{ren}\,(t')dt' \tag{13}$$

The following equation describes the dynamics of learning-by-doing in the renewable sector:

$$c_{ren,t} - c_{ren,t-1} = c_{ren,0}\,CKap^{-\mu_{ren}}_{ren,0}\,(CKap^{-\mu_{ren}}_{ren,t} - CKap^{-\mu_{ren}}_{ren,t-1})$$

$$\times \left(\frac{CKap_{ren,t-1}}{CKap_{ren,t}} \right)^{\beta_{ren}} \tag{14}$$
$$with\ c_{ren}(t=0) = c^{0}_{ren},$$

The learning parameter μ_{ren} determines the learning rate lr and reflects a learning rate of 15 %, i.e. investment costs decrease by 15 % with every doubling of cumulative installed capacity. Parameter β_{ren} within the last factor of the right hand side of the equation causes a dampening similar to $\beta_{res,l}$ in the learning-by-doing equation of the fossil resource extraction (equation 9). Set to $\beta_{ren} = 0.4$, it prevents learning that is too fast.

There are three sources of carbon dioxide emissions: fossil fuel combustion, leakage from sequestered CO_2, and emissions from land-use and land-use change. The latter are described by an exogenous time series. Since fossil resources are measured in tons of carbon, resource use R and emissions Em coincide, except for land-use emissions and Carbon Capturing and Sequestration (CCS):

$$Em(t) = R(t) + LULUC(t) - R_{cap}(t) + LEAK(t), \tag{15}$$

where R_{cap} denotes the amount of CO_2 captured in a given year and $LEAK$ denotes leakage.

CCS is modeled as a chain process distinguishing six steps: CO_2 is captured at point sources (1) and transported via pipelines to sequestration sites (2). There, the CO_2 needs to be compressed (3) before it is injected into the sequestration site (4). Then, it either remains in the site (5) or leaks into the atmosphere (6). Processes 1-4 are capital intensive and are modeled as capital stocks representing available capacities for the individual processes. Capacities are built up by investments according to the following equation:

$$K_{pq}(t) = \int_{t_0}^{t} \omega_q(t-t')\, \iota^{-1}_{pq}(t')\, I_{pq}(t')dt' \tag{16}$$

Variables K_{pq} denote the capacities, index p denotes the process step, and the index q denotes different investment alternatives such as one of five distinct capture technologies or one of six distinct sequestration alternatives. Weighting parameters ω introduce a depreciation scheme for different vintages of the capital stocks, similar to equation (11) in case of renewable energy. Investments are denoted I_{pq} and the investment costs are ι_{pq}. Investment costs for capturing capacity range from ~100 \$US/tC to ~450 \$US/tC depending on the specific capture technology. When the productivity of CCS investments is varied in parameter studies later on in this paper, the same relative change is applied to the investment costs for each technology.

In addition to the limitation inflicted by the necessity to build up capacity, the amount of carbon that may be captured is limited by a static and a dynamic constraint. The static constraint limits the amount of carbon which can be captured from a large power plant as a fraction of the resource use in the business-as-usual scenario. The dynamic constraint defines an upper limit of investments into the specific capture technologies in each period. The upper limit is defined as a share of the investments in the power generation sector. The rationale is that the capability of retrofit investments in large power plants depends on the total amount of investments undertaken in the power generation sector.

The injection of CO_2 into particular sequestration sites demands two types of facilities: compressors and injection wells (steps 3 and 4). The modeling approach takes into account that both facilities demand investments and secondary energy. In steps 5 and 6, the modeling approach considers the capacity constraint of each sequestration alternative *j* and leakage of sequestered carbon: Leakage is described by a rate, and the capacity of each sequestration alternative is the upper bound for the cumulative amount of CO_2 that is injected into each sequestration alternative.

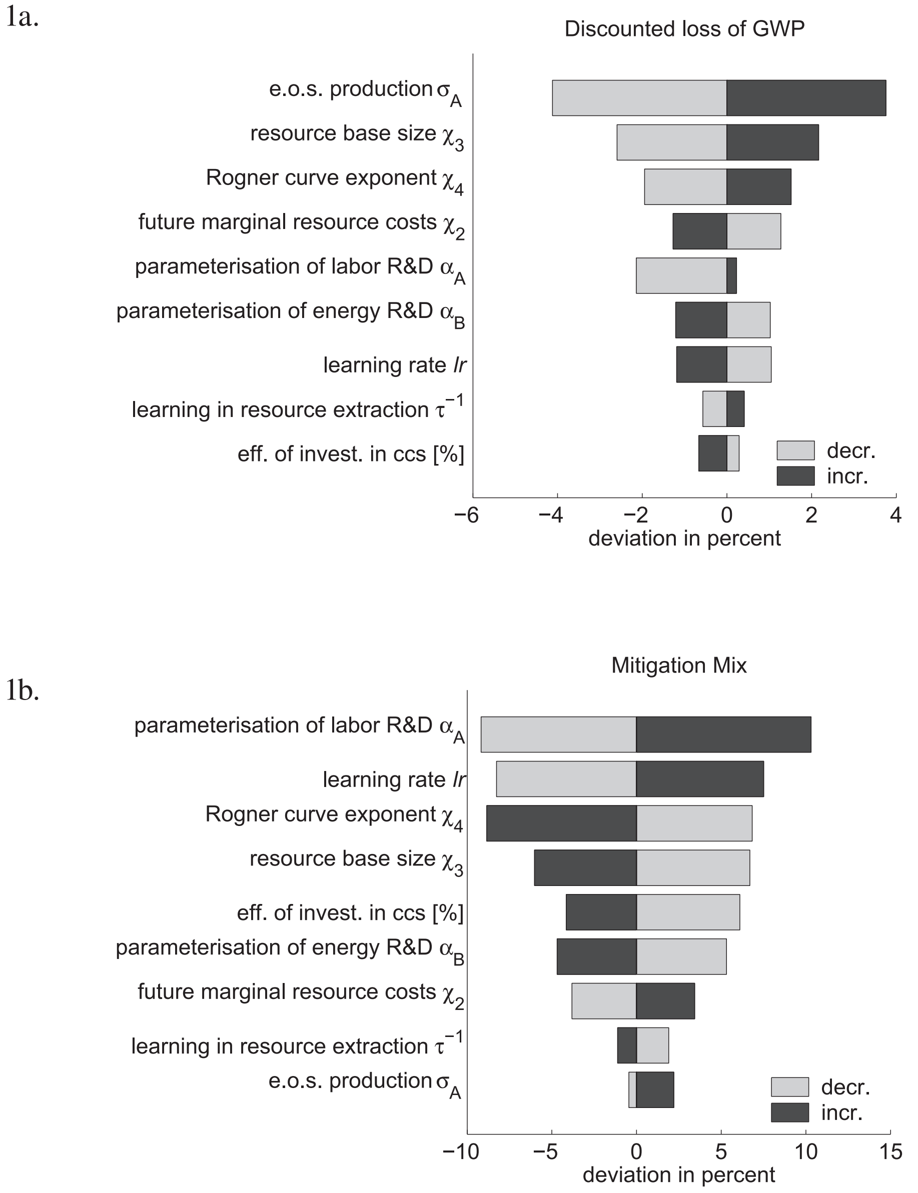
3. THE ROLE OF ENDOGENOUS TECHNOLOGICAL CHANGE IN MIND

In what ways does endogenous technological change matter in policy scenarios computed with MIND? In the following sections, we explore this question using sensitivity analysis and miscellaneous parameter studies (see Bauer et al, 2005 for initial parameter studies with MIND). In the sensitivity analysis, we rank important technology-related model parameters according to their influence on two model outputs: the opportunity costs of climate protection and the mix of options used for CO_2 mitigation. We then study the effect of parameter variations on the same model outputs and analyze the underlying economic dynamics. All model runs stabilize atmospheric CO_2 concentration level at 450 ppm.

3.1 Local Sensitivity Analysis

Figure 1a and 1b show the influence of important parameters of MIND on opportunity costs of climate policy (1a) and on the mix of mitigation options (1b). The former are measured as losses of gross world product (GWP), accumulated from 2000 to 2100 and discounted to present value at a rate of 5 %, relative to the business-as-usual scenario. The latter is represented by the ratio of the two dominant options, renewable energies and CCS, where a ratio of unity implies that the same amount of CO_2 reductions may be attributed to each of the mitigation options. Parameter influence is measured by the response of the model to a 5 % variation of the parameter. Taking the set of parameters from the model calibration as the starting point, we vary one parameter at a time, hence the effects reflect local sensitivity. As local sensitivity analysis assesses parameter sensitivity at only one point in parameter space it neglects the fact that sensitivities may vary tremendously at other points in parameter space. Using a measure of global sensitivity, i.e. a measure that takes into account simultaneous variation of several parameters, is preferable as it provides a remedy to this shortcoming.

Figure 1. Sensitivity Analysis



Figures 1a and 1b show the influence of important technological parameters on opportunity costs and mix of mitigation options, respectively. Metric is the deviation of the output in response to an up to 5% increase (decrease) of the parameter. The parameter "e.o.s. production" refers to the elasticity of substitution σ_A in aggregate industrial production, i.e. production of the gross world product.

However, local sensitivity analysis is used in this paper for the following two reasons. Firstly, the model response to a change in a single parameter, *ceteris paribus* , is an intuitive measure. Secondly, the computational burden for a local analysis is much lower. To emphasise, while this analysis sheds light on the influence of parameters and the potential influence of their uncertainties on model results, we do not explicitly test parameter uncertainties. Therefore, we make no statements about the relative importance of parameters in contributing to the uncertainty of computed results, but rather, about the ir potential to impact results themselves.

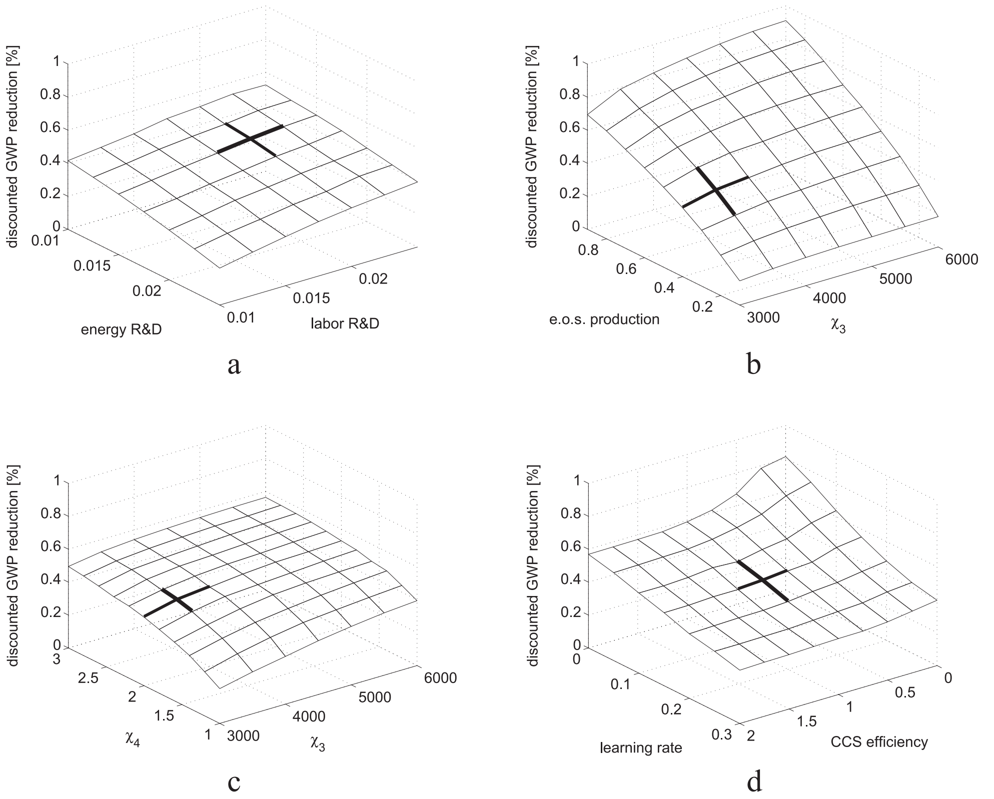
As Figure 1a indicates, the greatest influence on opportunity costs is exerted by the elasticity of substitution σ_A, followed by the parameters describing the availability of fossil resources, and the effectiveness of R&D investments in labor productivity. The latter and the top three parameters have a positive effect on costs, i.e. costs increase with the parameters, whereas the assumption of high marginal future fossil resources costs have a negative effect. Productivity of energy efficiency R&D and the learning rate of the renewable energy technologies rank next, followed by two more sector specific parameters, the learning parameter in fossil resource extraction and the efficiency of investments in CCS. Overall, the relatively small responses of the model to parameter variations (less than 5%) improves the confidence in the robustness of the computed opportunity costs. In the next two sections we will explore the reasons for this observation, and evaluate the role of technological change in deriving these results.

Figure 1b depicts the influence of parameters on the mix of mitigation options. It is immediately evident from a comparison between Figure 1a and Figure 1b that the ranking of parameters has changed. Most notably, the elasticity of substitution has dropped to the bottom rank, and two resource related parameters, χ_2 and χ_3, also emerge to fall in ranking. Conversely, the parameterization of labor R&D, the learning rate of renewable technologies, and the efficiency of CCS investments have risen in the hierarchy. Overall, the mitigation mix is more sensitive (with variations up to 10 %) than the mitigation costs in Figure 1a. This result comes as no surprise. Since GWP losses are closely related to social welfare, the maximization of which is the objective of MIND, GWP loss is deliberately kept to a minimum. The mix of mitigation options, on the other hand, is endogenously determined to minimize costs. It is intuitive that a change in the parameter values alters the competitiveness of mitigation options, hence its impact on the mitigation mix is significant.

3.2 Determinants of the Opportunity Costs

This section takes a closer look at the opportunity costs of climate protection. We present parameter studies varying two parameters simultaneously. This enables us to discuss the effects of varying these parameters, as well as analyzing the interdependencies between them, hence taking a first step beyond a local sensitivity analysis presented in Section 3.1. To an extent, this analysis remains very much local in character since many parameters remain fixed at their default levels. However, restricting the variation to two parameters at a time enables an intuitive graphical presentation of the results, which provides deeper and useful insights into the workings of MIND.

Figure 2. Parameter Studies of Mitigation Costs



a b

c d

Figures in this panel show discounted gross world product loss (discount rate is 5 %) for several parameter studies. In figure 2a, energy R&D and labor R&D refer to the productivity of investment into research that enhances the efficiency of the corresponding factor. In 2b, e.o.s. production refers to the elasticity of substitution in the aggregate industrial production sector. Parameters χ_3 and χ_4 in figure 2b and 2c refer to the size of the fossil resource base and the exponent of the Rogner curve, respectively. Figure 3d treats the learning rate of renewable technologies and the efficiency of investments in CCS technology. The pairs of default parameter values are indicated with a bold cross.

We start out by taking a look at the engine of endogenous growth in MIND: R&D investments that drive labor and energy efficiencies. Figure 2a displays the productivity of these investments. While the two parameters are similar with respect to the process they describe – accumulation of a knowledge stock increasing the productivity of an input factor to aggregate production – their effects on opportunity costs are contrary. An enhanced effectiveness of labor productivity R&D raises costs, while better energy efficiency R&D reduces GWP losses. This is due to opposite effects on the mitigation gap, i.e. the discrepancy of CO_2 emissions between business-as-usual and climate policy scenarios. More effective labor R&D stimulates additional economic growth and implies higher CO_2 emissions in the baseline. More effective energy R&D investments, on the other hand, facilitate much better energy efficiency in the baseline, and hence lowers CO_2 emissions.

The mitigation gap characterizes the challenge for the economy facing climate protection goals and manifests itself in the opportunity costs.

Figure 2b compiles two parameters with an effect of the second type: the elasticity of substitution in the aggregate production sector, and the estimated size of the available fossil resources. Figure 2b shows that costs increase with the elasticity of substitution. This too can be attributed to baseline effects: higher elasticity of substitution implies a more flexible production technology which induces higher economic growth in the business-as-usual scenario. Therefore, achieving 450 ppm requires a substantial departure from the baseline and is relatively costly. A variation of the resource base has a bigger impact on the mitigation costs if the elasticity of substitution is relatively high. Low values of the elasticity of substitution hinder economic growth and consequently imply a lower demand for energy. At low energy demand, relaxing the scarcity of the resource has a smaller effect. In general, a larger resource base allows higher economic growth in the business-as-usual case. When climate policy constrains resource use, it devaluates exhaustible resource as an economic asset and diminishes the rent income of their owners. The loss of rent income increases with the resource base because a relatively cheap and abundant resource can no longer be used as input in production.

We take yet a closer look at the fossil resource base. Figure 2c studies the variation of the size of the resource base χ_3 and parameter χ_4. Parameter χ_4 as well as the resource base are proxy variables for the technological progress in the extraction sector. Increasing χ_3, i.e. assuming more abundant resources, results in cheaper short to medium term supply of the fossil resource. Increasing χ_4 trades a slow and steady increase of the marginal costs for a steeper increase at a later time – thus making the resource cheaper and more easily available in the short to medium term. High values of χ_4 allow higher economic growth in the business-as-usual case and induce a relatively large mitigation gap. For high values of χ_4 the marginal costs of extraction are essentially constant. Under this condition, an increased resource base has moderate impact on macro-economic mitigation costs. For low values of χ_4, an increased resource base has a slightly higher impact on the macro-economic costs because marginal improvements in extraction already increase the shadow price of the resource. This parameter study shows that climate protection becomes relatively costly if there is a high rate of technological progress in the exploration and extraction of fossil fuels. Accelerated technological progress in the extraction sector makes climate policy more costly, because such policy devaluates assets (resources and capital stock in the corresponding sectors). Therefore, special attention ought to be paid to assumptions about resource availability and their uncertainties.

Contrary effects can be observed if technological progress decreases the costs of mitigation technologies. The impact on opportunity costs is shown in Figure 2d. We explore two parameters which are both closely related to mitigation options: the efficiency of investments into Carbon Capture and Sequestration technologies (CCS) and the learning rate of renewable energy technologies.

Varying these two parameters shifts the competitive advantage between the two mitigation options and, consequently, the extent to which they are used. It turns out that the efficiency of CCS investments has no strong impact on the overall opportunity costs if the learning rate of renewable energy technologies is relatively high. The reason is that renewables are modeled as a backstop technology, i.e. as a carbon-free energy source, and need no non-reproducible input for energy production. In contrast to the renewables, CCS investments only bridge from the fossil fuel age to a carbon-free era. CCS makes the transition of the energy system smoother but has severe limitations if fossil fuels become more costly because of increasing marginal extraction costs at the end of the 21st century. At the same time, renewable energy becomes cheaper because of learning-by-doing. It is plausible that this effect cannot be altered by high efficiencies of CCS investments. At low learning rates of the backstop technology, CCS becomes more important.

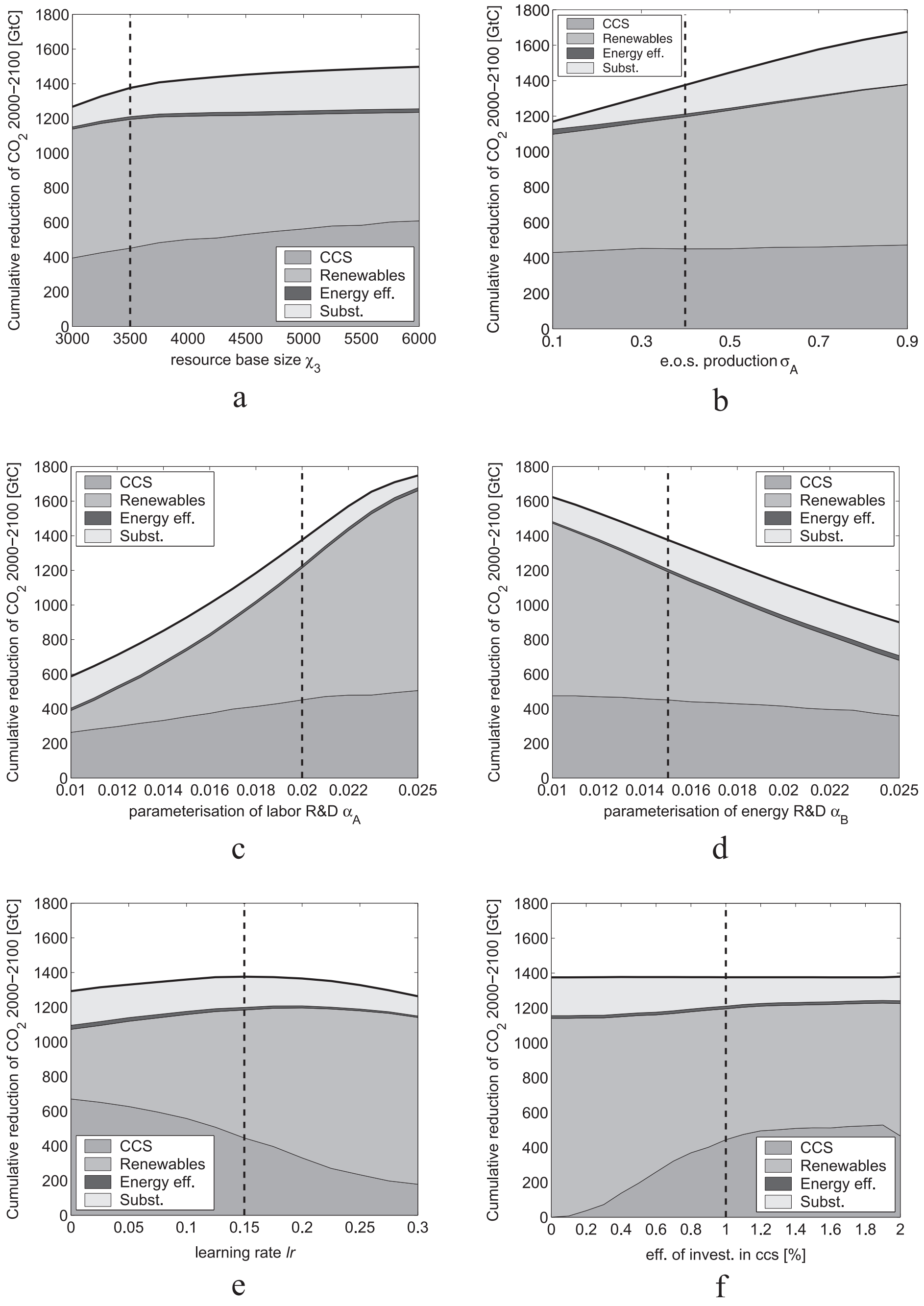
3.3 Mitigation Strategies

In this section we analyze the impact of the same parameters explored in the previous section on the option portfolio of an optimal mitigation strategy. Mitigation options are compared on the basis of the amount of CO_2 that they enable the economy to reduce. For the CCS option, this is straightforward: it is simply the amount of captured and sequestered CO_2 (less the amount that leaks from the sequestration site). In case of energy related mitigation options, i.e. renewable energy and energy efficiency improvements, the corresponding amount of “mitigated CO_2 emissions” was derived from the equivalent amount of energy from fossil fuels. In , the degree of efficiency on converting primary into final energy is determined endogenously in the production function of the fossil sector. In this ex post analysis, however, we estimate the “equivalent” amount of fossil energy by assuming a fix coefficient. The remaining mitigation options, namely energy savings by substitution of energy at the levels of energy transformation and aggregate production, are visualized as the difference to the total reduction of CO_2.

Figure 3a shows that the amount of CCS within the portfolio of mitigation options increases with the assumed resource base. The cumulative amount of CO_2 reduced by renewables within the next century decreases, energy efficiency remains constant and energy savings increase. An increasing resource base implies increasing rents for the owners. This increasing rent income makes CCS a more profitable option. Due to high economic growth and relatively cheap fossil fuels, the return on investment in renewables falls short of the returns on CCS investments.

In figure 3b, energy savings (reduction of energy consumption by substituting energy by capital in different sectors) become more profitable if the elasticity of substitution increases; at the same time, the importance of energy efficiency decreases.

Figure 3. Parameter Studies of Mix of Mitigation Options



Figures 3a-f show how the mix of mitigation options varies in parameter studies. CO_2 reductions caused by avoiding the use of fossil fuels (renewable energy, energy efficiency improvements, and substitution) are estimated from the alternative use of fossil fuels. Dashed lines indicate the default parameter value.

A more surprising result is obtained in figure 3c and 3d. In figure 3c an increasing productivity of R&D investment in labor enhancing activities also increases the share of renewables in the mitigation portfolio. The explanation is as follows: economic growth induces additional energy demand that is met by carbon-free technologies. Due to high economic growth, marginal extraction costs of fossil fuels increase sooner, and thus CCS is less competitive compared to renewables. In contrast, when R&D investments in energy efficiency become more productive, the mitigation gap shrinks, and the share of renewables within the mitigation portfolio decreases (3d). Interestingly, changes in the productivity of energy R&D investments affect the baseline rather than providing a more attractive mitigation option. In this study, the energy efficiency parameter varies from 63 to 245 % of its regular value in 2100 in the baseline, the latter implying that energy use in 2100 is decreased by 60%. Climate policy, however, only induces 0.4 to 2.7 % additional increases of the efficiency parameter. To sum, higher energy efficiency and a lower baseline for economic growth reduce the demand for renewables. The importance of the renewable energy option depends heavily on the underlying economic growth path.

As figure 3e shows, high learning rates in the renewable energy sector reduce the optimal amount of CCS substantially. In that sense CCS can be seen as a joker-option if the learning rate of the renewables is relatively low. It is also remarkable that energy savings are less important when the learning rate is relatively high because the energy demand can be met by the carbon-free renewables. Learning-by-doing reduces the price of electricity produced by renewables and increases the demand for renewables which reduces their costs further. This feedback loop makes CCS less important. As figure 3f indicates, this effect can be counteracted by an increasing efficiency of CCS-investments.

4. CONCLUDING REMARKS

In what ways does technological change matter? Our analysis shows that technological change works in two “directions”: we identify technological progress that permeates the entire economy and technological progress that is restricted in its effects to a single sector. Examples for such sector-specific technological change are learning-by-doing effects associated with renewable energy technologies and resource extraction, as well as technological progress in CCS, here modeled via its investment efficiency. In , parameters associated with such sector specific technological change have a significant impact[2] on the optimal mix of mitigation options. For example, an increased learning rate increases the share of renewables, and improved investment efficiency in CCS increases the share of CCS within the entire portfolio of mitigation options (Figures 1b and

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[2] We refer to the impact of a parameter in terms of a relatively large potential influence, i.e. a large sensitivity of results to changes of this parameter. Recall, however, that the actual uncertainty about parameters is not taken into account.

3ef). However, these parameters are less important in determining the overall opportunity costs of climate protection which measure the impact on the overall economy (Figure 1a).

In contrast, there is technological change with significant impact on the macro-economic growth process, evident in its influence on opportunity costs. Such technological change is described by parameters of the macro-economic environment, like the elasticity of substitution, and the parameters characterizing the effectiveness of labor- and energy R&D investments. Labor R&D investments in particular have a strong influence on macro-economic growth as well as the mix of mitigation options. Progress in resource extraction is an example of sector-specific technological change with a macro-economic impact. This progress is characterized by the parameters of Rogner's scarcity curve and has been shown to exert a significant influence on opportunity costs. The most prominent effect of these parameters is their impact on the baseline.

We conclude that feedbacks between the macro-economy and the energy system are crucial for determining mitigation costs and the development of the mitigation portfolio in time. The case of technological change in resource extraction shows how sector-specific processes may exert significant influence on the macro-economy, while the impact of labor R&D productivity on the share of renewable energy is an example of macro-economic influence on a distinct sector.

This has strong implication for policy. A sector-specific policy that fosters technological change in the extraction sector induced by increasing prices in the oil or gas market would increase the opportunity costs of climate protection. A policy that increases the economy-wide energy efficiency in all energy related sectors would reduce the costs of climate protection substantially. Enhancing technological change in the extraction sector makes sense, if decision makers intended only to increase energy security. Analysis here highlights that the impact of such a policy on the opportunity costs of climate protection must also be taken into account.

The results presented here indicate that partial-equilibrium models omitting intertemporal and inter-sectoral aspects can be misleading for designing a climate and energy policy. Thus, they stress the utility of hybrid models incorporating endogenous technological change at the sector level as well as at the macro-economic level. Moreover, hybrid models pose a coherent framework not only for the assessment of the opportunity costs and portfolios of mitigation strategies, but also for the design of climate and energy policy instruments.

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Chapter 3

Induced Technological Change: Exploring its Implications for the Economics of Atmospheric Stabilization:

Synthesis Report from the Innovation Modeling Comparison Project[*]

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Induced Technological Change: Exploring its Implications for the Economics of Atmospheric Stabilization:

Synthesis Report from the Innovation Modeling Comparison Project

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*Michael Grubb*** and Jonathan Köhler†*

This paper summarizes results from ten global economy-energy-environment models implementing mechanisms of endogenous technological change (ETC). Climate policy goals represented as different CO_2 stabilization levels are imposed, and the contribution of induced technological change (ITC) to meeting the goals is assessed. Findings indicate that climate policy induces additional technological change, in some models substantially. Its effect is a reduction of abatement costs in all participating models. The majority of models calculate abatement costs below 1 percent of present value aggregate gross world product for the period 2000-2100. The models predict different dynamics for rising carbon costs, with some showing a decline in carbon costs towards the end of the century. There are a number of reasons for differences in results between models; however four major drivers of differences are identified. First, the extent of the necessary CO_2 reduction which depends mainly on predicted baseline emissions, determines how much a model is challenged to comply with climate policy. Second, when climate policy can offset market distortions, some models show that not costs but benefits accrue from climate policy. Third, assumptions about long-term investment behavior, e.g. foresight of actors and number of available investment options, exert a major influence. Finally, whether and how options for carbon-free energy are implemented (backstop and end-of-the-pipe technologies) strongly affects both the mitigation strategy and the abatement costs.

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1. INTRODUCTION

The Innovation Modeling Comparison Project (IMCP) aims to look at the impact of induced technological change (ITC) on the economics of stabilizing carbon dioxide emissions at different levels. The IMCP is motivated by the conviction that endogenous technological change[1] (ETC) is vital in modeling economic dynamics over the lengthy time scales required in climate policy analysis. Despite considerable progress in ETC research, significant discrepancies among models as well as uncertainties of model results still remain. The IMCP advances the understanding of ETC by assessing these discrepancies and analyzing their potential causes. This paper summarizes a quantitative model comparison experiment using a broad range of relevant models.

Two types of uncertainties contribute to the discrepancy of the results from different models. First, there is *parameter uncertainty*, referring to a lack of empirical knowledge to calibrate the parameters of a model to their "true" values. Parameter uncertainty implies an uncertainty of the predictions of any one model and discrepancies may result even in case of otherwise very similar models. Parameter uncertainty is addressed in model specific uncertainty analyses including sensitivity analysis and parameter studies, and modeling teams in the IMCP were encouraged to explore parameter uncertainty in the individual papers collected in this special issue. Second, there is structural uncertainty or *model uncertainty*, defined as the uncertainty arising from having more than one plausible model structure (Morgan and Henrion 1990, p. 67). In this paper, we address model uncertainty.

In general, model uncertainty may be reduced by eliminating possible model structures from the set of plausible models. One way of doing so is validating models against empirical evidence to discriminate "better" models and consequently discard "bad" models. However, even "perfect validation" provides no proof that a model best explains reality. Alternatively, "Ockham's razor" proposes that if another model explains the same empirical phenomena using less specific or more intuitive assumptions and parameters, then it can be deemed preferable. Yet to this date, the theoretical and empirical foundation of technological change within economics remains insufficient to allow for a sound evaluation of models according to Ockham's razor. In other words, the uncertainties about the appropriate model structure remain.

Our approach to model uncertainty involves identifying discrepancies in results of different models running the same scenarios, and investigating their origins. The analysis follows four steps: First, we classify the models according to their structure. Second, we assess discrepancies in a central model output, namely the impact of climate policy on the economy, or the "costs" of climate policy.

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[1] We distinguish between *endogenous* and *induced* technological change: Technological change is *endogenous* (ETC) if its course is an outcome of economic activity within the model. Given an endogenous description, technological change in policy scenarios may exceed (or fall short of) its extent in the baseline, i.e. policies *induce* additional technological change which we refer to as ITC.

Third, we analyze the different model dynamics leading to the discrepancies using aggregated indicators of model behavior and drawing on structural information about the models. We measure the impact of technological change on these quantitative indicators, *ceteris paribus*. Finally, we take a close look at the energy system as a major contributor to possible climate change.

The objective of this comparison is improved understanding of how and whether technological change matters. Technological change is a hotly debated issue because its impact on mitigation costs and mitigation strategies has political consequences. Recently, some models have been developed incorporating endogenous technological change. Examples of the papers which compare these models in a qualitative way are Sijm (2004), Clarke and Weyant (2002), Löschel (2002), Weyant and Olavson (1999), Grubb, Köhler and Anderson (2002), and Köhler et al. (2006), the latter includes an up to date survey of ETC in the literature.

The next section briefly summarizes the literature on modeling comparison; in the third section, the participating models are characterized and a taxonomy of models is provided. Section 4 outlines the method of comparison used in the IMCP. In Section 5, we analyze the impact of ITC on mitigation costs, mitigation strategies, and energy mix. Section 6 offers some conclusions.

2. MODEL COMPARISONS IN THE LITERATURE

There is a broad literature on estimating the economic impact of climate change mitigation policies using models of various types. The Assessment Reports of the Intergovernmental Panel on Climate Change (IPCC) provide a comprehensive overview (IPCC 1996, 2001). Moreover, the Second and Third Assessment Reports (SAR and TAR) draw conclusions from comparative evaluations of these modeling studies. Among the original studies of model comparison, those of the Stanford Energy Modeling Forum (EMF) are particularly worth mentioning. This section briefly summarizes some of the key findings of previous model comparisons.

The SAR differentiates top-down (economic) and bottom-up (engineering) models, further distinguishing *Computable General Equilibrium* models (CGE), *optimizing* models, and econometric *macroeconomic* models among the top-down approaches. Top-down and bottom-up models have been known to differ greatly in their estimates of the costs of mitigation policies. The authors of SAR note that this classification is increasingly misleading as efforts are being made to combine features from macro and CGE models, and to incorporate bottom-up technological features in top-down models. Furthermore, they conclude that different assumptions about the economic reality represented in the models, e.g. about the nature of market barriers, have a far greater impact on the results than the type of the model. In their extended discussion of results from SAR, Hourcade and Robinson (1996) conclude that *"there is no* a-priori *reason that the two modeling approaches will give different results. Whether they* [bottom-up and top-down models] *do or not depends largely on their respective input assumptions"*.

Two Economics Reports of the PEW Center on Global Climate Change summarize the economics of climate change policy and the role of technology (see Weyant 2000, Edmonds et al. 2000). Both studies review why model results differ. Weyant (2000) attributes the differences to variations mainly in the baseline emission scenarios, different flexibilities regarding where, when, and which GHG emissions are reduced, and whether or not benefits from avoided climate change are taken into account. Once the effects of these differences are separated, the residual differences can be traced to substitution and technological change. Edmonds et al. (2000) emphasize Hourcade and Robinson's (1996) finding of the importance of assumptions underlying model design. Concerning the role of technological change, they note that technological change mitigates costs and occurs over long time horizons. They stress that technological change can be induced by policies, and that including induced technological change is important, however difficult.

On discussions about why studies differ, TAR revisits the top-down versus bottom-up controversy. Top-down models are distinguished into CGE and time-series-based econometric models, and TAR points out that the former type is arguably more suitable for describing long-run steady-state behavior, while the latter models are more suitable for forecasting in the short-run. TAR also notes that efforts are being made to eliminate these shortcomings (IPCC 2001, pp. 591).

EMF 19 (2004) set out to understand how models being used for global climate change policy analyses represent current and potential future energy technologies, and technological change. Weyant (2004) summarizes three main insights from the study: developing and implementing new energy technology is necessary for stabilizing atmospheric CO_2 concentration; the required transition will be costly to implement, and implementation will take many decades; but costs may be moderated if it is possible to pursue many options, to phase in new technologies gradually, and if supporting policies start soon.

In an extensive survey of the recent literature, Sijm (2004) focuses on models that exhibit features of endogenous technological change.[2] He separates bottom-up and top-down studies and finds major similarities in the outcomes of models in the former category, e.g. costs decline, the energy mix changes towards fast learners, and total abatement costs decline. Modeling studies in the latter category, however, show a wide diversity in outcomes with regard to the impact of induced technological change. He identifies variations in the following model features as possible explanations: ITC channels; optimization criteria; model functions; calibration; spillovers; and also aggregation; number and type of policy instruments; and the time horizon.

These modeling comparison exercises illuminate and outline reasons why models differ in their cost estimates. Several studies list induced technological change as a good candidate for explaining some of these differences. However, the extent of its impact and the precise reasons as to how and why technological change matters remain unclear in many cases. Focusing on the effects of ITC, all

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[2] For a recent collection of models incorporating ETC, see Vollebergh and Kemfert (2005).

participating modeling teams of the IMCP deliver scenarios in which technological change processes have been ‘switched off’ and ‘switched on’. A comparison between these scenarios allows on the one hand, a quantitative assessment of technological change and on the other hand, a further explanation of the underlying economic mechanisms that explain different model outputs.

3. MODEL CLASSIFICATION

The models considered in this comparative study have two common aspects: they incorporate technological change in innovative ways and allow an assessment of costs of global carbon dioxide mitigation. At the same time, a wide range of model types is represented in this project. Understanding the conceptions underlying the designs of different model types is necessary when comparing models within and across model types. In this section we give a summary of the concepts on which we base our discussion. We start with a general classification, which serves as a guideline for the brief introduction of the models that follows. As the major motivation for the design of many models as well as a key question in this study, we draw focus on the determination of the economic impact of climate policies in terms of social costs, and recapitulate different concepts of costs which are prominent in different model types.

3.1 Model Types in IMCP

In Table 1, we differentiate four models types, mainly characterized by their calculus, i.e. the mathematical paradigm underlying the computation.

1. *Optimal growth models* – maximize social welfare intertemporally.
2. *Energy system models* – minimize costs in the energy sector.
3. *Simulation models* – solve initial value or boundary condition problems (this includes econometric models, i.e. models which base a subset of their relationships on historical time series).
4. *General equilibrium market models* – balance demand and supply among multiple actors.

Many models in this study transcend the outlined categories. Whilst the modeling paradigm that underlies a model is useful for understanding its dynamics, we urge the reader to consult the individual papers for an in-depth discussion of the models.

These papers also include discussions of the model calibration and sensitivity analysis of crucial parameters. Model calibration is important to gauge the parameter uncertainties going into the models, and sensitivity analysis assesses the effect of these uncertainties. Model calibration includes equations of the basic model and the equations specifying how technological change behaves. That is the basic model describing macroeconomic variables (such as gross world product, energy demand, etc.) on the one hand, and how technological change affects the dynamics of these main variables and is affected by them on the other hand. For this analysis,

Table 1. Classification of Models in the IMCP

	Technological detail	
Calculus	*Top Down*	*Bottom Up*
Welfare maximization	Optimal growth models ENTICE-BR FEEM-RICE DEMETER-1CCS AIM/Dynamic-Global MIND 1.1	
Cost minimization		Energy system models MESSAGE-MACRO GET-LFL DNE21+
Initial value problems	Simulation models E3MG	
Static equilibrium + recursive dynamics	Computational general equilibrium models (CGE) IMACLIM-R	

all models are calibrated such that the main variables show similar behavior during the first twenty years of the projected time. Again, we refer the reader to the individual model papers for details.

Model uncertainty, in particular structural differences in the description of ETC is assessed in this report. For the purpose of model comparison, the diversity of assumptions underlying the models (Table 2) becomes an asset to this project as it allows for robust conclusions to be drawn.

3.1.1 Optimal Growth Models

Economic growth is a major driver for GHG emissions. Optimal growth models are aimed at understanding growth dynamics over long term horizons. The key property of neoclassical growth models is their social welfare maximizing behavior. Early growth models determined optimal capital accumulation. Endogenous growth theory extends this framework to include economic forces that explain technological change. Among the growth models represented in this study a varying degree of technological change is endogenous. In AIM/Dynamic-Global, growth accrues from autonomous energy efficiency improvements in addition to capital accumulation (the later is of course present in all models). DEMETER-1CCS, ENTICE-BR and FEEM-RICE use exogenous total factor productivity (Table 2, last column) hence ETC implemented in these models also contributes to economic growth. In MIND, growth is fully endogenous. These models derive a first-best or a second-best social optimum and may be used as intertemporal social cost benefit analysis of mitigation strategies. *First best models* like MIND implicitly assume perfect markets and the implementation of optimal policy tools. In *second best mod-*

Table 2. Endogenous Technological Change (ETC) in the Participating Models

	ETC related to energy intensity	ETC related to carbon intensity	Other ETC	Exogenous TC
AIM/Dynamic-Global	• Factor substitution in CES production • Investments in energy conservation capital raises energy efficiency for coal, oil, gas, and electricity	• Carbon-free energy from backstop technology (nuclear/renewables)		• AEEI for energy from coal, oil, gas, and for electricity
DEMETER-1CCS	• Factor substitution in CES production	• Carbon-free energy from renewables and CCS • Learning-by-Doing for both	• Learning-by-Doing for fossil fuels	• Overall productivity
DNE21+	• Energy savings in end-use sectors modeled using the long-term price elasticity.	• Carbon-free energy from backstop technologies (renewables/nuclear) and CCS • Learning curves for energy technologies (wind, photovoltaic and fuel cell vehicle)		• Technological progress energy technologies (other than wind, photovoltaics, fuel cell vehicle)
E3MG	• Cumulative investments and R&D spending determine energy demand via a technology index	• Learning curves for energy technologies (electricity generation)	• Cumulative investments and R&D spending determine exports via a technology index • Investments beyond baseline levels trigger a Keynesian multiplier effect	
ENTICE-BR	• Factor substitution in Cobb-Douglas production • R&D investments in energy efficiency knowledge stock	• Carbon-free energy from generic backstop technology • R&D investments lower price of energy from backstop technology		• Total factor productivity • Decarbonization accounting for e.g. changing fuel mix

CONTINUED

Table 2. Endogenous Technological Change (ETC) in the Participating Models (continued)

	ETC related to energy intensity	ETC related to carbon intensity	Other ETC	Exogenous TC
FEEM-RICE	• Factor substitution in Cobb-Douglas production • Energy technological change index (ETCI) increases elasticity of substitution • Learning-by-Doing in abatement raises ETCI • R&D investments raise ETCI	• ETCI explicitly decreases carbon intensity (see ETCI in the energy intensity column)		• Total factor productivity • Decarbonization accounting for e.g. changing fuel mix
GET-LFL	• Learning-by-Doing in energy conversion	• Carbon-free energy from backstop technologies (renewables) and CCS • Learning curves for investment costs • Spillovers in technology clusters		
IMACLIM-R	• Cumulative investments drive energy efficiency • Fuel prices drive energy efficiency in transportation and residential sector	• Learning curves for energy technologies (electricity generation)	• Endogenous labor productivity, capital deepening	
MESSAGE-MACRO	• Factor substitution in CES production in MACRO	• Carbon-free energy from backstop technologies (renewables, carbon scrubbing and sequestration) • Learning curves for energy technologies (electricity generation, renewable hydrogen production)		• Declining costs in extraction, production
MIND	• R&D investments improve energy efficiency • Factor substitution in CES production	• Carbon-free energy from backstop technologies (renewables) and CCS • Learning-by-Doing for renewable energy	• R&D investments in labor productivity • Learning-by-Doing in resource extraction	• Technological progress in resource extraction

Note: This table provides an overview of the diverse implementations of ETC in this study. Features of ETC were loosely grouped according to their presumed impact, relating them either to energy intensity reductions or carbon intensity reductions. Naturally, the exact effects of ETC in a complex model cannot be known ex ante with certainty.

els like FEEM-RICE market imperfections or sub-optimal policy tools are not removable or modifiable. Policy of non-reproducible input factors instruments would be necessary. In other words, they may take so called no-regret options into account. In this case, the opportunity costs of climate protection can be lower or sometimes even negative compared to the baseline, dependent on the design of climate policy.

In AIM/Dynamic-Global, ETC concerns energy efficiency (Masui et al. 2006). In addition to autonomous energy efficiency improvements, investments in energy conservation capital raise macroeconomic[3] energy efficiency in the manufacturing sector, i.e. ETC affects the energy efficiency parameters in the production function which increases if the energy conservation capital stock increases faster than the output in the manufacturing sector. AIM/Dynamic-Global divides the world into six regions and describes regions with nine sectors which are mostly energy related.

FEEM-RICE (Bosetti et al. 2006) is modeled after Nordhaus' regionalized integrated assessment model, RICE 99 (Nordhaus and Boyer 2000). It differentiates eight world regions and computes the global solution by solving a non-cooperative Nash game. ETC in FEEM-RICE is represented by an energy technological change index (ETCI) which is increased through R&D investments as well as by learning-by-doing in carbon abatement. Its impact is twofold: ETCI affects the partial substitution coefficients in a Cobb-Douglas production function, shifting income shares from energy to capital. Secondly, ETCI decreases the macroeconomic carbon intensity. FEEM-RICE is presented in two parameterizations, FAST and SLOW, reflecting different assumptions about the speed of technological progress, its effectiveness and the crowding out effects between different types of investments.

ENTICE-BR (Popp 2006) is based on Nordhaus' DICE model (Nordhaus and Boyer 2000), hence it does not resolve regions. Among other modifications, Popp incorporates in his model, an R&D sector with two knowledge stocks. They are built up endogenously by R&D investments, one affecting macroeconomic energy efficiency and the other lowering the price of a generic backstop technology[4]. Energy is produced either by this backstop technology, or from fossil fuels in a corresponding sector. Both ENTICE-BR and FEEM-RICE derive a second-best social optimum by simulating market behavior in an intertemporal optimization framework.

The model MIND (Edenhofer et al. 2006) is an intertemporal optimization model with a macroeconomic sector and four different energy sectors: resource extraction, fossil-fuel based energy generation, a renewable energy source, and carbon-capturing and sequestration (CCS). The growth engine in the macroeconomic sector is fueled by R&D investments in labor productivity and energy efficiency. There is no autonomous total factor productivity improvement. The investments in the different energy sectors are determined according to an intertemporal optimal investment time path. MIND derives a first-best social optimum

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[3] Here, we use the term *macroeconomic* to indicate an effect or process described at the macro level, e.g. described by one parameter for the economy.

[4] Backstop technologies provide carbon-free energy and are not subject to any scarcities.

and therefore calculates the potential of ITC for reducing the costs of climate protection if market failures and social traps at the international level are resolved by appropriate policy measures.

DEMETER-1CCS models a dynamic economic system which is intertemporally optimal for the representative household. The firms solve a per-period dynamic optimization problem, treating learning effects as external to the production decision level (Gerlagh 2006). Moreover, it comprises a composite good sector and different energy sectors for renewable energy sources (playing the role of a backstop-technology) and for fossil fuels. In the energy sector the costs are reduced through learning-by-doing.

3.1.2 Energy System Models

Energy system models usually derive a cost-minimum sequence of energy technologies for an exogenously given energy demand using linear programming. In more advanced versions, the energy technologies are improved by learning-by-doing. The main advantages of this approach are the detailed depiction of the energy sector and the possibility of basing technological change on an engineering assessment of different technologies. Three energy system models are participating: DNE21+, GET-LFL, and MESSAGE-MACRO.

DNE21+ differentiates eight primary energy sources in 77 world regions (Sano et al. 2006). Technological change has an endogenous description for wind power, photovoltaics, and fuel-cell vehicles; exogenous assumptions about technological change are made for other energy technologies. Energy demand in the end-use sectors is modeled using long-term price elasticities; gross world product (GWP) is exogenous to the model.

GET-LFL is a globally aggregated model differentiating eight primary energy sources (Hedenus et al. 2006). It includes a carbon capturing and sequestration (CCS) option which is used with different fossil fuels as well as with biomass. GET-LFL implements cost minimization with limited foresight in a partial equilibrium (energy market), implying an elastic energy demand. ETC in GET-LFL is implemented in learning curves for investment costs of carbon-free technologies as well as energy conversion technologies, and spillovers in technology clusters.

MESSAGE-MACRO. The MESSAGE model describes the entire energy system from resource extraction, through imports and exports, to conversion, transportation and end-use (Rao et al. 2006). Learning-by-doing is implemented for energy technologies. MESSAGE is solved in an iterative process with the economy model MACRO, allowing for some feedbacks between energy system and the macroeconomic environment, such as an impact on GWP.

3.1.3 Simulation and Econometric Models

We use the term simulation model to refer to models that start at a given state of the economy; then continue to calculate the next time step. In mathematical terms, they solve initial value problems or boundary value problems given as systems of differential equations. Econometric simulation models are additionally based on time series data, i.e. the equations are estimated from data.

Econometric models are represented by the Tyndall Centre's E3MG model (Barker et al. 2006). It is based on a post-Keynesian disequilibrium macroeconomic structure with two sets of econometric equations (describing energy demand and export demand) estimated using Engle-Granger cointegration. E3MG differentiates 20 world regions modeled with input-output structures, 41 industrial sectors, 27 consumption categories, twelve fuels, and 19 fuel users.

3.1.4 General Equilibrium Models

General equilibrium models compute demand/supply equilibria in an economy modeled in distinct, interdependent sectors. Implicitly, households and firms within these sectors try independently to optimize their welfare and their profits, respectively. Computable General Equilibrium models (CGE) are prominent examples of this type. CGE models calculate static equilibria at each point in time prescribing some growth dynamic in between time steps, i.e. they are recursive dynamic. This guarantees not only that all markets are cleared but also that a Pareto-optimum is achieved. Sectoral resolution and the dynamics of relative prices are the main strengths of CGE models.

IMACLIM-R is solved recursively but includes an endogenous growth engine that differs from standard CGE approaches (Crassous et al. 2006). The world is disaggregated into five regions, each made up by ten economic sectors. Cumulative investments drive both the energy efficiency and the labor efficiency at the same time. IMACLIM-R represents formation of mobility needs through infrastructures and technical progress in vehicles. Three transportation sectors (air, sea, and terrestrial) are differentiated in which energy efficiency is driven by fuel prices. Additionally, energy technologies in electricity generation improve via learning-by-doing.

3.1.5 A Comment on Model Types

Different modeling frameworks were created for different problems, with each model design tailored to address a specific set of questions. The characteristics of the modeling framework as well as the primary questions that guided its designs must be kept in mind when comparing the model results. Repetto and Austin (1997) note that macro and CGE models complement each other in predicting short-term and long-term responses to a climate policy. Making models to predict century long economic behavior poses a great challenge in modeling frameworks that rely on past data or the present structure of the economy. Growth models using an optimizing framework allow endogenous savings and investment decisions with unlimited foresight while many recursive dynamic CGE models restrict optimizing behavior of its agents to a sequence of static equilibria. Hence, the time path of emissions and investments derived by most CGEs are not intertemporally cost-effective. This lack of optimality is not a shortcoming of these models as they try to replicate the outcome of decentralized markets in which market imperfections are inherent. In contrast to recursive CGE models, an optimal economic growth model allows an understanding of transition paths and an assessment of what decentralized markets could achieve if appropriate policy instruments were applied. On the other hand, most intertemporal economic growth models lack economic detail and offer only limited insights into sectoral dynamics. Energy system models focus on sectoral dynamics providing very detailed predictions. When restricted to the energy sector, they neglect feedbacks with the macroeconomic environment, e.g. the revaluation of capital. The integration of energy system models with macroeconomic models is a topical subject under scrutiny and a feature of several models in this study.

Three models, MIND, MESSAGE-MACRO and E3MG, adopt a hybrid approach, i.e. they combine features from different model designs to address the gap between them. MIND integrates technological detail similar to energy system models in the framework of a growth model. MESSAGE-MACRO adds an economic environment to an energy system model by iterating the models MESSAGE and MACRO. E3MG includes a cost minimizing energy system sector within a Keynesian econometric model.

Finally, we note on the scope of the models. While all models are well calibrated, some models make very specific assumptions to explore special scenarios. Three models in particular are explorative in character. First, IMACLIM-R adopts a pessimistic view of technological change by assuming strong inertia and by neglecting carbon-free energy sources from backstop technologies. Second, AIM/Dynamic-Global focuses on the investment in energy-saving capital as a mitigation option, and largely neglects other options. As a consequence, economic growth cannot be decoupled from emissions. Third, FEEM-RICE is presented in a FAST version where especially optimistic assumptions are made about learning and the level of crowding-out.

4. METHODS OF MODEL COMPARISON

The following section outlines the IMCP approach of quantitative model comparison, specifically which scenarios were run, and which model outputs were reported. The effects of climate policies may be explored by comparing scenarios of climate protection with a business-as-usual scenario (baseline). In accordance with Article 2 of the UNFCCC which postulates stabilizing greenhouse gas concentrations, we investigate climate policy scenarios with the goal of stabilized CO_2 concentration. We focus on carbon dioxide as the most influential GHG, defining three policy scenarios stabilizing CO_2 concentrations at levels of 450ppm, 500ppm, and 550ppm, respectively. Where possible we also report results for a stabilization level of 400ppm. For this stabilization level the probability to meet the 2°C target is substantially increased (Hare and Meinshausen 2004). The 2°C target is perceived by some scientists and influential politicians, CEOs (like Lord Browne) and governmental bodies (like the EU Commission) as an interpretation of Article 2 of the UNFCCC. The concentration levels selected are somewhat arbitrary and serve to explore model responses to increasingly ambitious policies. As we prescribe a policy goal rather than a policy, model results represent a way of conforming to the policy goal and may guide the design of actual climate policy measures.

To assess the model response to climate policies and in particular the role of ITC, scenarios should ideally harmonize all other assumptions and also model calibration in order to isolate the effects of different implementations of ITC. It is known that the business-as-usual scenario has strong impact when evaluating the consequences of climate policies: assuming lower economic growth and therefore lower CO_2 emissions implies that climate protection poses a lesser challenge to the economy. Where models prescribe gross world product (GWP) and/or emissions exogenously, data from the Common POLES/IMAGE baseline (CPI) was used (Vuuren et al. 2003). However, harmonizing economic output and emissions in models which determine these numbers endogenously proves to be difficult if not impossible. Here, modeling teams have made an effort to calibrate their models to the CPI baseline, but there remain differences that must be taken in account when interpreting results.

Carbon dioxide concentration caps could not be imposed in models that do not include a carbon cycle submodel to translate emissions into concentrations. Such models either prescribe CO_2 emission paths corresponding to the selected concentration levels exogenously, or constrain the overall centennial carbon budget. Differences in the implementation of carbon cycle models may imply that the same concentration level requires more stringent emission paths. Care was taken that the carbon cycle models showed good agreement.

4.1 Scenario Definitions With and Without ITC

To assess the impact of ETC model output, stabilization scenarios were run with and without induced technological change. The baseline scenarios in IMCP comprise all components of endogenous technological change potentially incorporated in the considered model. A policy scenario ‘with’ induced technological change refers to a scenario in which additional endogenous technological change is induced by climate policy. In contrast to this, a policy scenario ‘without’ induced technological change means that climate policy cannot induce endogenous technological change beyond the baseline scenario. Therefore, in a policy scenario without ITC, technological change simply follows the time path of the baseline scenario as if it was given exogenously.[5] A comparison between ‘with’ and ‘without’ induced technological change measures the extent to which climate policy induces technological change in addition to baseline ETC. Table 3 summarizes these scenario definitions.

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[5] The time paths of ETC related variables in the baseline simulation are stored and then prescribed as exogenous, fixed time series in this scenario.

Table 3. Summary of IMCP Scenario Definitions

The *baseline* is a business-as-usual scenario. Technological change is determined endogenously.
Policy scenarios with ITC impose a policy goal of CO_2 stabilization at three different levels (450, 500, 550ppm CO_2) or comparable
*Policy scenarios without IT*C impose the same policy goal but restrict technological change to the extent found in the baseline scenario

4.2 Model Output and Indicators

The broad range of models is a key asset of this comparison, naturally comparable model outputs that are available in all models are of an aggregate nature. More specific outputs might allow deeper insights into some models but would exclude others. The selected model outputs (e.g. GWP, emissions, incremental costs of carbon, energy use, and the fuel mix) and the derived indicators (e.g. macroeconomic costs and sector costs, energy- and carbon intensity) reflect this trade off.

Despite the effort to harmonize assumptions and scenarios among models, it remains a challenging task to determine why model results differ, i.e. to disentangle the role of ITC from other assumptions. In addition to the analysis offered in this paper, modelers were asked to elaborate on the calibration of their model and its sensitivities in their paper contributions to this special issue, thus providing a starting point to assess the assumptions underlying the model calibration and their implications.

4.3 Concepts of Mitigation Costs

The SAR distinguishes four types of mitigation costs (IPCC 1996, p. 269). This taxonomy of costs provides a useful guide for the interpretation of results and is therefore recapitulated in the following:

1. *Direct engineering costs of specific technical measures:* These numbers provide some information about the costs of a mitigation measure or a specific technology. The cost estimates are mainly derived from engineering process-based studies of specific technologies. Examples include the costs of switching from coal to gas. In this model comparison, they are presupposed in all models.
2. *Economic costs for a specific sector* are computed in sector-specific models, which allow the integration of a multitude of mitigation measures, often in a partial equilibrium framework. For example, energy system models assess the sectoral costs of the energy sector.[6]
3. *Macroeconomic costs* reflect the impact of a given mitigation strategy on the level of the gross domestic product (GDP) and its components. At this level of analysis, feedbacks between sectors and

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[6] Note that MESSAGE-MACRO goes beyond this by linking with the MACRO model.

the macroeconomic environment are accounted for. Such “general equilibrium effects” can be calculated by models which encompass either the whole economy, or coupled models of specific sectors and macro-economy. Thus, macroeconomic costs include the effects of engineering costs and sector-specific costs.

4. *Welfare costs*: The GDP variations, underlying the assessment of macroeconomic costs, do not provide an adequate measure of human welfare because the ultimate goal of economic activities is not producing GDP but allowing consumption of private and/or public goods and leisure. Mitigation policies, however, may increase investments and thus GDP while at the same time reducing consumption. Therefore, GDP is not a reasonable indicator for human welfare. However, per capita consumption is also a flawed indicator for welfare because human welfare is not always a linear function of per capita consumption. Therefore, most intertemporal optimization models assume in accordance with some empirical evidence that the utility index is an increasing function of per capita consumption, and marginal utility is decreasing with consumption. This implies that costs measured in per capita consumption are exaggerated or underestimated depending on the per capita consumption level. Moreover, the utility index depends also on the distributional issues and non-market traded goods and bads. Economists who rely on welfare theory may argue that the utility index could be modified according to fairness criteria and public goods. Therefore, this index could be used as a reliable indicator for human welfare.

Within IMCP, we analyze the impact of mitigation strategies on the second and third types of costs. Welfare implications along the lines of item 4 are not assessed explicitly because the models participating in IMCP do not share a common measure of welfare.

It seems worthwhile to note that all these cost concepts leave room for interpretation and may fuel a debate about the explanatory power of mitigation cost estimations. When GWP losses and consumption losses per capita are reported in absolute numbers, these are naturally large and may create the impression that mitigation is a costly option. Put into perspective as relative percentage of the net present value of the GWP in the business-as-usual scenario, mitigation may be seen as only postponing economic growth for several months. A simple thought experiment illustrates this point: Assume that GWP growth of 2% per year in the business-as-usual scenario. If mitigation policy lowered growth to 1.97%, GWP losses over the whole century discounted by 5 % would amount to 1%. In consequence, the annual GWP that would have been achieved in 2100 is now reached in 2101 (see Azar and Schneider 2002 for a similar argument). Does this imply that mitigation costs nearly nothing for humankind? One could argue that with these trillions of dollars the lives of millions of poor people could be rescued, e.g. by investing in clean water facilities. On the other hand, damages caused by non-action may destroy the rural habitats of millions of people elsewhere which also rarely count in terms of GWP. There is need for further investigation of the extent to which rapid climate change affects the welfare of people. Whilst acknowledging that different social outcomes can be hidden behind an aggregated number like GWP and the limitations of this approach, some useful insights about the impact of ITC can be drawn using GWP. Clearly, a situation where GWP is increased because of ITC is preferable to a situation where climate policy reduces the opportunities to invest in other desirable global projects.

In the context of IMCP we report GWP losses and consumption losses in terms of relative net present value which means that we measure the net present value losses between the business-as-usual scenario and the policy scenario and relate them to the net present value of GDP in the business-as-usual scenario. This allows a comparison of the cost estimations of different models.

When interpreting mitigation costs, it is necessary to recall that in the IMCP we compare mitigation costs at given stabilization levels. Some models, e.g. ENTICE-BR and FEEM-RICE estimate climate change impacts caused by specific stabilization levels. Therefore, the benefits of avoiding such impacts are reflected in the GWP losses in these models. In the IMCP, we inform the reader only about the mitigation costs of achieving a certain stabilization level irrespective how much damages can be avoided by the predefined stabilization levels. In the cases of ENTICE-BR and FEEM-RICE the mitigation costs are reduced further by the damages caused at the specific stabilization level. Therefore, these GWP losses can be interpreted as net mitigation costs. In the following section we discuss the impact of technological change on these mitigation costs.

5. RESULTS AND DISCUSSION

This section presents the collected data as follows: First we outline and analyze the costs of achieving specific stabilization targets. Second, we analyze the necessary emission reductions in the different models in terms of their effect on carbon intensity, energy intensity, and gross world product. Third, the transformation of the energy system which is a key challenge to meet the climate protection targets is described and evaluated.

5.1 Mitigation Costs within Different Model Types

In this section we refer simultaneously to two different representations of mitigation costs. In both representations – Figure 1 and in Figure 2 – we show the mitigation costs as a loss of gross world product (GWP). Figure 1a shows mitigation costs from different models relative to the respective baseline GWP in the case when technological change is switched on (cf. scenario definitions in Table 3). In Figure 1b the cost estimations are reported when technological change is switched off, Figure

1c indicates the additional mitigation costs for the scenarios without technological change, i.e. the differences between Figure 1a and Figure 1b. Figure 1c shows the potential to induce technological change in the different models: the larger the cost increase when ITC is switched off, the lower the potential of endogenous technological change incorporated in the implementation in that model. If a models incorporated no endogenous technological change, Figure 1c would indicate no additional costs because costs with ITC would be the same as costs without ITC.

In Figure 2 the mitigation costs are shown as a function of the cumulative CO_2 reduction. The plotted data points correspond to the 550, 500 and 450 ppm stabilization scenario. The main purpose of Figure 2 is to relate costs to the mitigation gap which has to be overcome by the different models. In some models the costs are relatively low because of a small mitigation gap and not because of a strong impact of ITC on the costs. In all but two models, mitigation costs are computed as the difference in cumulated GWP (2000 to 2100) between baseline and policy scenarios, discounted at a rate of 5% and relative to (discounted) baseline GWP of the same time span.[7] As there is no endogenous GWP in DNE21+ and GET-LFL, they present instead energy system costs and producer/consumer surplus in the energy sector, respectively.[8]

By plotting the costs at different stabilization levels against the corresponding cumulative CO_2 reductions (also 2000 to 2100), the costs are put into perspective of the mitigation challenge that each model is confronted with in the policy scenarios.

The severity of the challenge is determined by the ‘mitigation gap‘, i.e. the difference between predicted business-as-usual emissions and admissible emissions in the policy scenario. Models tend to agree on the latter, which is a property of the carbon cycle modules in the models, but advocate various predictions of business-as-usual GWP growth and CO_2 emissions. Consequently, so called baseline effects have a strong influence on the results. Figure 2a depicts results from scenarios with ITC; for the scenarios in Figure 2b, ITC was disabled.

With one exception (E3MG), the models agree about the trend of costs: lower concentration targets imply larger costs. Also, costs rise disproportionately with CO_2 reductions.

In Figure 1a and Figure 2a, two models (E3MG and FEEM-RICE-FAST) show negative costs, i.e. gains from implementing climate policies. In the case of E3MG, this originates from the Keynesian treatment of demand-side long-term

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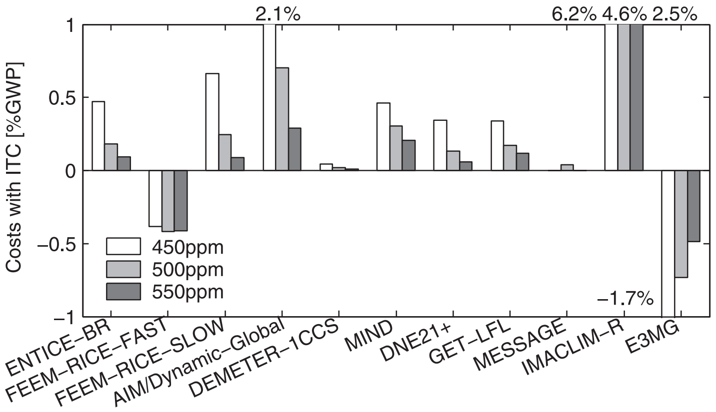
[7] We use a 5% rate to discount GWP reductions from all models to make numbers comparable among models and to other studies in the literature. The rates of pure time preference used in models that anticipate future development vary: ENTICE-BR and FEEM-RICE use a 3% rate initially which declines over the course of the century; AIM/Dynamic-Global applies a 4% discount rate; the rates of pure time preference are 3% and 1% in DEMETER-1CCS and MIND, respectively; the energy system models (DNE21+, GET-LFL, and MESSAGE-MACRO) use a 5% discount rate. There is no (macroeconomic) discounting in E3MG (except in the electricity sector) and IMACLIM-R.

[8] Surplus and energy system costs are converted to the same metric as the GWP losses, i.e. their difference between baseline and policy scenarios is presented relative to the present value of baseline GWP.

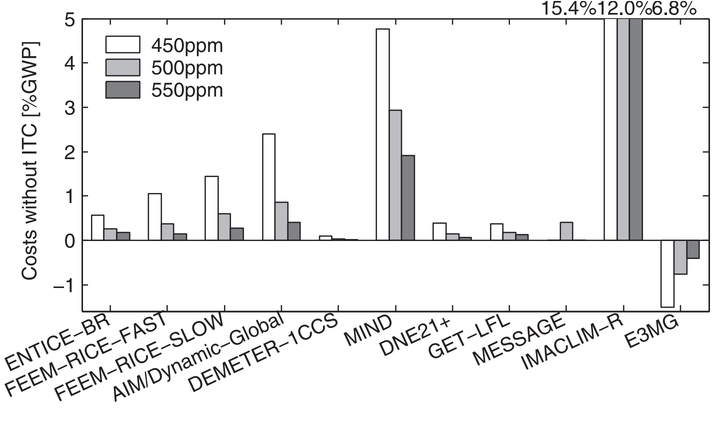
Figure 1. Mitigation Costs

Figure 1a shows loss of gross world product, except for DNE21+, which reports the increase in energy system costs relative to the baseline, and GET-LFL, which reports the difference in producer and consumer surplus. Figure 1b displays the corresponding data from the scenarios without ITC. Figure 1c shows the difference between Figure 1a and Figure 1b.

(a) Mitigation costs with ITC



(b) Mitigation costs without ITC



c) Difference of mitigation costs with ITC and without ITC

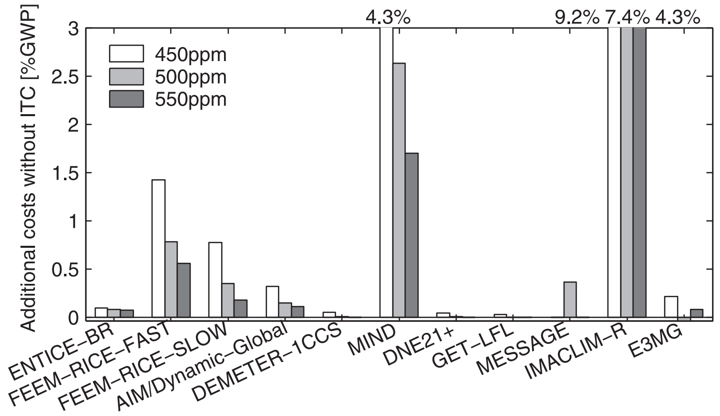
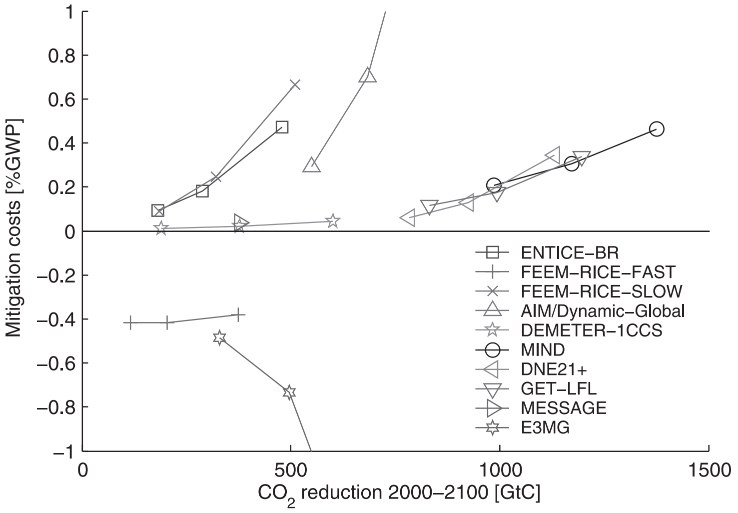


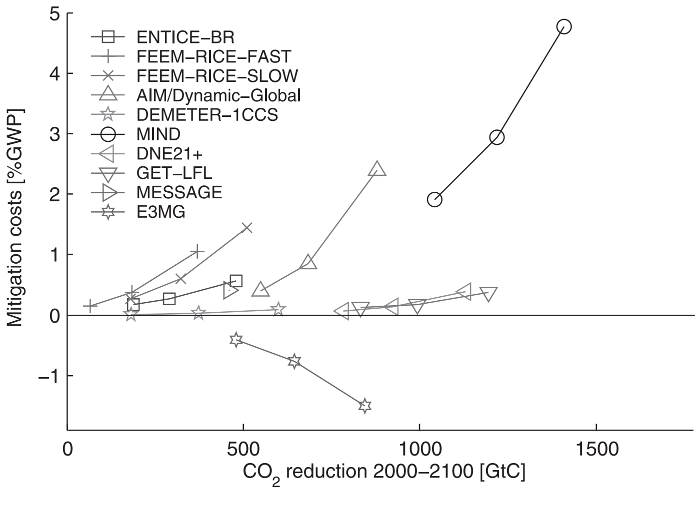
Figure 2. Mitigation Costs as a Function of Cumulative CO_2 Reduction

All models report loss of gross world product except the DNE21+ which reports the increase in energy system costs relative to the baseline, and GET-LFL which reports the difference in producer and consumer surplus. The plotted data points correspond to the 550, 500, and 450ppm stabilization scenarios (with increasing CO_2 reductions). In case of MESSAGE-MACRO, the presented scenario is 500ppm stabilization. Not shown for scaling reasons are GWP losses from IMACLIM-R which range from 2.5-6.2% in scenarios with ITC and 6.8-15.4% in scenarios without ITC.

(a) Mitigation costs with ITC relative to corresponding CO_2 reductions



(b) Mitigation costs without ITC relative to corresponding CO_2 reductions



growth that assume increasing returns to production and under-employment of labor resources in the global economy. In E3MG, policy-driven increases in carbon prices lead to more investment and output. In the case of FEEM-RICE-FAST the negative costs are the consequence of the optimistic assumptions on the effects of R&D investments and of the role that stabilization targets have in inducing more R&D investments. This reduces the inefficiencies in the global R&D market that are calibrated in their second-best baseline scenario.

We now discuss these results in more detail by model design and by individual model. We start with cost estimates of energy system models, which are relatively low, partially due to neglected general equilibrium effects. In a second part we consider the results of general equilibrium market models and simulation models which calculated relatively high mitigation costs because they are focused on price effects and neglect intertemporal investment dynamics. Finally, the optimal growth models within IMCP are discussed.

5.1.1 Energy System Models

Mitigation costs in the energy system models DNE21+, GET-LFL (Figure 1 and Figure 2) differ from those reported by other models in this exercise, which measure the loss of GWP (or welfare). The opportunity costs of climate protection are measured as the increase in energy system costs compared to the baseline in DNE21+, and measured in terms of producer/consumer surplus relative to the baseline in the case of GET-LFL. We emphasize that using alternative metrics in our comparisons is problematic. In fact, while macroeconomic models are less adept to account for the system engineering costs in the energy sector, some system engineering models do not report on the aggregated implications of mitigation for total GWP. Thus, as the energy sector accounts for the partial equilibrium effects, the mitigation costs appear relatively low in Figure 1 and Figure 2. MESSAGE-MACRO adopts a hybrid approach, combining a systems engineering and macroeconomic model, and thus calculates energy system costs as well as GWP losses. However, it remains open to debate whether all intertemporal equilibrium conditions hold in this framework and thus all relevant components of macro-economic mitigation costs are taken into account. For the sake of consistency with the macroeconomic models, Figure 1 and Figure 2 reports loss in terms of % GWP.

The main advantage of energy system models is their higher resolution with respect to technology representation, emphasizing internal plausibility and consistency of structural change in the energy system. They are hence better at accounting for costs related to barriers of technology diffusion and adoption than macroeconomic models, where technology is traditionally represented in a more stylized and generic way. The downside of using purely systems engineering approaches is that the reported energy system costs do not provide a comprehensive account of potential welfare losses outside the energy sector. As discussed above, costs of DNE21+ and GET-LFL presented in Figure 2 are thus relatively small compared to the majority of the macroeconomic models. The costs of mitigation depicted by MESSAGE-MACRO are seen to be relatively low as well, but mainly because of the small CO_2 reductions required to meet the 500-ppm stabilization target.

From a methodological point of view, the three systems engineering frameworks differ in particular with respect to representation of energy demand. In DNE21+ demand is price inelastic, i.e. feedbacks from changes within and outside the energy sector are not considered. GET-LFL takes into account price-elastic energy demand and therefore considers rebound effects in a partial equilibrium of the energy market. In partial equilibrium models, producer and consumer rents may be diminished by climate policy. Therefore, consumer and producer surpluses present a better estimate of the mitigation costs than energy system costs in this model. Both these estimates of energy system costs are relevant measures of the costs imposed by climate policy, because the transformation of the energy system is one of the greatest challenges posed by constraining CO_2 emissions. In MESSAGE-MACRO the price response of energy demand is estimated via its macroeconomic module (MACRO), where the economy is viewed as a Ramsey-Solow model of optimal long-term economic growth. In particular, feedbacks between energy and non-energy sectors are determined by relative prices of the main production factors capital stock, available labor, and energy inputs, subject to optimization.

Figure 1c compares the mitigation costs from Figure 1a (with ITC) and Figure 1b (without ITC). It is apparent from the results of DNE21+ and GET-LFL that ITC effects within the energy system are relatively small compared to those given by macroeconomic models, which account also for GWP changes outside the energy sector. Again, this might not come as a surprise because these energy system models calculate only partial equilibrium effects. Another reason may be that for the DNE21+ model, learning-by-doing to only selected technologies (wind, photovoltaic, and fuel cell vehicle). GET-LFL, however extensively incorporates learning-by-doing. In this case, climate policy does not induce significant progress for two reasons: floor costs for carbon capturing and sequestration and biomass are already nearly realized in the baseline scenario mainly because of spillover effects in technology clusters. Additionally, abundant resources of natural gas help to close the mitigation gap without further resorting to the carbon-free energy technologies which lack learning potential in the scenario without ITC. Results of the latter model in particular illustrates that technological detail is needed to understand possible compensation mechanisms that might limit inducement effects of climate policies in the energy sector.

Figure 1 includes the GWP losses from MESSAGE-MACRO (for the 500ppm scenario only). In the scenario without ITC, mitigation costs are much higher. However, comparability to the results from other models is limited, since MESSAGE-MACRO ran a fixed cost “without ITC” scenario. In other words, the structure of the energy system changes towards today’s best practice technologies (given specific resource and environmental constraints). In contrast, the other models have defined exogenous technological enhancements in the scenarios without ITC. The effect of ITC in these and other macroeconomic models are discussed next.

5.1.2 General Equilibrium Models

CGE models are represented in the IMCP by IMACLIM-R. CGE models have been known to predict high costs and indeed, IMACLIM-R estimates GWP losses for 550, 500, and 450ppm stabilization targets at 2.5, 4.6, and 6.2% (Figure 1). As expected, these numbers are the highest cost estimates in this and there are reasons inherent to the model structure that explain this tendency.

Models like IMACLIM-R calculate a general equilibrium taking into account the relative price effects not only in the energy sectors but in all sectors. This way, climate policy not only induces a transformation of the energy system but also a revaluation of all capital stocks in the energy sectors and in turn in energy demand sectors. It follows that resources within the economy need to be reallocated according to the changed equilibrium. Hence in a general equilibrium model, climate policy has the potential to trigger a greater transformation than that of the energy system alone. Pitted against the need for change throughout the economy are potentially larger – economy wide – flexibilities to react to the restrictions of climate policy. However, recursive dynamic CGE models lack foresight as well as the flexibility of endogenous, sector specific investment decisions.

In particular, the IMACLIM-R model assumes that investments in the composite good sector simultaneously enhance labor productivity and energy productivity, i.e. investments in physical capital exhibit an externality. Additionally, labor productivity is improved by learning-by-doing. Climate policy induces increases and reallocations of investment in the energy sectors including the corresponding learning-by-doing. Due to learning-by-doing energy prices decrease and cause an additional energy demand – a rebound effect. These investments in the energy and transport sectors crowd out investments in the composite good sector and reduce economic growth. The reduction of investments in the composite good sector also lowers the growth rate in labor productivity, which reduces economic growth further. The double dividend of increasing investments becomes a double burden if investments have to shrink. Among other things, the crowding out effect and this double burden increase the opportunity costs of climate protection – an effect which is very pronounced in IMACLIM-R. Moreover, the interplay between inertia in the transport sector, imperfect foresight and non-optimal carbon tax profile induced further welfare losses. These welfare losses can be considerably lowered by efficiency gains and technology diffusion.

Without induced technological change, costs increase further in IMACLIM-R, demonstrating that the implementations of ETC endow the models with additional flexibility (Figure 1c). In IMACLIM-R, mitigation costs for the 550, 500, and 450ppm scenarios climb to 6.8, 12.0, and 15.4%, respectively.

5.1.3 Simulation Models

In E3MG, CO_2 permits and taxes are imposed on the economy in order to achieve the required stabilization targets. In contrast to other long-term studies but consistent with many shorter-term studies (e.g. IPCC 2001, p. 516), climate policy induces GWP gains. This result can be understood in comparison with the second-best solutions of optimizing models. These try to reproduce the market behavior which in general exhibits all sorts of market imperfections – like unemployment, postponed price adjustments, etc. – by relaxing assumptions about perfect market clearing. A crucial feature in E3MG is that although product markets clear, labor and other markets may not clear. Part of the effect of including ITC in the model is to raise growth by more labor transfer from traditional to modern sectors in the world economy.

This effect of taxation in E3MG is due to the fact that investors are limited in their foresight. In a perfect foresight model we would expect that investors adjust their portfolio of investment according to long-term price and taxation expectations.

5.1.4 Optimal Growth Models

Four of the models in the IMCP are implemented in the framework of growth models subject to intertemporal welfare maximization (MIND, ENTICE-BR, AIM/Dynamic-Global, DEMETER-1CCS, and FEEM-RICE, the latter in FAST and SLOW parameterizations). The large differences in CO_2 reductions necessary for stabilization between these models are caused by different baseline projections of GWP and the corresponding emissions. These different projections are a direct result of implementing ETC within these economy models. Whereas optimal growth models without ETC make an assumption about GWP growth, these models make assumptions about ETC which then contribute to overall GWP growth. This makes GWP growth a result of how ETC is modeled rather than an assumption. In most optimal growth models in the IMCP overall technological change is determined by an exogenous total factor productivity in addition to an implementation of ETC. MIND differs in this respect, describing technological change fully endogenously. All models share a common starting point in 2000. However, large differences result over the course of the century.

With the exception of AIM/Dynamic-Global, the cost predictions of the growth models in Figure 2 are low (below 1% GWP up to the 450ppm scenario). We have argued above that general equilibrium effects tend to raise the opportunity costs of climate policy, but these models are endowed with perfect foresight. In conjunction with endogenous investment possibilities this allows models to act flexibly thus avoiding large mitigation costs.

AIM/Dynamic-Global incorporates perfect foresight but studies only a single endogenous mitigation option. Energy efficiency depends on a stock of energy conservation capital. Investment in energy conservation capital improves energy efficiency and is a decision variable of the optimization. AIM/Dynamic-Global also includes carbon-free energy from renewables and nuclear power, but investments in these options cannot be induced by climate policy – only investments in energy conservation are a control variable. This demonstrates the impact of flexibility on mitigation costs and how the exclusion of mitigation options increases the costs substantially.

In contrast, MIND includes investment decisions into capital stocks of energy technologies, including the backstop technology in particular. We attribute the low cost estimates of these models to this flexibility.

ENTICE-BR and FEEM-RICE-SLOW compute slightly higher costs compared to MIND. ENTICE-BR incorporates a backstop technology which improves through R&D investments. However, this effect is overcompensated by the built-in crowding out effects caused by investments in the energy sector. In addition, the backstop technology displays most of its effects in the baseline scenario, independent of stabilization targets. In FEEM-RICE-SLOW costs are low because of the combined effect of learning-by-doing and R&D investments. An increase in R&D investments induced by a stabilization target enhances learning-by-doing as well. This makes R&D investments more profitable by oncreasing benefits from climate change reductions. ENTICE-BR and FEEM-RICE GWP numbers include benefits of climate policy, and that the gross numbers would be slightly higher.

In FEEM-RICE-FAST, there are negative mitigation costs, i.e. gains from mitigating carbon. The FEEM-RICE model is a second-best model in the sense that market imperfections occur in the baseline due to externalities in the R&D investments. Regions invest too little in R&D because of their non-cooperative behavior. If faced with climate policy, they are induced to increase their R&D investments, which get closer to cooperative levels. That is, an improvement of R&D investment is a by-product of climate policy. Therefore, climate policy has a clear net benefit. However, this net benefit changes to net costs if the learning-rate is slow and the crowding out effect between different types of investments is large.

The DEMETER-1CCS model also computes a second-best solution of the world economy accounting for independent actions of firms and households. DEMETER-1CCS's cost estimates are among the lowest in this study, for a number of reasons. In DEMETER-1CCS households are endowed with perfect foresight, hence even though firms show a static profit maximizing behavior, the model is at an advantage in averting mitigation costs. Moreover, the model makes optimistic assumptions about substitution possibilities between fossil fuels and carbon-free energy, and backstop technologies. The latter are assumed to exhibit high learning rates (20% for renewables and 10% in case of CCS), and the share of energy from these sources is not restricted, e.g. there is no sharp increase in costs when the energy supply has to rise as it does in many energy system models. Moreover, CO_2 emissions are low in the baseline scenario, so that complying with policy scenarios poses a smaller challenge than in other models.

If technological change is switched off (Figure 2b), costs increase. The comparison of Figure 1a and Figure 1b in Figure 1c shows that the cost reduction potential of ITC varies between different models: In FEEM-RICE-FAST as well as in FEEM-RICE-SLOW, ITC shows a large potential for reducing the mitigation costs when low stabilization scenarios should be achieved. Both versions of FEEM-RICE show remarkably similar behavior without ITC, in particular, GWP gains in FEEM-RICE-FAST have turned into losses, hence the observed effect can be attributed to "fast" technological change.

In AIM/Dynamic-Global disabling energy conservation investments has some influence on mitigation costs. The option of energy conservation investments is shown to have significant influence, but in comparison with options in other models, this option is less important.

In MIND, mitigation costs increase sharply when ITC is switched off. MIND demonstrates that removing backstop technologies when switching ITC off has a significant impact.[9] In scenarios without ITC, the MIND model exhibits mitigation costs comparable to costs in CGE models.

In ENTICE-BR the net effect of ITC is small because of two effects: first, investments in the energy sector are less productive than investments in the rest of the economy. Therefore, less technological progress is induced in the policy scenario. Second, the exogenously determined total factor productivity further reduces the impact of endogenous technological change on the model output.

5.1.5 Stricter Climate Policy (400ppm Stabilization)

Table 4 shows that a few models achieve a feasible solution when faced with a stabilization target of 400ppm (DEMETER-1CCS, MIND, FEEM-RICE, and GET-LFL). In general, the reason why many models cannot derive a feasible solution can be found in the inflexibility of the energy system to manage the required cumulative emission reductions. The inflexibility comprises phenomena like boundaries for the diffusion of backstop technologies, limited sets of mitigation options or myopic investment behavior.

Table 4. Mitigation Costs for 400ppm Stabilization

	Mitigation costs [%GWP]	
Model Name	**With ITC**	**Without ITC**
DEMETER-1CCS	0.07	0.17
FEEM-RICE-FAST	0.01	3.1
FEEM-RICE-SLOW	2.0	3.7
MIND	0.76	8.9
GET-LFL	0.62	0.67

5.1.6 Robust cost estimate

The IMCP set out not only to learn from the differences in model results, but also to identify robust findings. Is it possible to identify a robust estimate of

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[9] In MIND, the availability of renewable energy sources and carbon capturing and sequestration is considered an option of ETC because its use depends on the costs of carbon, consequently, in the scenarios without ITC, the extent of renewables and CCS is restricted to the baseline. In all other models, the availability of technologies is not considered as "ETC", e.g. in DEMETER-1CCS's scenarios without ITC, renewables and CCS may be used; however there is no learning-by-doing for these technologies in this scenario. Therefore, if endogenous technological change is switched off, MIND can only reduce energy consumption and GWP.

climate protection costs across models in the IMCP?

One might be hesitant to see robustness in the broad range of costs e.g. in the case of 450ppm stabilization, ranging from benefits to costs greater than 6% of aggregate GWP 2000-2100 (at present value). However, the range is reduced considerably when we recognize that three models are of a predominantly exploratory nature, i.e. their intent is not to give a best estimate but to explore an extreme scenario. These are: IMACLIM-R, which explores the role of the transportation sector under the assumption that energy sector and transportation sector are inflexible and externalities of investments in physical capital are biased against energy efficiency; AIM/Dynamic-Global limiting mitigation options to investments in energy conservation capital, hence emissions cannot be decoupled from economic growth in the long-run (these two models arrive at the highest costs in this study); FEEM-RICE-FAST exploring the possibility of "fast" technological change, which then results in benefits of climate protection rather than climate protection costs.

If we furthermore consider E3MG separately, because it is fundamentally different with its Keynesian rather than neoclassical point of view, we are thus left with a set of seven models and cost estimates that range from 0.04% to 0.66% for 450ppm stabilization. Average climate protection costs among these remaining models are 0.39, 0.16, and 0.1%, for 450ppm, 500ppm, and 550ppm stabilization, respectively. Here, the MESSAGE-MACRO model is only included in the 500ppm average because it did not run the other scenarios. If we exclude the two energy system models that do not report costs in terms of GWP, the numbers only slightly change to 0.41, 0.16, and 0.1 percent, for 450ppm, 500ppm, and 550ppm stabilization, respectively. These last numbers average over 4, 5, and 4 models, respectively. Table 5 summarizes these values along with average costs at alternative discount rates, illustrating the influence of the discount rate on the cost estimate.

In view of this and with the considerable uncertainties about model structure and other assumptions in mind, it seems a robust conclusion from the presented energy system models and optimal growth models to expect climate protection costs of up to one percent.

5.2 Mitigation Strategies for Different Stabilization Scenarios

In this section we identify the contributions of different carbon mitigation options towards achieving an overall mitigation target, and we assess the role of technological change in the mitigation effort. Kaya's identity[10] provides a set of indicators that pinpoint the different ways taken by models to meet a given target, namely the attribution of total carbon dioxide emissions to global economic output, energy intensity of GWP, and carbon intensity of the energy:

$$CO_2 = \frac{CO_2}{} \times \frac{PE}{} \times GWP \qquad (1)$$

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[10] Kaya's identity originally also differentiates between income effect (GWP per capita) and a population effect. As an exogenous population scenario is used in this study, we can neglect this factor.

Table 5. Average Discounted Abatement Costs

Concentration level [ppm CO2]	5% [%GWP]	Declining discount rate[a] [%GWP]	2% [%GWP]	1% [%GWP]	undiscounted [%GWP]
450 ppm	0.41	0.64	0.71	0.83	0.95
500 ppm	0.16	0.25	0.28	0.32	0.37
550 ppm	0.10	0.14	0.16	0.18	0.19

a. Declining discounting rates were adopted from the Green Book (HM Treasury 2003) starting at 3.5% for the first 30 years, then dropping to 3.0% until year 75, and 2.0 until year 125.

Table 5 shows abatement costs averaged over central models, i.e. we exclude models with a predominant explorative nature and we restrict the average to GWP losses only ignoring the different metrics from GET-LFL and DNE21+. That is, the above averages include ENTICE-BR. FEEM-RICE-SLOW, DEMETER-1CCS, MIND, and MESSAGE.

$$PE \qquad GWP$$

Here, CO_2 denotes emissions, PE primary energy, and GWP is gross world product. To facilitate interpretation and to help track down the features underlying these aggregate effects in the models, we summarize endogenous and exogenous technological change in the individual models in Table 2 and attribute the features of technological change to their likely effects in terms of either energy intensity or carbon intensity. Of course, the complex nature of the models does not allow a definite classification. Still, these preliminary classifications may serve to structure features of technological change and guide interpretation, for comprehensive model descriptions we refer to the literature references in Section 3.

5.3 Decomposition Analysis

The indicators output, energy intensity and carbon intensity are chosen because they provide information about fundamental differences in the mitigation strategies pursued by the individual models. Yet because of their highly aggregate nature, they abstract from the technological and implementational details in the models, thus allowing quantitative comparison across models.

Reduction of carbon intensity makes it possible to maintain a high level of energy use, putting relatively little stress on the economy as a whole (the climate issue is 'solved' in the energy sector). If this solution is not feasible (this depends largely on availability of carbon-free technologies), energy intensity must be decreased (implying a reduction of energy) to comply with the climate policy. Forcing the economy to use drastically less energy can amount to 'choking' it, i.e. it may lead to a reduction in output (gross world product). The decomposition analysis allows quantification of the contribution of carbon intensity, energy intensity and output reduction to the required effort of emission reduction. For the purpose of this modeling comparison we use the refined Laspeyres index method (Sun 1998, Sun and Ang 2000). We apply the decomposition analysis to the differences of cumulative values between baseline and policy scenario. Figure 3 displays the decomposition of the centennial CO_2 reductions along Kaya's identity for different models.

5.3.1 Mitigation Strategies to Comply with 550ppm Stabilization

The stacked bars in Figure 3 show the CO_2 savings in the 550ppm policy scenario from the baseline cumulated over the century. Additionally, shading indicate how much reductions in carbon intensity, energy intensity, and output (GWP) contribute to these savings.

The necessary carbon dioxide reductions differ widely between models. The cumulative reductions necessary to comply with a 550ppm concentration cap range from ~116GtC to ~987GtC (in FEEM-RICE and MIND, respectively), with correspondingly great differences in the challenge that these reduction pose for an economy.[11] We stress that models tend to agree on the maximum cumulative CO_2 emissions for a given stabilization scenario: averages among models for cumulative CO_2 emissions are 589, 783, and 931 GtC for 450, 500, 550 ppm stabilization scenarios, respectively. The corresponding standard deviations are 72, 77, and 92 GtC. The differences in Figure 3 stem mainly from different CO_2 emission paths in the baseline: cumulative CO_2 emissions in the baseline range from 980 to 2000 GtC, mean 1430, with a standard deviation of 323 GtC. To account for such baseline effects, we will base our analyses on measures that are relative to this 'mitigation effort' as much as possible.

Note that baseline growth and CO_2 emissions seem unrelated to model types. This is not very surprising when growth and emissions are exogenous and therefore arbitrary. In other models, it is possible to calibrate growth and emissions, e.g. in recursive CGE models, by a variation of exogenous model parameters like the total factor productivity. In the optimal growth models, total factor productivity, efficiency of R&D investments, and elasticity of substitution can be adjusted to approximate a given baseline scenario. However, the baseline is not determined by exogenous parameters alone but also by the endogenous features of technological change. This implies that CO_2 emissions of such models cannot be fully harmonized. Nevertheless, there is no reason to assume that models with endogenous technological change exhibit an inherent trend to particularly high or low emission scenarios.

A group of models (IMACLIM-R and AIM/Dynamic-Global) share similar behavior. Here, the larger part of the CO_2 reductions can be attributed to lowered energy intensity and cut-backs in production. They also show the largest cut-backs in production of all models. A possible explanation is that an inability to provide enough carbon-free energy (which would show up as carbon intensity reduction) forces economies to reduce the energy input (evident in the reduced energy intensity) to an extent where it harms the economy (visible as GWP reduc-

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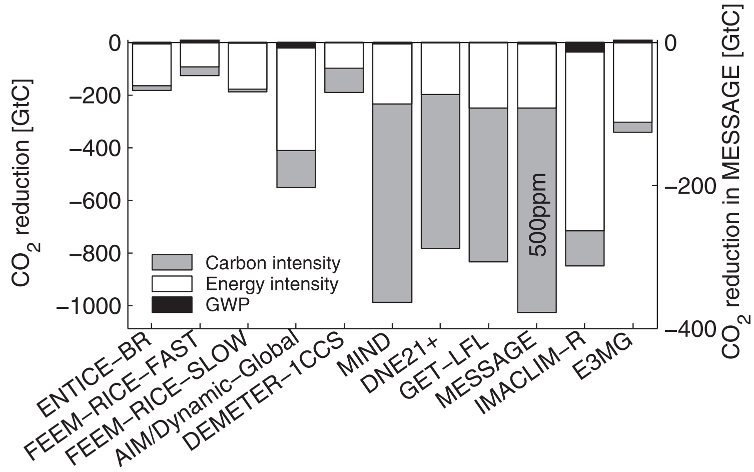
[11] An obvious corollary is that emission reductions are necessary to meet even the 550ppm policy goal despite the presence of ETC in the baseline.

Figure 3. Cumulative CO_2 Reduction for the 550ppm Stabilization Scenario

CO_2 reductions are attributed to reductions in carbon intensity, energy intensity, and gross world product using decomposition analysis. Note that the 550ppm scenarios are not available from MESSAGE-MACRO and we therefore display results from their 500ppm scenario using a separate scale on the second y-axis.



tions). IMACLIM-R resorts to decreasing energy intensity and reducing GWP because it does not incorporate a backstop technology. Here, the increasing energy price reduces energy demand and induces additional investments in the electricity- and transport sectors which crowd out the overall investments in the composite good sector which are needed to induce economic growth. An optimum, cost-effective tax profile would probably lower costs compared to the exogenous linearly increasing tax imposed in these scenarios.

The RICE/DICE models, FEEM-RICE and ENTICE-BR, show strikingly similar behavior but this differs substantially from the remaining growth models. Here, the predominant mitigation strategy is to increase the energy efficiency. FEEM-RICE does allow explicitly for carbon intensity reduction as well as for energy intensity reduction. However, both are driven by the same index of technological change. Hence the ratio of reductions in carbon- and energy intensities is implied by model structure and calibration, and it is not a degree of freedom in the model. Both FAST and SLOW versions of the FEEM-RICE rely more on energy intensity reduction than on carbon intensity reduction. The FAST version shifts the mitigation strategy towards carbon intensity reductions. ENTICE-BR explicitly includes a backstop technology so one might expect a bigger carbon intensity effect. However, carbon-free energy is already strongly represented in the baseline (the share of renewables rises from 4% in 2000 to 11% in 2100). The required CO_2 abatement is therefore small and can be met by energy efficiency improvements via R&D investment in a corresponding knowledge stock and factor substitution.

DEMETER-1CCS behaves differently. Here, energy intensity reductions and carbon intensity reductions make equally large contributions, while production cut-backs are kept at a minimum. A low emissions baseline and optimistic assumptions about substitution possibilities and carbon-free energy sources play a key part in this and were discussed in detail in the preceding section.

In energy system models, the mitigation strategy relies heavily on carbon intensity reduction, i.e. CO_2 emissions are mitigated largely by switching to low carbon energy sources. Indeed, all these models include options to build up a backstop technology providing carbon-free energy, and in each case learning curves are implemented for some backstop technologies. At the same time, a significant share of the CO_2 reductions is attributed to reductions in energy intensity implying some sort of energy conservation. In DNE21+, energy demand is exogenously given. However, energy savings in end-use sectors in climate policy scenarios are modeled using long-term price elasticities. GET-LFL implements learning-by-doing in energy conversion technologies as well as a price dependent energy demand in a partial equilibrium. In MESSAGE-MACRO runs, energy demand is determined in the MACRO economy model, which allows energy to be substituted by other factors.

Remembering that MIND includes a reduced form energy sector that borrows from bottom-up energy system models, the similar ratios of carbon and energy intensity in MIND and in the energy system models is no surprise. Rather, it indicates that energy system dynamics are successfully approximated by the reduced form model. Furthermore, MIND consistently describes the macroeconomic environment taking into account general equilibrium effects. Hybrid models like MIND therefore constitute an attempt to bridge the gap between top-down and bottom-up models in order to assess the importance of the investment dynamics.

In E3MG most of the necessary reductions are attributed to reduced energy intensity. There are three routes by which carbon intensity and energy intensity are affected: First, an increasing price of carbon induces a reduction in energy demand, and second, a switch to carbon-free technologies within the power and transport sectors. Finally, the share of fossil fuels in the overall energy mix is slightly decreased because the elasticity of substitution in the energy and transport sector is very low.

5.3.2 Effects of Enhanced Climate Policies

Figure 4 indicates the change of the portfolio of mitigation options, if instead of 550ppm CO_2 concentration, the more ambitious level of 450ppm has to be achieved. How and in which way do the mitigation strategies change when a more demanding climate protection goal is pursued? Bars in Figure 4 give the change of the mitigation portfolio in terms of the contributions to overall CO_2 reduction in Figure 3. They are symmetrical because an increased share of one option is always balanced by a corresponding decrease in one or more other options. For example, a 20% increase of the carbon intensity effect accompanied by the corresponding 20% decrease of the energy intensity effect in the case of DEMETER-1CCS implies that the contribution of carbon intensity rises from 50% to 70% whereas the contribution of energy intensity drops to 30%.

Figure 4. Change of the Mitigation Strategy with More Ambitious Climate Policy

The bars in this figure give the absolute differences between the percentages describing the contributions of the options in the 550ppm and the 450ppm scenarios. There is no result for MESSAGE-MACRO because only the 500ppm scenario was available.

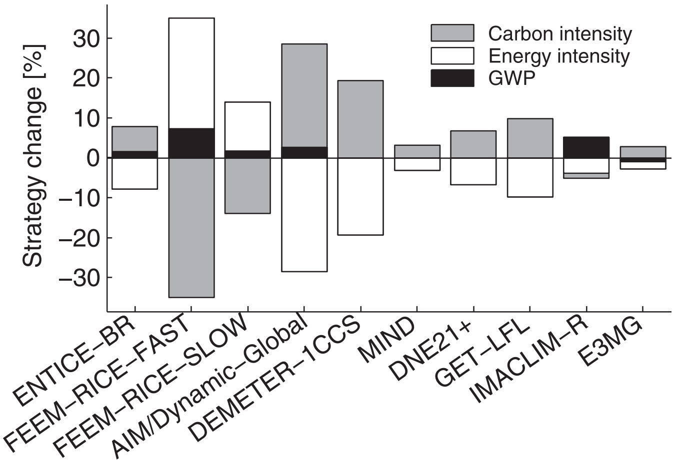


Figure 4 shows that lowering the stabilization level has different impacts on the portfolio of mitigation options in the models. Whilst several models show little change (e.g. MIND and E3MG), others show substantial changes. Large changes may indicate that favorable mitigation options which contribute to CO_2 abatement in laxer policy scenarios have been exhausted hence other options are increasingly deployed for more stringent climate policies. Small changes suggest that the greater challenge is addressed much the same way as the lesser challenge.

In DEMETER-1CCS, the contribution of carbon intensity reduction increases by nearly 20% to a share of 70%. In other words, carbon free energy from renewables and CCS now contribute to mitigation to a similar extent as they do in energy system models. The reason lies in the fact that the 550ppm scenario in DEMETER-1CCS is relatively close to the baseline, and a large share of the necessary emission reductions can be accomplished by energy savings. In contrast, the 450ppm concentration target requires a much more substantial departure from the baseline, and the option of factor substitution decreases in relative importance.

In many models (ENTICE-BR, AIM/Dynamic-Global, DEMETER-1CCS, MIND, DNE21+, GET-LFL, E3MG) we observe a similar pattern of change in the portfolio: to achieve 450ppm stabilization, a mitigation strategy is chosen that incorporates a larger share of carbon intensity reduction than in case of the 550ppm stabilization. In all of these cases, a carbon-free technology is implemented, and this change can be attributed to a heavier use of carbon-free energy in the energy mix. Exceptions to this pattern are FEEM-RICE and IMACLIM-R. FEEM-RICE and IMACLIM-R have in common, the feature that they do not model a carbon-free energy technology. This seems to limit their potential to reduce carbon intensity compared to models with a backstop technology. The difference is particularly striking when FEEM-RICE is compared to ENTICE-BR. The two models share the general model structure of Nordhaus' DICE/RICE models, yet only the latter incorporates a backstop technology with the consequence that it becomes possible to increase the contribution of the carbon intensity effect.

In IMACLIM-R, most of the additional CO_2 reductions are accomplished by reducing GWP. The limited potential of carbon- and energy intensity reduction is largely exhausted at the 550ppm stabilization concentration. The reduction potentials are limited due to capital inertia preventing the retirement of old capital. As before in the 550ppm scenario, a rebound effect in the transportation sector and crowding out of growth inducing investments in composite goods determine the GWP losses.

5.3.3 Mitigation Strategies With and Without ITC

Figure 5 shows how the portfolio of mitigation options changes when features of endogenous technological change are disabled, i.e. technological change is restricted to the extent computed in the baseline. The bars give the change in portfolio (cf. Figure 4). Large changes indicate that including the possibility for ITC has a big impact on the mitigation strategy.

MIND, FEEM-RICE, and IMACLIM-R show relatively large changes. In MIND, the modelers' understanding of ITC plays an important part (see Footnote 9).[12] When the common definition of ITC is applied, changes in MIND are closest to the changes in DEMETER-1CCS, i.e. there are much smaller changes. Four models show little change (AIM/Dynamic-Global, DNE21+, GET-LFL, and ENTICE-BR) because model behavior with and without ITC is very similar.

In Figure 5, ENTICE-BR, FEEM-RICE, DEMETER-1CCS, and MIND share the same sign for the change in the contribution of carbon intensity reduction. In these models, the carbon intensity effect decreases implying that the *induced* technological change works more towards decarbonization rather than reducing energy intensity. Naturally, this mirrors the fact that these models implement features of endogenous technological change that are related to decarbonization, e.g. learning curves for backstop technologies. Two qualifications apply: MIND also includes endogenous energy efficiency reduction. In this case, Figure 5 shows that induced carbon intensity reductions outweigh induced energy intensity reductions. Secondly, in FEEM-RICE-SLOW the contribution of carbon intensity decreases from an 11% contribution to -23% contribution. Here, the average global carbon intensity is *higher* in the policy scenario without ITC than in the baseline because under climate policy, a larger share of global energy use is al-

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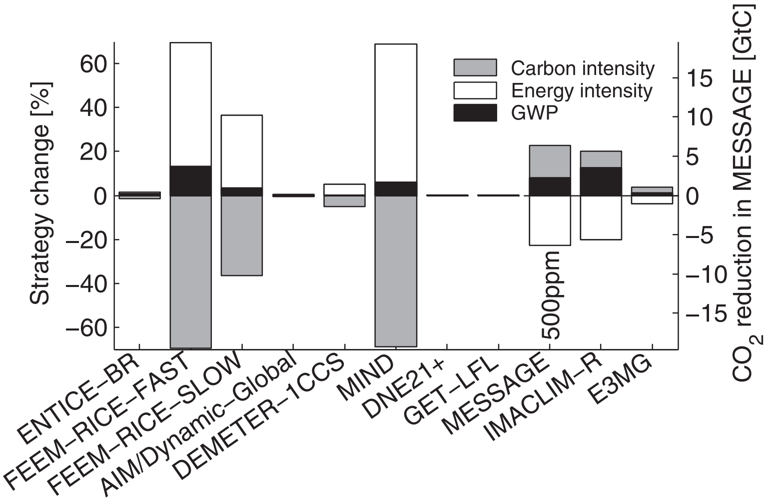
[12] A small carbon intensity effect remains, because the fixed amount of renewables represents a greater share of the (reduced) total energy in the policy scenario without ITC than in the baseline, which implies reduced carbon intensity for the energy mix.

Figure 5. Change in Mitigation Strategies when ITC is Disabled in the 550ppm Scenario

The bars in this figure give the absolute differences between the percentages describing the contributions of the options in the scenarios with ITC and without ITC. For message-macro, the 500ppm scenario is used instead.



located to countries with relatively high carbon intensity (U.S., Europe, and other high income countries), thus raising the global average relative to the baseline.

Conversely, in E3MG, MESSAGE-MACRO, and IMACLIM-R, the climate policy induces a larger contribution of energy intensity reduction, though for differing reasons. In IMACLIM-R, stabilization levels without technological change can only be achieved with a substantial reduction of GWP because of the sunk costs in the energy system, the constant rate of exogenous technical change and the absence of sequestration options. The carbon tax induces no additional change in the pace of technological change. The economy only adapts to the imposed carbon tax through a changed energy mix (see the increasing carbon intensity in Figure 5 if technological change is switched off). Therefore GWP has to be reduced in order to compensate decreasing energy intensity.

In E3MG the key feature of the model underpinning the ITC results is that GWP growth has been made endogenous, with technological change having a major influence (via export equations). However, endogenous technological change only has a small decarbonization effect on the global economy. Energy demand and supply is very small in relation to the rest of the economy, around 3-4% of value added, and technological change is led by improvements in the use of machinery and information technology and communications. These improvements allow long-term growth to proceed by decreasing energy-intensity if technological change is switched on. The growth itself ultimately comes from the demand by consumers for goods and services, promoted by technological and marketing innovations.

Disabling ITC possibilities increases the contribution of GWP reduction to mitigation in all cases. This comes as no surprise: Removing the flexibility of inducing further technological change from the model makes it more difficult for the models to reduce CO_2 emissions without cutbacks in production.

5.4 Timing of Mitigation Options

Figure 6 depicts the timing of the mitigation options (adopted from Gerlagh 2006). We show the reduced carbon intensity in the 450ppm policy scenario relative to the baseline versus the reduced energy intensity as a time trajectory, from 2000 until 2100 with bullets set every 20 years. A trajectory where both options contributed to the same extent would run along the bisector. Steeper or gentler slopes indicate a preference for carbon intensity reduction or energy intensity reduction, respectively.

Interestingly, in a majority of models, the trajectory bends to the left with time indicating that carbon intensity reduction becomes increasingly more important. A plausible explanation is the widespread use of carbon-free technologies that need to be built up gradually by investments, and often become increasingly more productive through learning-by-doing. The trajectory of IMACLIM-R illustrates well, how lack of a backstop technology prevents this change in the mitigation strategy: the model sticks to its mainly energy saving strategy over time. FEEM-RICE-SLOW shows similar behavior: the reduction of energy intensity dominates the reduction of carbon intensity (i.e. the slope of the trajectory is less than unity) because of a missing backstop technology.

Similar to the other models, FEEM-RICE initially increases the reduction of both energy intensity and carbon intensity. While FEEM-RICE-SLOW retains this mitigation strategy, FEEM-RICE-FAST decreases reductions of carbon intensity. As mentioned before, carbon intensity and the elasticity of substitution are driven by the same endogenous index of technological change in FEEM-RICE, and the relation of carbon intensity and energy intensity is therefore determined by model structure.

In GET-LFL energy demand is reduced by an increasing energy price, which in latter periods is compensated by a stronger reduction of carbon intensity.

5.5 Energy Mix

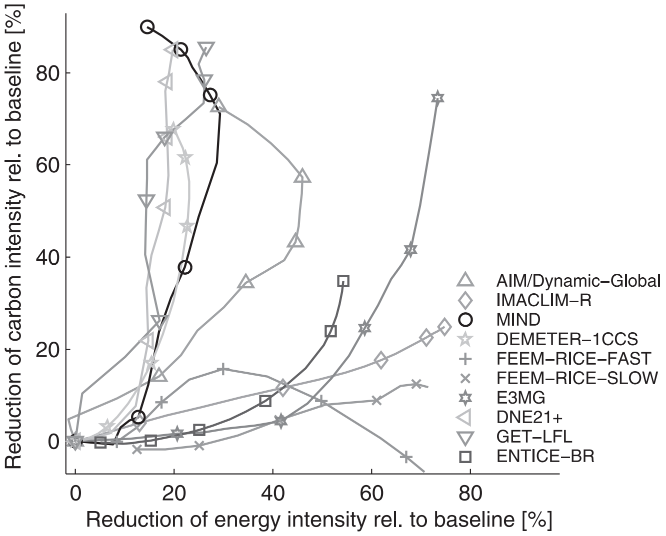
In the previous section, we showed that the dynamics in the energy sector, e.g. the development of a carbon-free technology, have a key impact on carbon abatement. In this section we take a close look at the projected development of the energy system and the role of ITC.

Figure 7 shows the development of the energy system characterized by the mix of energy sources at the beginning (2000), middle (2050) and end of the century (2100). Five energy sources are distinguished, namely three fossil energy sources (coal, gas, and oil) plus renewable energy sources, and nuclear fission. If additional energy sources were implemented in a model which could not be subsumed in these categories, or if a model does not differentiate between

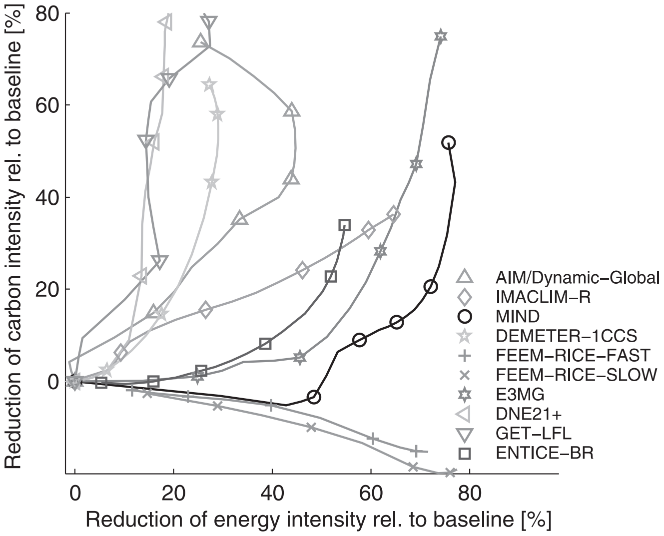
Figure 6. Trajectories in Energy Intensity/Carbon Intensity Space

Trajectories start at the origin and bullets are set 20 years apart. Figure 6a shows the 450ppm scenario with ITC, Figure 6b the same scenario without ITC.

(a) Strategy trajectory with ITC



(b) Strategy trajectory without ITC



the categories, the data is presented in the categories of "aggregate fossil" and "aggregate non-fossil" energy sources. Results are reported in three columns per model giving the baseline energy mix, the 450ppm policy scenario with ITC, and the 450ppm scenario without ITC.[13] In 2000, the three cases coincide. The models FEEM-RICE and ENTICE-BR are not shown as these models do not compute energy in Joules but incorporate "carbon services" to productions measured in carbon instead. In the case of MESSAGE-MACRO, results from the 500ppm scenarios are displayed instead of the unavailable 450ppm scenarios.

5.5.1 Different Formulations of the Backstop

We have seen that implementing a backstop technology can make a great difference in how models respond to climate policy goals. In accordance with the literature, we define a backstop technology as a carbon-free technology whose usage is not restricted by scarcity of non-reproducible production factors. What makes backstop technologies so important in carbon abatement?

In Figure 8, we sketch model behavior given two different assumptions about backstop technology. The price of energy from a fossil resource is indicated in black, and an exogenously set price for energy from the backstop technology is indicated in light gray. In contrast, the price of energy from a backstop technology is plotted in dark gray for an endogenously determined backstop price. Solid time paths indicate business as usual, and slashed curves are induced by a policy goal. We assume that imposing a policy goal brings down the price of energy from the backstop technology because larger investments in carbon-free energy sources need to be made and therefore more learning occurs. The price of energy from fossil resources rises due to the costs of the corresponding emissions, e.g. through carbon taxes or emission permits.

Under climate policy, the price of non-backstop-technologies (like exhaustible resources) is rising sharply and intersecting the exogenous backstop price, at which point the latter becomes economical and is used to an extent that keeps the energy price at this same level (intersection 1).

For the backstop technology that is explicitly modeled, i.e. capacity is being build up, and its price changes according to a learning curve, the backstop technology is competitive much earlier and at a lower price (intersection 2). The price of carbon-free energy declines from the beginning, indicating that investments are being made in anticipation of the later competitiveness. Intersection 3 illustrates that this may even be the case in the absence of a policy goal.

From these illustrations we conclude that the cost-decreasing potential of backstop technologies is strengthened when lowering prices endogenously is an option in the model, furthermore, if economic agents possess the foresight and the possibilities to make early investments in order to use this option.

There are models in IMCP without a backstop technology (IMACLIM-R and FEEM-RICE). As we have seen, these models mainly reduce energy intensity

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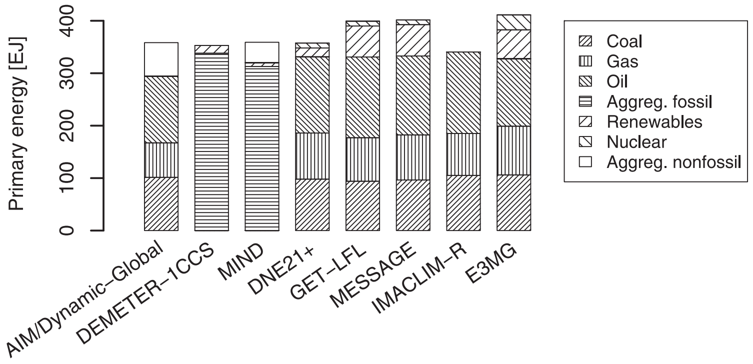
[13] Alternatively, the laxer scenarios could have been used to arrive at much the same conclusions. We decided on the most stringent case because here the observed effects are more pronounced. The alternative figures were omitted due to limited space.

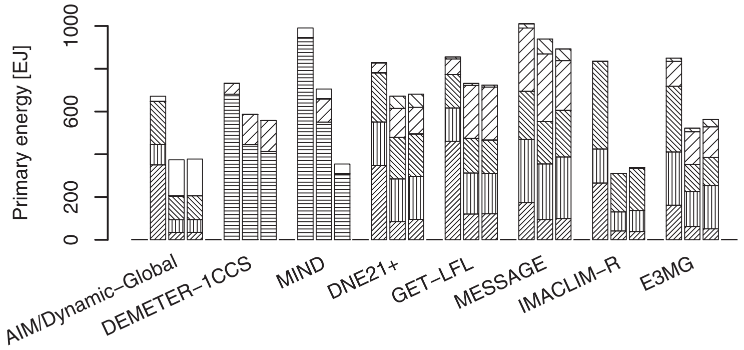
Figure 7. Energy System Represented by the Contributions of Different Energy Sources to the Overall Primary Energy Consumption

In 2050 and 2100, the three bars per model display the energy mix in the baseline scenario, 450ppm policy scenario, and 450ppm policy scenario without ITC. In 2000, these three cases coincide. We use darker shading for energy from fossil fuels and lighter shading for carbon free energy sources. Data from the 500ppm scenario is shown in case of MESSAGE-MACRO. Also in case of this model, the third bar represents a fixed costs scenario and not the usual scenario "without ITC."

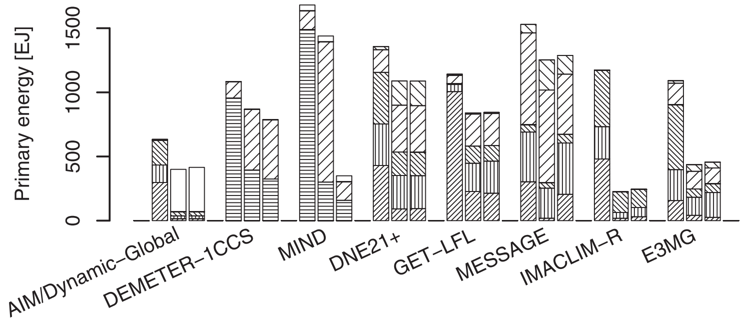
(a) Energy mix in 2000



(b) Energy mix in 2050



(c) Energy mix in 2100



to achieve climate protection goals.

Those models that incorporate carbon-free energy from backstop technologies (i.e. rather than prescribing an exogenous price, the backstop technology is endogenous to these model) are of the second type discussed above (ENTICE-BR, AIM/Dynamic-Global, DEMETER-1CCS, MIND, GET-LFL, DNE21+, MESSAGE-MACRO, and E3MG).

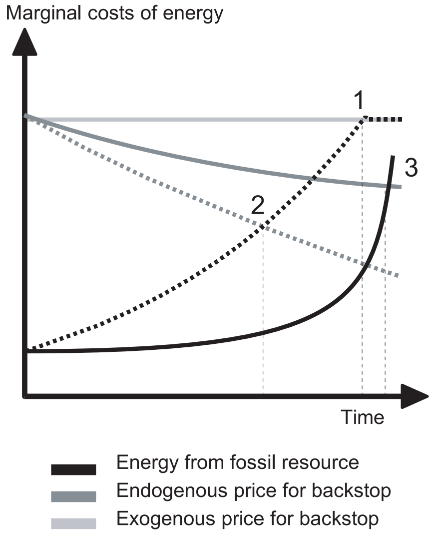
It is also interesting that especially in GET-LFL the investments in the backstop technology are undertaken long before the break-even-point is achieved. The reason is that intertemporal optimum decision-making anticipates the temporal spillover effects (learning-by-doing or accumulation of knowledge through R&D). The model GET-LFL is only a limited foresight model. Nevertheless, this feature implies that temporal spill-overs are partially internalized. In GET-LFL the impact of the backstop technology on the overall energy mix is very modest because in both cases the backstop technology has gained a substantial proportion of the energy mix in the business-as-usual scenario (Figure 7). In GET-LFL enough cost reduction potential has already been realized in the business-as-usual scenario. Moreover, the GET-LFL model assumes a high share of gas in the fossil fuel mix, so that a modest reduction in the energy demand makes it possible to achieve climate protection goals even without much ITC.

In DEMETER-1CCS, ITC has only a moderate impact on the energy mix for two reasons: First, the business-as-usual scenario already assumes some learning as the backstop technology is introduced as a technological option in 2025. Hence the cost reduction potential in the policy scenario is limited. Second, the business-as-usual scenario also assumes a decreasing fossil fuels price path, thus the marginal effect of learning-by-doing is limited and the break-even point is changed little.

Figure 8 also helps to understand the role of technological change in the resource extraction sector. Similar to technological change in the case with backstop technology, it could reduce the growth rate of the price of energy from fossil fuels by making more fossil resources available at lower costs. If learning-by-doing was assumed, the effect would be more pronounced in the baseline than in the policy scenario, which would widen the gap between the resource price with and without policy goal. Cost reductions of fossil fuels due to technological progress decreases the competitiveness of the backstop technology and therefore increases the opportunity costs of climate protection. Note, that sensitivity analysis in MIND supports this qualitative insight – technological progress in the extraction sector is one of the most sensitive parameters in determining the opportunity costs of climate protection (Edenhofer et. al. 2006). Thus, it would be interesting to see other model types including realistic representation of endogenous technological change in resource extraction and its effects on resource availability into their estimates of climate protection costs.

Another aspect is illustrated by Figure 7: as discussed above, some models will rather cut back on energy use relative to business-as-usual than provide carbon-free (or low carbon) energy. This is evident in Figure 7 when overall energy consumption in the policy scenarios is much lower than in the baseline; ex-

Figure 8. Different Formulations of Backstop and Resource Scarcity



amples are IMACLIM-R, and E3MG. Other models manage to make almost as much energy available as in the baseline by changing to low carbon or carbon-free energy sources, e.g. MIND, DEMETER-1CCS and the energy system models. This echoes the findings from the previous section, and is in fact one of the underlying factors influencing whether a model implements a mitigation strategy of carbon intensity reduction or energy intensity reduction.

5.5.2 Shadow Prices, Carbon Taxes and Path Dependency

The price of carbon plays a different role in different models (Figure 9 and Figure 10). First best models of the economy (e.g. MIND) make the implicit assumption that all market imperfections may be cured. Hence, the result of welfare maximization in these models is a Pareto-efficient solution without any further restrictions. In these models, the shadow price of carbon represents the social costs of carbon. Second best models, e.g. general equilibrium models, simulate market behavior, i.e. the model incorporates distortions that cannot be removed by policy instruments for institutional or political reasons. The carbon tax in DEMETER-1CCS represents a second-best optimum in the sense that it is imposed on the economy in order to guarantee the achievement of the stabilization level and a minimum of welfare losses subject to the market distortions that cannot be removed by policy instruments because of institutional or political inertia.

In the other models in Figure 9 (IMACLIM-R and E3MG) the imposed tax does not represent a second best optimum because the carbon tax only allows the achievement of a stabilization level irrespective of its welfare implications. The carbon tax profiles in IMACLIM-R and E3MG are prescribed exogenously, i.e. they are non-optimum.

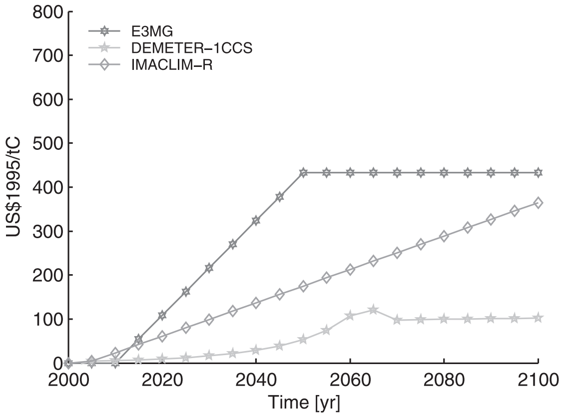
In the class of optimal growth models, the carbon price is a dual variable and represents the social costs of carbon (Figure 10). Moreover, the time path of carbon follows an optimum path which could be interpreted as an ideal market for carbon permits or as an imposed optimal carbon tax. In energy system models the carbon price is also a dual variable in an optimization framework. However, the carbon price does not necessarily represent the total social costs of carbon because of the omitted feedback loops between the energy sector and the macro-economic environment in that partial-equilibrium framework.

The carbon price also reflects the effect of ITC in some models. In nearly all models the carbon price is higher in the scenarios without technological change. However, in MIND the carbon price behaves differently: it increases exponentially

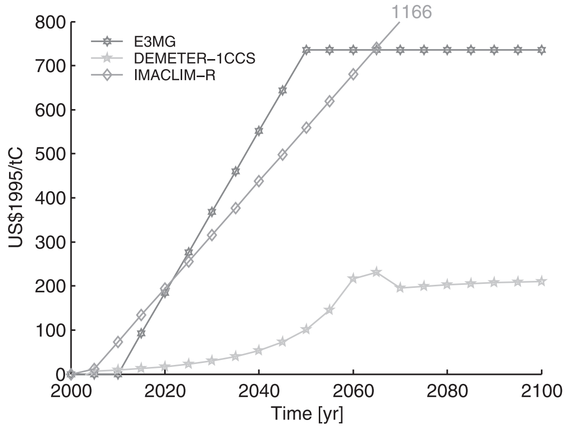
Figure 9. Carbon Tax

Figure 9 a shows the 450ppm CO2 stabilization scenario with ITC, Figure 9b shows the corresponding scenario without ITC. Values greater than $800 per ton of C were cut off; the corresponding maximum value is given.

(a) Carbon tax with ITC



(b) Carbon tax without ITC



in the case without ITC but it peaks and decreases if ITC is switched on.

There is an interesting pattern in carbon price development in some models: towards the end of the century, the shadow price reaches a maximum and begins to decline. This is true for all scenarios with ITC in MIND and in the 450ppm scenario for DEMETER-1CCS. If the price of the backstop technology decreases over time, even without an increasing shadow price of emissions (and fossil fuel price), the backstop technology remains competitive with fossil fuels. In contrast to a model with an exogenous price of the backstop technology, learning-by-doing of the backstop technology creates a path dependency because its price is determined endogenously by investments in learning-by-doing. There is no longer an incentive for investors to promote fossil fuels after the energy system is transformed because the price of the backstop technology also declines with the transformation of the energy system. The shadow price in most energy system models increases throughout the century indicating that the transformation of the energy system is not completed before 2100. This may be in part because renewables or nuclear power (as backstop technologies) are not able to substitute fossil fuels until the end of the century, due to bounds on market share for renewables, moderate price increases for fossil fuels that remain too low to trigger a transformation, and relatively optimistic assumptions about CCS. The remaining share of fossil fuels will turn carbon into a scarce factor in production with a positive price.

Path dependencies occur if the transformation to a carbon-free energy system is irreversible in that the carbon-free technologies become the least cost set of options.

5.5.3 The Specific Role of Carbon Capturing and Sequestration

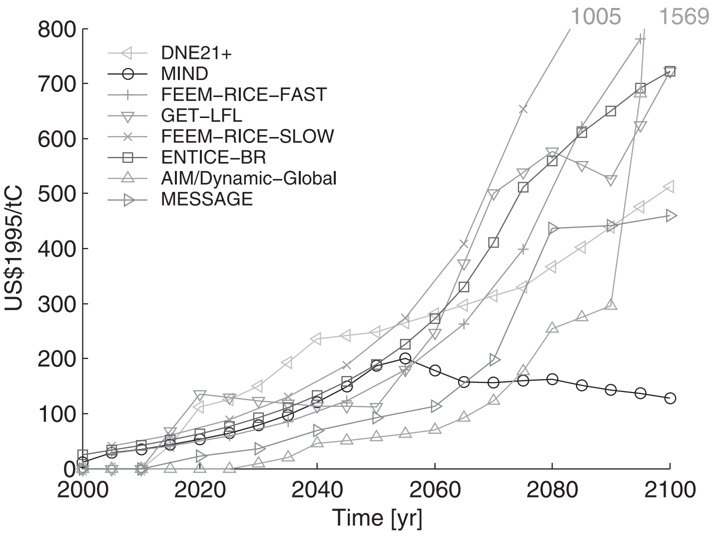
Among the participating models, five explicitly incorporate the option of capturing and storing CO_2 emissions from combustion (DEMETER-1CCS, MIND, DNE21+, GET-LFL, and MESSAGE-MACRO). Figure 11 shows how much CO_2 is captured in different scenarios, accumulated over the century. Figure 12 gives the corresponding time paths of carbon capturing and sequestration (CCS) for one exemplary scenario (500ppm CO_2 stabilization).

As one would expect, Figure 11 shows that the more challenging the climate policy target, the more CO_2 is captured and stored. There is no CCS in the baseline, as capture and storage of CO_2 is costly and hence only becomes economical in the presence of climate policy. DNE21+ is an exception, because the model includes an option to use CCS in the context of enhanced oil recovery which makes CCS economical in its own right. The contribution to overall abatement (the difference of cumulative emissions between baseline and policy scenarios) is substantial, in particular in MIND, DNE21+, and GET-LFL. However, nowhere is CCS the dominant mitigation option but rather, it is always predicted to be one among many (we conclude this from the fact that captured CO_2 is only a small proportion of the difference of emissions in baseline and policy scenario).

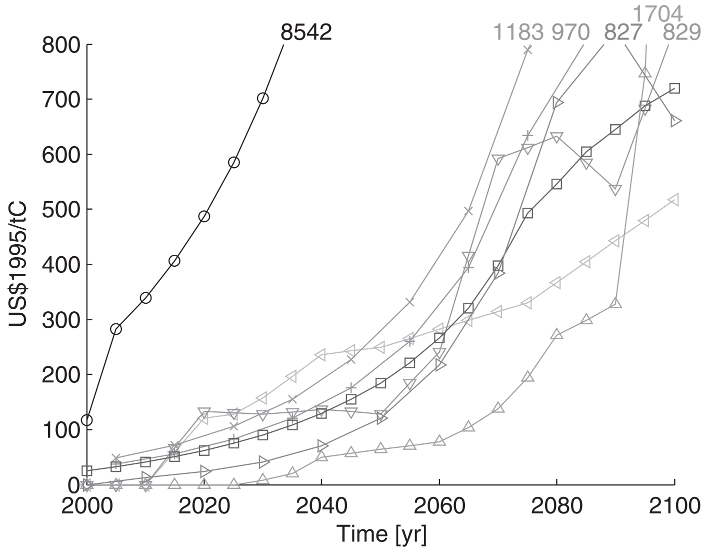
Figure 10. Shadow Price of Carbon

Figure 10a shows the 450ppm scenario with ITC, Figure 10b shows the corresponding scenario without ITC. In case of MESSAGE-MACRO, the figures show numbers from the 500ppm scenario instead of the 450ppm scenario. Values greater than $800 per ton of C were cut off; the corresponding maximum value is given.

(a) Shadow price with ITC



(b) Shadow price without ITC



As mentioned before, the models show agreement on the allowable carbon budget in the policy scenarios, yet they predict divergent cumulative emissions in the baseline. This affects the predicted extent of CCS. DEMETER-1CCS and MESSAGE-MACRO, on the one hand show fairly low baseline emissions and in turn low predictions for CCS. On the other hand the remaining three models are faced with a greater need to reduce emissions and resort to a stronger usage of the CCS option. Both groups, DEMETER-1CCS and MESSAGE-MACRO as well as MIND, DNE21+ and GET-LFL show good agreement in their predicted utilization of the CCS option.

Figure 12 shows the development of CCS over the course of the century. The five models show diverse behavior. In two of the linear-programming energy system models (DNE21+ and GET-LFL) the capacity of CCS increases almost linearly with time and is still rising at the end of the century. This suggests that the rapidity of increasing this capacity is restricted, but no (anticipated) constraints to the volume of CCS are effective yet. GET-LFL includes CCS in combination with energy production from biomass. Thus in GET-LFL CCS is indeed not constrained by fossil fuel scarcity.

In contrast, CCS in DEMETER-1CCS levels off towards the end of the century. Here, CCS activity has reached at least a temporary equilibrium. Possibly the low emission profiles in the baseline allow these models to reach a CCS capacity that is both sustainable and sufficient for the policy target.

MIND and MESSAGE-MACRO show yet another type of behavior. In MIND, capacities for CCS are built up even faster than in the energy system models, but after a peak around mid-century the usage of CCS declines. Similarly, in MESSAGE-MACRO CCS peaks in 2080 and declines. Both models respect the scarcity

Figure 11. Captured CO_2 and Total CO_2 Emissions

The figure summarizes usage of the CCS option in the baseline and two policy scenarios as a share of total amount of CO_2. CO_2 that is not captured is emitted.

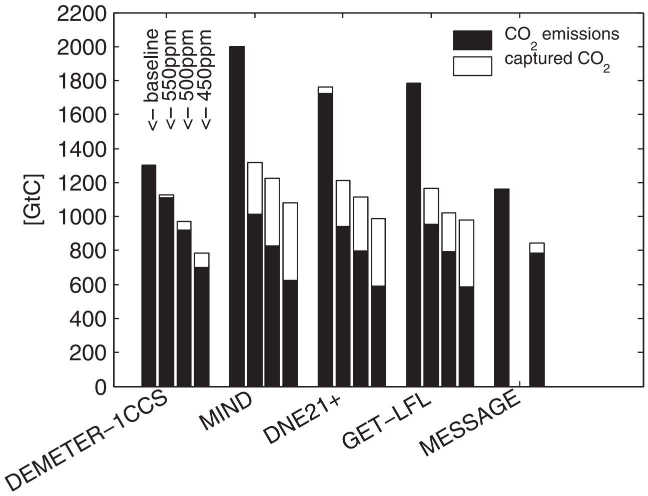
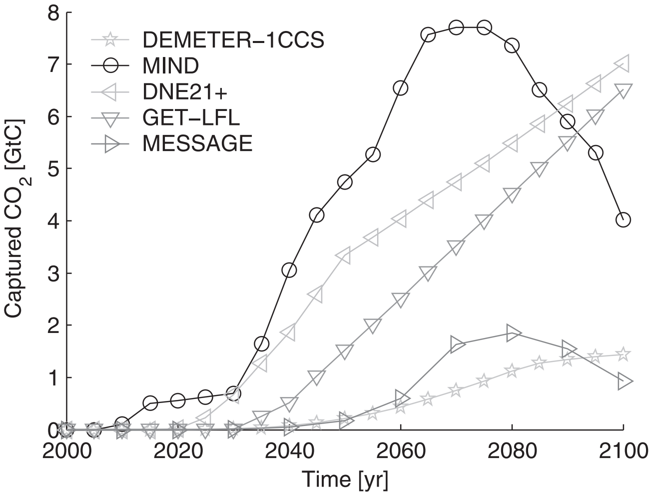


Figure 12. Carbon Capture and Sequestration Over the Course of the Century



of fossil fuel resources increasing costs on the utilization of CCS in the long-run. While CCS is at a competitive advantage over renewable energy technologies due to cheap fossil fuels early on in MIND and MESSAGE-MACRO, this advantage is lost as renewables become more economical due to learning-by-doing.

Two more features contribute to the temporary nature of CCS in MIND: readily available storage sites are subject to scarcity[14], and MIND includes leakage from storage sites at a fixed rate (i.e. the same percentage leaks from the storage site in each time period), implying that CCS does not prevent but only strongly delays emissions into the atmosphere. The leakage rate is highly uncertain, but it plays an important part in determining whether CCS constitutes a temporary rather than a permanent solution. It would therefore be instructive to see whether other models confirmed this result from MIND (Bauer et al. 2005), when leakage is included.

Carbon capturing and sequestration (CCS) is different from backstop technologies because it is dependent on non-reproducible inputs, e.g. fossil resources[15]. Furthermore its extent is limited by the availability of storage sites. If all relevant intertemporal social costs are taken into account, CCS is only a temporary solution until the backstop technology becomes competitive. CCS is an end-of-pipe technology allowing in the best case a welfare improving postponement of the diffusion of the backstop technology. In a theoretical analysis,

[14] In MIND, the assumption is that with the rising utilization of CCS, increasingly long pipelines are needed to transport CO_2 to the storage site. In general, spatial aggregation within the models and limited knowledge about the location of suitable storage sites add to the uncertainties in modeling CCS.

[15] GET-LFL also includes CCS in combination with energy production from biomass.

Edenhofer et al. (2005b) show that temporary welfare gains from CCS increase when (a) the discount rate is increased, (b) the energy penalty is decreased, (c) the operation and maintenance costs (O&M) are reduced, (c) the leakage rate of deposits are lowered, (d) the capacity of deposits is increased and (e) the costs of the fossil fuels are decreased. Gains are also higher when the price of the backstop technology is high and/or when its learning rate is low.

The CGE model within IMCP has not incorporated CCS so far. In general, CGE models could inform about the market potential of CCS under different policy scenarios. However, CGE models allowing only for a recursive dynamic are not appropriate for deriving realistic market behavior because they implicitly assume purely myopic investment behavior which is arguably an exaggerated or extreme behavior.

6. CONCLUSION

This model comparison aims to draw robust results on ETC by identifying both the differences between and the underlying mechanisms of the multitude of participating models. We find that the participating models describe a wide range of possible futures, with and without climate policy. Although there is no consensus on the potential role of induced technological change, we identify crucial economic mechanisms that drive ITC. This modeling comparison exercise demonstrates a large influence of the following determinants:

1. Baseline effects
2. First-best or second-best assumptions
3. Model structure
4. Long-term investment decisions
5. Backstop and end-of-the-pipe technologies

6.1 Baseline Effects

All models in the IMCP incorporate endogenous technological change in their baseline, sometimes in addition to exogenous technological change. In effect, baseline emissions are difficult to harmonize and vary widely. Both endogenous and exogenous components contribute to this mitigation gap. In some models optimistic assumptions about exogenous parameters result in relatively low costs which are then due not to induced technological change, but mainly to exogenous assumptions. In addition, if the baseline scenario already includes many positive effects of technological change related to energy and carbon savings, then the introduction of stabilization targets does not induce much addtional technological change. Consequently, the cost difference between scenarios with and without ITC is small.

6.2 First Best or Second Best Assumptions

It has important consequences whether a *first best or a second best* world is modeled: First best models implicitly assume perfect markets and the implementation of optimum policy tools. In other words, first best models preclude so called no-regret options. Therefore, they are inherently more pessimistic about the costs of climate protection because climate protection reallocates scarce resources which are utilized in an optimum way in the baseline to climate friendly investments. In contrast, second best models assume that climate policy can positively affect market imperfections as a side effect. Compared to first best models the opportunity costs of climate protection in second best models can be lower and even negative, depending on the design of policy.

6.3 Model Structure

Previous model comparison exercises have shown that CGE models tend to calculate higher mitigation costs than energy system models or economic growth models (Löschel 2002); we find that this result still holds. However, the underlying reason is not necessarily the model type, but rather in assumptions commonly made by “CGE modelers”, “energy system modelers”, and “economic growth modelers”, e.g. about foresight and intertemporal behavior of the agents.

It turns out that energy system models calculate low mitigation costs because they only assess the impact of mitigation strategies on energy system costs. Yet partial equilibrium analysis explicitly omits general equilibrium effects - partial equilibrium models by definition exclude feedback loops between the energy sector and other sectors of the economy. In particular, energy system models implicitly assume that investments within the energy sector can be funded by the economy at a constant rate of interest. However, this assumption is not justified when an ambitious climate policy is imposed in the system. This would depreciate capital stocks in various sectors and therefore also change the return on investment in the energy sector. Consequently, the changed return on investment induces a reallocation of investments across sectors. This investment dynamic is a major determinant of macroeconomic costs of climate policy which is neglected in partial equilibrium analyses. Moreover, most energy system models neglect rebound effects and the crowding-out implications of investments. The impact of these general equilibrium effects emerge to be significant.

In contrast, CGE models demonstrate the quantitative impact of general equilibrium effects. However, recursive CGE models reduce the flexibility of long-term investment behavior remarkably. By assumption, investment shares for different sectors are fixed even if an ambitious stabilization level is imposed on the economy. Some CGE models include a backstop technology, however, its costs are independent of the timing of investments. Mitigation costs are overestimated because of the underlying assumptions that investors are myopic.

The econometric model in IMCP describe a second best world. Imperfections on the labor market and design of the carbon tax allow substantial welfare improvements from climate policy. The policy implication is clear. Policy makers can claim that climate policy is a free lunch. However, it should be emphasized that second best do not claim that climate policy is the only way or the best way to cure market failure. If better solutions exist, then climate policy is no longer a free lunch but has positive opportunity costs. It seems promising to calculate these opportunity costs based on the strength of both frameworks.

Optimal growth models allow greater flexibility. Some of the optimal growth models are already designed as multi-sectoral and intertemporal optimization models comprising a reduced form energy sector. These models demonstrate the effect of full temporal and sectoral flexibility. In contrast to energy system models they do not assume that the differences of the return on investments across sectors can be ignored. It turns out that an appropriate timing of investments has the potential to reduce the mitigation costs substantially. In particular, the optimum timing of backstop technologies (like renewables) and end-of-pipe technologies (like CCS) has a great potential for cost reduction.

6.4 Long-term Decision Making: Foresight and Flexibilities

Assumptions about *long-term investment decisions* exert a major influence: The number and flexibility of mitigation options has been shown to have an impact on mitigation costs (Edenhofer et al. 2005a). This observation is confirmed in this study.

Perfect foresight enables investors to anticipate necessary long-term changes and to control investment decisions accordingly, including possible externalities such as learning-by-doing. The multi-sector optimal growth models in this study demonstrate the potential of perfect foresight to reduce mitigation costs. Models allowing for flexible and long-term investment decisions achieve an equilibrium that can be characterized by low emissions and low macroeconomic costs. Naturally, assuming perfect foresight is normative rather than descriptive, i.e. its model results are motivation for policies rather than an exploration of its effects.

The assumption of intertemporal optimization may exaggerate the potential of ITC to reduce mitigation costs because the rationality and foresight of investors and entrepreneurs implicit in their intertemporal optimization behavior represents an optimistic assumption. The assumption of great foresight of the actors in such models becomes more realistic when a macroeconomic policy ensures credible expectations. Currently, the number of uncertainties for investors is large, including uncertainty about emission targets, well-designed international tradable permit schemes, subsidies for R&D investments, well-behaved capital markets allowing for long-term investments, and competition and globalization on the energy market. A stable macro-economic environment and clear long-term emission targets are crucial for the transformation of the energy system. Therefore, a focus for post-Kyoto discussions beyond 2012 should be the design of policy instruments allowing for long-term investments.

6.5 Backstop and End-of-the-pipe Technologies

Finally, the results depend on the design of *backstop and end-of-pipe technologies*: Whether and how a carbon-free energy source is implemented has an essential impact on mitigation costs as well as on the mix of mitigation options.

If a model allows for endogenous long-term investments in backstop technologies and/or end-of-pipe technologies, then mitigation costs are substantially reduced and the stabilization targets can be met without drastic declines in energy consumption. Moreover, available carbon-free energy sources shift the abatement strategy towards decarbonization rather than energy saving.

Nearly all models conclude that more ambitious climate protection goals increase the costs. It should be noted that this is not a trivial statement because due to learning-by-doing, mitigation costs could be decreased if less ambitious stabilization targets are imposed. However, modeling teams in IMCP assume that learning-by-doing has its clear limits because of floor costs, barriers of diffusion and other market imperfections like insufficient internalization of intertemporal or interregional spillovers.

Over the past decade the debate has been focused mainly on the learning-by-doing potential of backstop technologies. However, this study shows that this is only one aspect. Another key factor determining the competitiveness of the backstop is technological progress in the fossil fuel sector. Assumptions about the fossil fuel sector and its potential for technological change are crucial for determining costs and strategies. Therefore, further modeling efforts should also focus on a more realistic representation of technological progress within the fossil fuel sector.

Moreover, all models indicate carbon costs that rise with time in the early years, and most maintain this across the century. However, some models which incorporate backstop technologies and carbon capturing and sequestration show a "hump" in the time path of carbon permit prices, i.e. carbon costs peak and decline afterwards. This supports what some technical change analysts have supposed: experience from learning-by-doing or the reality of sunk costs introduce a path dependency scenario development, and thus the marginal costs of maintaining low emission levels decrease in the long term due to cumulative learning effects and the usage of a broad range of mitigation options like improvement of energy efficiency, the diffusion of backstop technologies and the temporary use of end-of-pipe technologies.

6.6 Hints for a Future Research Agenda

This modeling comparison exercise takes a first step in assessing the quantitative impacts of ITC on mitigation costs and mitigation strategies. We assess the impact of ITC is isolated by imposing ceteris paribus conditions, i.e. ITC is induced by climate stabilization targets in a setting where boundary conditions and parameters remain unchanged.

Beyond the IMCP, we recommend research expansion two ways. First, future model comparisons could refine the harmonization of the participating models to a baseline of central variables (capital stock, investments, direction of technological change) and parameters in order to minimize baseline effects. Second, more sophisticated ceteris paribus scenarios could be run, e.g. exploring the impact of single ITC options rather than enabling and disabling all ITC as it was done here.

Not all important aspects of ITC could be addressed in this study. They should be explored in future model comparisons, e.g. regional spillovers. Moreover, while this study restricted policy intervention to imposing stabilization levels (i.e. represents only the targets approach to policy), the effects of different policy instruments are neglected. An exercise comparing policy instruments across different model types could accelerate research on optimal climate policy design.

IMCP allows to set out a formulation of an agenda to improve modeling design. First, we have explored some reasons for the gaps between top-down and bottom-up models and discussed several models that begin to bridge this gap. These hybrid models seem a promising starting point from which to develop a coherent framework incorporating intertemporal, intersectoral and interregional effects of induced technological change. Second, as it has turned out in the IMCP, assumptions about long-term investment behavior have a strong impact on mitigation costs and strategies. Therefore, experiments with different assumptions about long-term expectations and long-term flexibility of investment behavior would be highly valuable. Third, the way carbon-free energy is made available has turned out to have a major influence on the response of the model to climate policy goals and therefore deserves attention. This is explored by many models implementing backstop- and/or end-of-the-pipe technologies. We argue that endogenous technological change in the extraction sector of fossil fuel is a complementary prerequisite for a comprehensive understanding of ITC. Many modeling teams within IMCP have incorporated learning-by-doing of the backstop technology. In contrast to this, endogenous technological change in the exploration and extraction sector of fossil fuels has not received as much attention. There is significant technological change (e.g. in the resource extraction sector) with a potentially strong influence on the opportunity costs of climate protection. A better understanding of the underlying dynamics may therefore both satisfy scientific curiosity and also provide a prerequisite for improving the design of climate policy.

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Chapter 4

The Effects of Tariffs on Coalition Formation in a Dynamic Global Warming Game[*]

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The Effects of Tariffs on Coalition Formation in a Dynamic Global Warming Game

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Abstract

The prospects for cooperation on climate protection beyond 2012 are currently uncertain. Thus policy instruments which foster participation in International Environmental Agreements (IEA) are in demand. Among the instruments under discussion are trade sanctions. Multi-region optimal growth models are a state of the art tool for integrated assessment, but introducing trade sanctions distorts the competitive equilibrium, making it difficult to compute numerically. We introduce trade and trade sanctions into a model of coalition stability to assess the potential of trade sanctions to support an IEA. Trade is modeled by having all countries produce a generic output good, but adopting national product differentiation (Armington assumption). Coalitions are free to impose tariffs on imports from non-cooperating countries. We solve the model numerically using a refined version of Negishi´s (1960) basic algorithm. We then apply the model to analyze the influence of tariffs on international cooperation. The model suggests that there is indeed significant potential to raise participation through trade sanctions, even when goods from different countries are nearly perfect substitutes. Furthermore we investigate the effect of trade sanctions on global welfare, environmental effectiveness, and the credibility of the tariff mechanism.

JEL classification: C61; C72; H41; Q54; Q58

Keywords: Climate change; Self-enforcing international environmental agreements; Trade sanctions; Coalition stability; International cooperation

1 Introduction and Motivation

Combining elements of the economic, the energy and the climate system, Integrated Assessment Models (IAMs) have become an indispensable formal tool in the realm of climate policy analysis. There are numerous examples, ranging from Nordhaus' (1994) seminal DICE model to the latest generation of regionalized models featuring high levels of sectoral and technological detail.[1]

A prominent class within the IAM family consists of optimal growth models; these

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[1] See, for example, Kypreos and Bahn (2003), Barker et al. (2006), Crassous et al. (2006), Bosetti et al. (2006).

build on a tradition going back to Ramsey (1928), and view accumulation and economic growth as driven by agents' intertemporally optimized investment decisions. Examples include the RICE/DICE family of models (Nordhaus, 1994, Nordhaus and Yang, 1996), and its modifications such as FEEM-RICE (Bosetti et al., 2004) or ENTICE (Popp, 2004), as well as the MIND (Edenhofer et al., 2005) and DEMETER (Gerlagh, 2006) models.

Two main aspects justify the use of intertemporal optimization in the context of climate policy: First, Edenhofer et al. (2006) argue that this framework is appropriate whenever the research question requires an economic model to be run over long time horizons and to capture structural changes. Indeed, inertia in the climate system requires to adopt time horizons of more than a century. Second, Turnovsky (1997, pp. 3), arguing from a more theoretical point of view, backs the intertemporal utility maximization of a representative agent as the preferred way to give macroeconomic models a firm micro-foundation and make them suitable for welfare analysis. Although critics point to the fact that assumptions such as perfect foresight and strict rationality are actually at odds with reality, results from such models retain their usefulness (at least) in terms of a first-best benchmark.

To come closer to the political reality of a world consisting of self-interested and sovereign nation states, optimal growth models, just like other IAMs, have over time passed from a uni-regional world[2] representation to a decentralized multi-regional[3] formulation. Unfortunately, even the sole introduction of emissions trade comes at the cost of a substantial aggravation of the numerics required to compute competitive equilibria. The calculation of trade flows and price vectors would in principle be straightforward with Negishi's (1960) algorithm. But in the presence of an externality like the climate feedback, an appropriate modification of the algorithm is required.[4] The additional effort is, of course, justified by the need to estimate the regional distribution of climate damages and mitigation costs, as well as by the new possibility to compute scenarios in which only a group of nations—a ‘climate coalition’—decides to cooperate on climate change.

In our work we follow the multi-regional modeling approach and formally extend it in two ways: first, international trade in goods is introduced by dropping the common assumption[5] that all countries produce the same perfectly substitutable good; instead we assume that goods are differentiated according to their place of origin.[6] This approach—sometimes referred to as Armington assumption—is often encountered[7] in CGE modeling and allows to reproduce international cost spillovers from mitigation policies.[8]

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[2] E.g. DICE (Nordhaus, 1994) and MIND (Edenhofer et al., 2005).

[3] E.g. RICE (Nordhaus and Yang, 1996) and WITCH (Bosetti et al., 2006).

[4] Implementing trade in these models is challenging (Nordhaus and Yang, 1996; Eyckmans and Tulkens, 2003). Nordhaus and Yang (1996) mention that “a major cause of the long gestation period of this research has been the difficulty in finding a satisfactory algorithm for solving the intertemporal general equilibrium.”

[5] E.g. in the RICE (Nordhaus and Yang, 1996) and WITCH (Bosetti et al., 2006) models.

[6] This model of international trade is discussed, e.g., in Feenstra et al. (2001).

[7] E.g. Bernstein et al. (1999), Kemfert (2002).

[8] In models without trade, one country’s carbon constraint bears no economic consequences for other countries. This seems contradictory when thinking of shifts in competitive advantage and specialization (‘carbon leakage’), as well as of the negative consequences for some countries if fossil fuel de-

Second, we introduce another feature that is incompatible with the basic Negishi approach, namely a tax distortion in form of a punitive tariff duty.

The first part of the paper emphasizes the formal aspects of solving such a model structure for a competitive equilibrium. We describe our solution approach that draws on work by Kehoe et al. (1992) and Leimbach and Edenhofer (2007), and illustrate how a validation of the competitive equilibrium is obtained.

To demonstrate the usefulness of the model set-up, an application to a current issue in climate policy is presented in the second part of the paper. Namely, we analyze the scope for regional cooperation—that is the viability of a 'climate coalition'—and investigate whether tariffs can help to increase participation in such a coalition.

This question seems timely in view of the currently meager prospects for full international cooperation after the expiry of the Kyoto Protocol in 2012. Indeed, a lively debate has emerged on the scope for regional cooperation, and various supportive policy instruments have been brought up in the literature, such as R&D protocols (Barrett, 2003, Carraro et al., 2002), a technology fund (Benedick, 2001), a Marshall Plan (Schelling, 2002), and, last but not least, trade sanctions (e.g. Aldy, Orszag and Stiglitz, 2001).

The use of trade restricting tariff duties has been proposed in the form of energy or CO_2 border tax adjustments, with the double objective to deter free-riding and to ease the loss of competitiveness for coalition members. The debate has so far focused on the question of whether tariffs are feasible under legal (Biermann and Brohm, 2005) and implementation (Ismer and Neuhoff, 2007) aspects. However, another question is whether their employment would be credible, given that orthodox economic theory suggests that the distortionary effects of tariffs would be welfare depressing for all parties.

More specifically, Stiglitz (2006) proposes to raise participation in a climate treaty by imposing trade sanctions against non-signatories. He argues that this is possible and even required in the legal framework of the World Trade Organization (WTO): products from countries that allow unconstrained emissions are implicitly subsidized which warrants to prohibit or tariff the import of such products. Perez (2005) gives a detailed analysis of the legal implications of such a proposal concluding that recent precedents (the so-called "shrimp decision") suggest that the WTO will not interfere with such tariffs. Similar to these trade sanctions, Nordhaus (1998) proposes border tax adjustments to enforce compliance with harmonized carbon taxes.

The effects of trade sanctions on coalition formation have also been analyzed within formal models (Barrett, 1997; Finus and Rundshagen, 2000), albeit to lesser extent. As mentioned before, the widely used optimal growth models do not naturally accommodate trade in goods (other than emissions trade), and are therefore normally unsuitable for an analysis of the effects of tariffs. Thus, existing formal studies of trade sanctions and international cooperation either utilize a static modeling framework (Barrett, 1997) or Computable General Equilibrium (CGE) models (Kemfert, 2004).

For the purpose of this paper, we apply the model in a stylized—that is not empirically calibrated—form in order to explore the scope for tariffs in international cooperation. We find that under the assumption of price- as well as tariff-taking behavior of all

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mand plunges.

countries, the imposition of tariffs on non-coalition members unequivocally raises the scope for international cooperation. However, the coalition's welfare gains start to decline once the tariffs go beyond a certain threshold, and—at a still higher level—tariffs actually become welfare decreasing and thus lose credibility. We interpret the observed effects as a consequence of the model's representation of international trade: when each country's representative output good can only be imperfectly substituted by goods from other countries, but all countries must behave as price-takers, then the tariff constitutes an indirect price setting mechanism, which helps coalition countries to capitalize on their implicit market power and increase their terms-of-trade. However, similar to an optimum tariff rate or monopoly price, the benefits from this increase start to vanish once the tariff exceeds a certain level.

In line with economic theory our model shows that the introduction of tariffs distorts the otherwise efficient markets, and hence, global welfare would be higher without tariffs. We find, however that these losses are easily offset by the gains of increased cooperation that are induced by these tariffs. With respect to environmental effectiveness, we find that in our model carbon leakage is small, i.e. emission increases in free-riding countries do not outweigh the abatement effort of the coalition.

Although we employ the model and the algorithm in an exemplary way in order to explore the scope for tariffs in coalition formation, it can be easily extended to other research questions, e.g. to investigate the effects of differentiated border tax adjustments (BTA) on coalition formation, or to analyze the long-term structural effects of different (optimal, non-optimal) carbon taxes.

The remaining part of the paper is organized as follows: The next section presents the model; Section 3 explains the solution algorithm. In Section 4, we discuss its application to coalition stability in a model with import tariffs, and Section 5 concludes.

2 Model Structure

We begin by stating the problem: we introduce a multi-actor growth model with climate change damages and tariffs on trade flows.

2.1 Preferences

Each region i is modeled following Ramsey (1928), i.e. the maximization of discounted utility endogenously determines the intertemporal consumption-investment pattern.

$$welfare_i = \int_0^\infty e^{-\rho t}\, l_{it}\, U\left(c_{it}/l_{it}\right)\, dt \tag{1}$$

Instantaneous utility U is an increasing and concave function of per capita consumption c/l. It is weighted with the region's total population l and discounted with a rate of pure time preference ρ.

In a world where goods from different countries are imperfect substitutes, utility depends on the consumption of both domestic c^{dom} and foreign goods c^{for}, which are combined into a so-called Armington aggregate via a CES (Constant Elasticity of

Substitution) function.

$$c_{it}=\left[s^{dom}\left(c_{it}^{dom}\right)^{\rho^A}+\sum_j s_j^{for}\left(c_{ijt}^{for}\right)^{\rho^A}\right]^{\left(1/\rho^A\right)} \tag{2}$$

The elasticity $\sigma^A>0$ is determined by the parameter $\rho^A \in (0,1)$ according to $\sigma^A = 1/(1 - \rho^A)$. Share parameters s^{dom} and s_j^{for} characterize the relative preference for domestic and foreign goods and add up to one.

2.2 Technology

We assume a macroeconomic production function F of the Cobb-Douglas form that depends on two input factors, capital stock k and labor supply l.

$$F\left(k_{it},l_{it}\right)=\left(k_{it}\right)^{\beta}\left(a_{it}l_{it}\right)^{\left(1-\beta\right)} \tag{3}$$

Hence, technology is constant-returns-to-scale and with decreasing marginal productivity in both factors. The productivity parameter a grows exogenously at the constant rate gr and thus incorporates labor-augmenting technological progress.

$$\frac{d}{dt}a_{it}=gr\cdot a_{it} \tag{4}$$

While labor is given exogenously, capital can be accumulated by investment:

$$\frac{d}{dt}k_{it}=in_{it} \tag{5}$$

2.3 Climate dynamics

Greenhouse gas emissions e are generated as a byproduct of production. The autonomous decrease of emission intensity at a constant rate ν may be enhanced by investments im in abatement capital km. Parameter $iekm$ determines the investments' efficiency.

$$e_{it}=\sigma_{it}\ y_{it}\exp\left(-\nu t\right) \tag{6}$$

$$\sigma_{it}=\left(1+km_{it}\right)^{-\psi} \tag{7}$$

$$\frac{d}{dt}km_{it}=iekm\cdot im_{it} \tag{8}$$

The climate system is represented in a stylized way based on Petschel-Held et al. (1999). The total stock of atmospheric greenhouse gases ce grows due to the instantaneous emissions of all countries

$$\frac{d}{dt}ce_t=\sum e_{jt} \tag{9}$$

and is linked to the greenhouse gas concentration $conc$ according to

$$\frac{d}{dt} conc_t = B\ ce + \beta^P \sum e_{jt} - \sigma^P \left(conc_t - conc_0 \right) \tag{10}$$

The concentration, in turn, determines the change of global mean temperature *temp* by

$$\frac{d}{dt} temp_t = \mu \log\left(conc_t / conc_0 \right) - \alpha^P \left(temp_t - temp_0 \right) \tag{11}$$

Similar to Nordhaus and Yang (1996), temperature changes cause climate change damages, destroying a fraction 1- Ω of economic output:

$$\Omega_{it} = 1 / \left(1 + dam1_i \left(temp_t \right)^{dam2_i} \right) \tag{12}$$

$$y_{it} = \Omega_{it}\ F\left(k_{it}, l_{it} \right) \tag{13}$$

2.4 Trade and tariffs

We impose an intertemporal budget constraint enforcing that export value and import value are ultimately balanced.

$$\int_0^\infty \sum_j p_{ijt}^m\ m_{ijt}\ dt = \int_0^\infty \sum_j p_{ijt}^x\ x_{ijt}\ dt \tag{14}$$

Imports received by *i* from *j* are denoted by m_{ij}, exports from *i* to *j* by x_{ij}. Naturally, imports and exports that describe the same trade flow must be the same, hence $m_{ijt} = x_{jit}$. Imports become foreign consumption goods after import tariffs—if any—have been deducted in the form of iceberg costs.

$$c_{ijt}^{for} = \left(1 - \tau_{ij} \right) m_{ijt} \tag{15}$$

$$tr_{ijt} = \tau_{ij}\, m_{ijt} \tag{16}$$

Tariff revenues *tr* are recycled without the consumer realizing the origin of the revenues. We close the economy by stating the physical budget constraint, which balances the available economic output with consumption, both investment options, and exports to the rest of the world.

$$y_{it} = c_{it} + in_{it} + im_{it} + \sum_j x_{ijt} \tag{17}$$

Finally, we need to update the Armington equation (Equation 2) to incorporate the tariff revenue *tr*.

$$c_{it} = \left[s^{dom} \left(c_{it}^{dom} \right)^{\rho^A} + \sum_j s_j^{for} \left(c_{ijt}^{for} + tr_{ijt} \right)^{\rho^A} \right]^{\left(1/\rho^A \right)} \tag{18}$$

3 Solving for a Nash Equilibrium

The model features two distortions preventing that competitive equilibrium and social planner solution coincide: climate change damages caused by emissions, and import tariffs. In this section, we describe an algorithm that finds a Nash equilibrium for such models.

Our approach to compute a competitive equilibrium builds on Negishi (1960), Kehoe et al. (1992), and Leimbach and Edenhofer (2007). For a discussion of algorithmic alternatives we refer to Leimbach and Edenhofer (2007). Negishi (1960) shows that a competitive equilibrium maximizes a particular social welfare function which is a weighted sum of the utility functions of the individual consumers. Hence maximization of such a social welfare function may be used to compute a competitive equilibrium. Similarly, Kehoe et al. (1992) use joint maximization to compute competitive equilibria but extend the scope to economies with externalities. They analytically demonstrate the equivalence of a set of optimization problems and the competitive equilibrium.

To find an equilibrium, we iterate individual welfare maximization for all players in addition to a maximization of aggregate social welfare, an approach similar to the one proposed by Leimbach and Edenhofer (2007). We do so by fixing variables of the optimization problems at previously determined levels.

3.1 Finding a Nash equilibrium

To solve our model for a Nash equilibrium, we repeat the following three steps until convergence is reached.

- *Step 1*

  We start by finding a Nash equilibrium in emissions $e = \{e_t\}$, $e_t = (e_{1t}, ..., e_{Nt})$ which are determined by the investment decisions in production capital *in* and abatement capital *im*, i.e. we solve a fix point problem $e = G(e)$ where G is the self-interested response of players to other players' emission trajectories. We compute G by solving

  $$\forall_i \quad \max_{\{in_{it}, im_{it}\}} welfare_i$$

  $$\text{subject to} \quad \text{Equations } 1\text{-}13,\ 15\text{-}18$$
  $$\text{and } m_{ijt} = \overline{m_{ijt}},\ x_{ijt} = \overline{x_{ijt}},\ e_{kt} = \overline{e_{kt}} \text{ for } k \neq i$$

  with trade flows m_{ijt} and x_{ijt} and other players' emissions e_{kt} fixed to their previous levels, as indicated by the bars.

- *Step 2*

  Next, we search for a competitive equilibrium in trade flows (m, x) with $m = \{m_t\}$, $m_t = (m_{ijt})$ and $x = \{x_t\}$, $x_t = (x_{ijt})$, while keeping the emission externality fixed at the level $\bar{e}$ found in Step 1. This is done by solving the fix point problem $tr = H(tr)$, with $tr = \{tr_t\}$, $tr_t = (tr_{ijt})$, and H the response of the social planner to a given tariff revenue constraint $\overline{tr}$. H is computed by solving the joint optimization

$$\max_{\{in_{it}, im_{it}, m_{ijt}, x_{ijt}\}} \sum \delta_i \; welfare_i$$

subject to Equations 1-13, 15, 17-18
and $e_{it} = \overline{e_{it}}, tr = \overline{tr}$

The parameters δ_i represent the regions' weights within the joined social welfare function, and are also referred to as Pareto or Negishi weights.

- *Step 3*

  By using price information derived from the Lagrange multipliers of the maximization problem, we determine deficits and surpluses in the intertemporal budget constraints (Equation 14). We balance the budgets by adjusting the welfare weights δ_i and repeating steps 1-3.

Convergence is reached when the intertemporal budget is in balance and the fix point equations in steps 1 and 2 are satisfied.

3.2 Numerical verification of the Nash equilibrium

We verify the resulting 'candidate' Nash equilibrium strategies in emissions and trade numerically by comparing them to the results of the following maximization problems:

$$\forall_i \qquad \max_{\{in_{it}, im_{it}, m_{ijt}, x_{ijt}\}} welfare_i$$

subject to Equations 1-18
and prices p^m_{ijt}, p^x_{ijt}

which include the budget equation (14) with market prices from the final model solution. Deviations of this model from our solution should be within the order of magnitude of numerical accuracy only, which is what we find (not shown). In particular, simultaneous clearance of all international markets confirms the Nash equilibrium in international trade.[9]

3.3 Partial Agreement Nash Equilibria

For the application of this algorithm to self-enforcing International Environmental Agreements (IEA), we need to extend the algorithm from plain Nash equilibrium to Partial Agreement Nash Equilibrium (PANE). Whereas in the Nash equilibrium there is no cooperation, PANE defines partial cooperation as socially optimal behavior among a subset of players (the coalition). PANE is a Nash equilibrium of the coalition (acting as one player) and all non-members. Within the coalition, a utilitarian social welfare

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[9] Note that we do not attempt to show uniqueness of the identified equilibrium. Indeed, Kehoe et al. (1992) demonstrate how general equilibrium models are prone to multiplicity in the presence of externalities. However, they also show that this occurs when the externality is rather large. In our case, where tariffs and climate damages are on the scale of percents and ten percent, respectively, we assume that the issue of multiple equilibria is still negligible. This is corroborated by the fact that our numerical simulations produced robust results without indication of multiple equilibria.

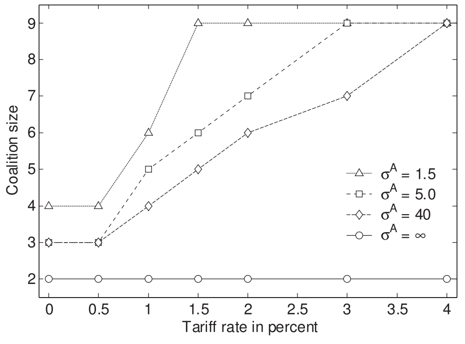

Figure 1: Largest stable coalitions for a given tariff.

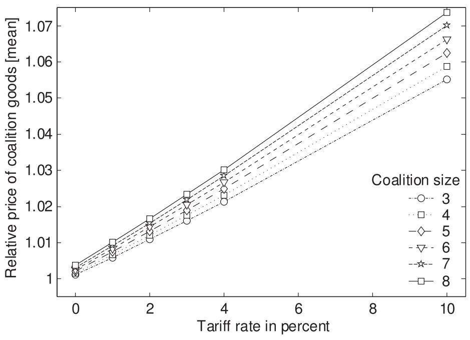

Figure 2: Relative price of coalition goods.

function, i.e. the equally weighted sum of all individual welfare functions, is maximized.

4 Application to International Cooperation on Climate Change

In this section we apply our model to the analysis of import tariffs as a trade sanction against non-signatories of an International Environmental Agreement (IEA). Following the literature on self-enforcing IEA (e.g. Carraro and Siniscalco, 1992; Barrett, 1994), we consider coalitions that are internally and externally stable, i.e. members of the coalition cannot improve their situation by leaving the coalition and joining the group of non-members which free-ride on the effort of the remaining coalition, and neither do non-members have an incentive to join the coalition.

To avoid the black-box effect and to facilitate an interpretation of the qualitative effects produced by the model, we restrict the following analysis to the symmetric case of nine perfectly identical countries.

4.1 Results

Tariff's Influence on Participation

Our model confirms that tariffs are potentially an effective instrument to increase the scope for international cooperation: participation in the coalition becomes unambiguously higher when a tariff on imports from non-member countries is applied. This result is illustrated in Figure 1: in the absence of tariffs, the largest stable coalition has only three or four members, while a tariff rate between 1.5 to 4 percent is sufficient to induce full cooperation.

This effect can be understood in the light of the model's representation of international trade, in which each region produces an imperfectly substitutable good and hence disposes—not at the firm, but at the country level—of some market power.[10] In

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[10] In this context, market power is to be understood as an aggregate property of whole countries, and is

effect, a small tariff on imports from non coalition-members exploits this market power and leads to a rise in the relative price of goods produced by coalition members (see Figure 2). The latter obtain a net benefit from this positive terms-of-trade effect, similar in its mechanics to what is known from the analysis of optimal tariffs or monopolistic pricing. Since by assumption only coalition members can apply such a tariff, it constitutes an incentive to join the coalition.

Note that the relative price of coalition goods also rises just as a function of the size of the coalition, even in the absence of any tariff (Figure 2 at $\tau = 0$). This happens because the emission cuts realized by coalition countries diminish their output, and hence there is—with respect to the business-as-usual—a reduced supply of coalition goods. If demand is inelastic ($\sigma^A < \infty$), the relative price must consequently go up. In fact, the possibility to pass on mitigation costs to free-riders via such terms-of-trade effects also explains how larger coalitions can be ‘stabilized’ even without tariffs by simply decreasing the elasticity of substitution to a sufficiently low level, as seen in Figure 1 at $\tau = 0$.

The graph in Figure 1 also shows that the effectiveness of tariffs is reduced in the presence of higher elasticities of substitution. For example, a tariff of 1 percent induces a stable coalition with six out of nine member countries when $\sigma^A = 1.5$, five members when $\sigma^A = 5$ and four members when$\sigma^A = 40$. Since a higher elasticity implies higher substitutability and hence lower market power, this behavior is fully consistent with our explanation. Indeed, in case all goods are perfect substitutes ($\sigma^A = \infty$) , the tariff loses its clout entirely, as expected.

Environmental Effectiveness of Cooperation

A common argument brought forward against climate coalitions with incomplete membership is the leakage problem: the effectiveness of any collective effort by the coalition could be undermined, if not annihilated, by free-riders who increase their emissions in response to the coalition's reductions. As Figure 3 illustrates, the extreme case of 100 percent leakage rate is not present in our model. Instead we observe that an increase in the coalition size unambiguously results in a reduction of cumulative global emissions. Free-riding does cause some leakage, but the extent is limited and would not warrant the discouragement of cooperation between a subset of countries (Figure 4).

The missing indication of the parameter values for τ and σ^A in Figures 3 and 4 hints at another behavioral characteristic of the model: emission trajectories are fully determined by the coalition size, and do not depend on the Armington elasticities or the tariff rate.[11] Perhaps counterintuitive, this observation is actually in line with the model assumptions: we defined utility as the logarithm of a linearly homogeneous function, which, by using the indirect utility function and an exact price index, can be rewritten as a sum of two terms, the first related to the output level, and the second to the relative

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due to the fact that each country’s representative output bundle is somewhat different. However, there is no monopolistic market structure as such, since the firms making up each country’s economy always behave competitively. In fact, *all* Nash equilibria in this study represent competitive equilibria based on price-taking behavior.

[11] The coalitions’ stability of course depends on their value.

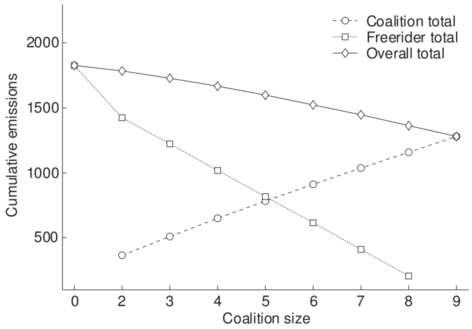

Figure 3: Effect of coalition formation on total cumulative emissions.

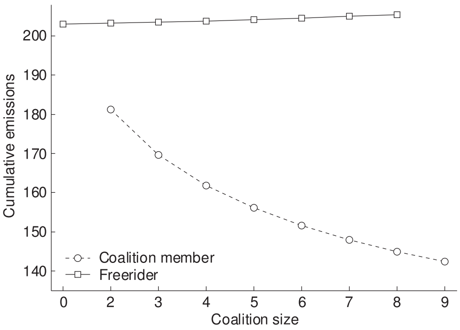

Figure 4: Average free-rider and coalition member emissions as function of coalition size.

prices and the elasticity of substitution. Price changes induced by a tariff or a change in σ^A have an influence only on the latter, but do not change the optimal capital accumulation and, as a direct consequence, output levels and emissions remain the same.

Credibility of Tariffs

Threatening to impose tariffs is only credible if the coalition is better off with than without tariffs.[12] Within our model characterized by national product differentiation, tariffs provide an indirect means for coalition countries to exploit their implicit market power. Thus, a tariff should be beneficial as long as it is not too high, the limit depending on the elasticity of substitution. This intuition is confirmed in Figure 5, which shows how a coalition's welfare changes with increasing tariffs.

As expected, welfare initially increases, but starts to decline after reaching a maximum value and eventually drops below zero. The threshold value at which the welfare effect becomes negative marks the maximum tariff rate that is still credible.

Although the observed qualitative pattern is robust with respect to parameter changes, the specific value of the maximum tariff as well as the potential welfare gain depend on the elasticity of substitution σ^A and on the coalition size: both increase with lower elasticities and smaller coalition sizes. For example, at $\sigma^A = 20$ tariff rates of less than 10 percent are credible for any coalition size, while at $\sigma^A = 100$ the cut-off is already at about 2 percent. This dependence on σ^A can again be explained in terms of the greater market influence that can be realized with a lower elasticity. The observable higher welfare gain for *smaller* coalitions is a consequence of higher tariff revenues: in the presence of large coalitions, there are only few free-riders left whose goods are actually subject to tariff duties, while there are payments from almost all trading partners if the coalition has only two members.

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[12] This concept of credibility is rather shortsighted: when considering only the welfare effects of tariffs on themselves, coalition members ignore that tariffs may increase participation and thus bring about net positive welfare effects even when 'incredible' according to this concept. This shortsightedness is, however, consistent with the employed shortsighted concept of stability.

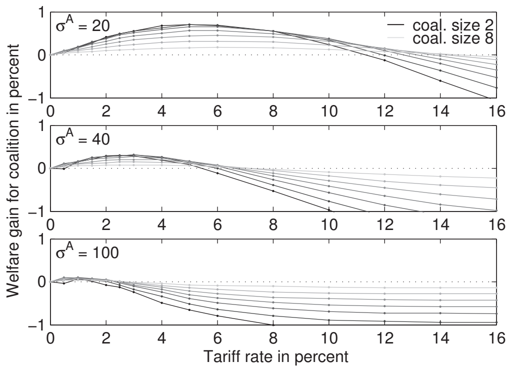

Figure 5: Credibility of imposing tariffs.

Welfare Implications of Tariffs

Tariffs have an ambiguous effect on global welfare: on the one hand they can increase global welfare because they enhance the scope for cooperation. On the other hand—as free trade advocates might object—they distort free trade and thus undermine global efficiency, which ought to cause a loss of welfare which could in the worst case outweigh the gains. We compare the two opposing effects in Figures 6 and 7.

Figure 6 shows gains induced by tariffs measured as the difference in global welfare between the largest stable coalition with a given tariff rate and the largest stable coalition in the absence of tariffs.[13] As can be seen, the welfare gains are quite significant and reach up to 65 to 80 percent for full cooperation, depending on the coalition size and corresponding welfare levels without tariffs (see Figure 1).

In contrast, the welfare losses caused by the distortionary effects of tariffs are shown in Figure 7. They are measured by taking the largest stable coalition at each tariff rate and computing the increase in global welfare achieved by dropping all tariffs (ignoring that the coalition may not be stable anymore). In agreement with standard economic theory the graph shows welfare losses that increase steadily with the tariff rate. However, the welfare losses due to the trade distortion are one order of magnitude smaller than the gains achieved by furthering cooperation. In normative terms, this suggests that the trade distorting effect of tariffs should be an acceptable price to pay in exchange for more inclusive climate coalitions.[14]

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[13] Normalized (in both figures) to the scale defined by the welfare gap between the Nash equilibrium and social optimum.

[14] It might seem counterintuitive that welfare losses in Figure 8 are higher when goods are better substitutes, especially since in the limit case $\sigma^A \rightarrow \infty$ tariffs become ineffective and hence welfare losses drop to zero. The intuition behind this effect is as follows: Tariffs have two effects, an income effect and a substitution effect. The income effect (due to the price increase of coalition goods) is predominantly of distributional nature, leaving global welfare largely unaffected. The substitution effect, on the other hand, causes a decline in the total volume of world trade, which bears welfare costs for all countries. This deviation from the socially optimal trade volume increases with higher elasticities of substitution, and thus becomes more pronounced for large values of σ^A.

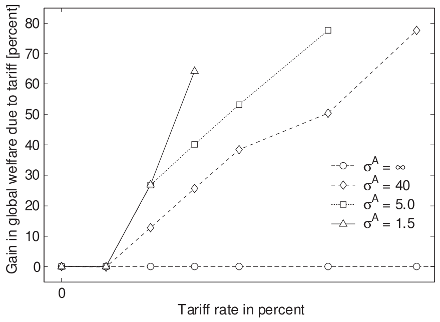

Figure 6: Gains in global welfare due to tariffs.

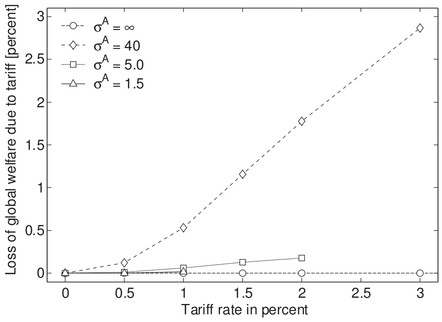

Figure 7: Losses in global welfare due to tariffs.

4.2 Sensitivity Analysis

A central result in the previous section was that a tariff levied on imports from free-rider countries in the order of magnitude of a few percent sustains full cooperation on emissions reduction. In this section, we explore in how far this result continues to hold when the values of the model's key input parameters are systematically changed to *high value* and *low value* estimates. In order to keep the computational costs manageable, we stick to an exploration of local sensitivities.[15]

Figure 8 reports sensitivities obtained from the variation of nine parameters. Indicated are the lowest tariff rates that still support full cooperation for the chosen parameter values. The numerical values for high and low are reported next to the data-point, while the parameters' name and default value is given at the bottom of the figure. The results show that for all parameter variations, full cooperation can still be achieved by adjusting the tariff rate. Furthermore, the required tariff rate does not exceed five percent for our selection of low and high values.

Barrett's (1994) conclusion that cooperation is harder to achieve when it is most needed helps to understand the sensitivities. The largest impact is exerted by the rate of pure time preference ρ, which is known to have a strong impact on growth and the (associated) emissions: patience boosts savings leading to more production. Additionally, the weight of future damages is increased. Varying parameters of the damage function immediately lessens or exacerbates the need for coordinated mitigation. Also the next two most sensitive parameters, the exogenous rates of decarbonization ν and productivity growth *gr* are again closely related to emissions and economic growth, and therefore the urgency of environmental cooperation.

In addition to the local sensitivity analysis, we also explore the consequences of a structural change in the model: in Equation 4 we assumed exogenous technological

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[15] Our approach is similar–albeit much more concise–to the sensitivity analysis of the DICE model in Nordhaus (1994, Ch. 4). Parameter variations leading to Nordhaus' alternative high values are comparable to ours. Moreover, five of the eight identified most sensitive parameters have counterparts in our analysis. As one difference, in our study the uncertainty of climate dynamics is solely assessed by varying the damage function.

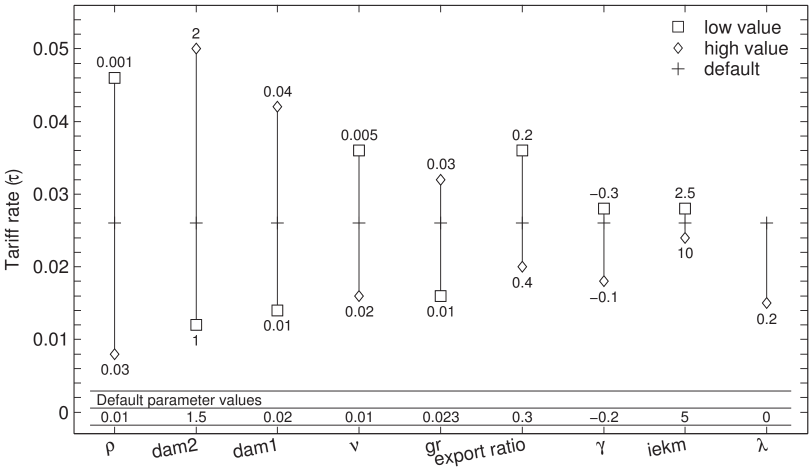

Figure 8: Local sensitivity analysis. The figure shows how the tariff rate necessary to induce full cooperation changes when key input parameters are replaced by lower or higher values.

progress, at the constant rate *gr*. Alternatively, we might follow the concept of Jones and Williams (1998) and depict the productivity parameter *a* as a knowledge stock that evolves endogenously according to

$$\frac{d}{dt} a_{it} = gr\left(iea \cdot ia_{it}\right)^{\lambda}\left(a_{it}\right)^{\varphi} \tag{19}$$

The new control variable *ia* represents R&D investments[16], *iea* their efficiency, and λ and ϕ parameters for "stepping on toes" and "standing on shoulders" effects, respectively.[17] To test the influence of endogenous technological change, we choose $iea = 1.7e3$, $\lambda = 0.15$, and $\phi = 0.2$, which reproduces the average growth rate of the default model with exogenous technological change. The latter case is recovered from Equation 19 by setting $\lambda = 0$, $\phi = 1$. The impact of this structural change is no larger than the parameter variations (see last column in Figure 8).

In the main part of this paper, we restrict the analysis to symmetric regions. This greatly reduces the number of computations needed to determine the largest stable coalition: for *n* symmetric regions, *n* model evaluations suffice (in our case 9), whereas *n* heterogeneous regions require 2^n-*n* model runs (in our case 503). In Table 1 we take one step towards heterogeneous regions by exploring the impact of "stylized" heterogeneity. To this end, we define three different scenarios with heterogeneous parameters.

First, scenario 1 (row 4) incorporates heterogeneity by assigning each region a different amount of initial capital k_0. As can be seen, even though the poorest and richest regions differ by a factor 20, the effect on the tariff rate needed to induce full cooperation is all but negligible. Indeed, cooperation becomes a little easier.

Heterogeneity should constitute a more serious obstacle to cooperation when there

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[16] Of course, these investments need to be deducted from the budget in Equation 15.

[17] See Jones and Williams (1998) for a detailed discussion of the equation.

		Region									Tariff
Parameter	Scenario	1	2	3	4	5	6	7	8	9	τ
dam2		1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	
iekm	*default*	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	0.028
k0		34.0	34.0	34.0	34.0	34.0	34.0	34.0	34.0	34.0	
k0	*1*	3.4	11.1	18.7	26.4	34	41.7	49.3	57.0	64.6	0.026
dam2	*2*	1.75	1.69	1.63	1.56	1.5	1.44	1.36	1.31	1.25	0.034
iekm		4.0	4.25	4.5	4.75	5	5.25	5.5	5.75	6	
dam2	*3*	2	1.88	1.75	1.63	1.5	1.38	1.25	1.13	1.0	0.042
iekm		3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	

Table 1: Impact of heterogeneity. The last column shows the smallest tariff rate τ that is sufficient to induce full cooperation; τ was varied between 0.01 and 0.05 using a step size of 0.002. Only parameter values that differ from their defaults in rows 1-3 are listed, i.e. scenario 1 shows a variation of initial capital k_0, scenarios 2 and 3 show experiments that effect mitigation costs (via iekm) and climate change damages (via dam2).

are some regions with high damages and high mitigation costs (high interest in cooperation) and some with low damages and low mitigation costs (low interest in cooperation). This hypothesis is tested in scenarios 2 and 3, shown in rows 5-6 (moderate heterogeneity) and 7-8 (strong heterogeneity), where the damage and mitigation cost parameters have were set accordingly.

We find that this type of heterogeneity does not prevent full cooperation either, even though higher tariff rates are necessary. Whether the increased level of tariffs is due to heterogeneity remains an open question: both the damages and mitigation costs are determined through nonlinear functions. Hence, even though we varied the parameters such that their average value across all countries remains the same, average damages and average mitigation costs may well have changed due to the introduction of heterogeneity.

5 Conclusions

This study makes a methodological and a policy contribution to the integrated assessment modeling of climate change. We present a model in the tradition of multi-regional optimal growth models that includes trade relationships between regions. Including climate damages and punitive tariffs introduces two external effects into the model. Thus the competitive equilibrium will fail to be socially optimal and a more elaborate approach than social welfare maximization is necessary to find an equilibrium solution.

We address this challenge by presenting an algorithmic extension to the approaches by Negishi (1960) and Kehoe et al. (1992). We illustrate model and algorithm by applying the model to the current issue of trade sanctions as an instrument to foster participation in an international environmental agreement. We find:

- When the coalition imposes tariffs on imports from free-riding regions, participation in the coalition rises. Global social welfare rises along with participation despite small welfare losses due to the distortion caused by the tariff instrument.
- To threaten non-members with trade sanctions is credible as long as the tariff rate is small, where 'small' depends on the Armington elasticity. For large tariff rates coalition members would be better off not to sanction trade.
- Non-members respond to emission cuts on the part of the coalition by raising their own emissions, but we find this leakage effect to be small.

These results are comprehensible in light of the underlying theoretical model of international trade: following the concept of national product differentiation, goods produced by different regions are assumed to be imperfect substitutes among each other. Yet all countries act as price takers in a competitive equilibrium. Introducing tariffs in this context allows coalition members to capitalize on their potential market power. The elasticity of substitution between goods determines the ease with which non-members can avoid coalition goods, and hence puts a limit on the potential clout of the tariff instrument.

The application of the model nevertheless identifies some robust qualitative relationships and clearly demonstrates the usefulness of the algorithm. In fact, the treatment of externalities sketched in this paper can easily be transferred to similar dynamic games with externalities. Finally, in order to put numbers on the identified qualitative effects, heterogeneous regions should be introduced and be calibrated to real world regions. This would further enhance the policy relevance of the model results.

Acknowledgements

We would like to thank Carlo Carraro, Michael Finus, Carsten Helm, and Britta Tietjen for discussions of an earlier draft of this paper, and two anonymous referees for their comments. All remaining errors are, of course, our own. The model experiments made extensive use of the ***SimEnv*** (Flechsig et al., 2008) multi-run simulation environment. Kai Lessmann and Robert Marschinski received funding from the European Commission within the ADAM project (project 018476-GOCE).

Appendix: Parameter Choices

Table 2 lists our choice of parameters. We restrict this study to the case of symmetric players, hence a calibration to real world regions is out of question. Nevertheless we selected a set of parameters such as to produce a scenario that appears plausible. This appendix lists the assumptions we made.

The choice of the pure rate of time preference has received much attention since Stern (2007) suggested a significantly lower value (0.001) than earlier studies, e.g. 0.03 in Nordhaus (1996). We strike middle ground by selecting $\rho = 0.01$, but explore both Stern's and Nordhaus' choices in our sensitivity analysis.

We chose the rate of exogenous labor enhancing technological change *gr* such that long term economic growth averages at 2.1 percent per year, which is within the range of the IPCC SRES family of development scenarios (IPCC, 2000).

With initial labor and labor productivity at 1.0, we chose initial capital such that the savings rate is approximately constant at 23 percent during the first decades, i.e. the economy is on a balanced growth path. This figure corresponds to the world's empirical average of 23 percent between 1990 and 2002 (Bank for International Settlements, 2004, 28)

We frequently vary the Armington parameter σ^A that determines the elasticity of substitution in our experiments using values between 1.5 and 40. We compare these result to the limit case of an infinite σ^A and explore the transition to the limit using a high value of $\sigma^A = 100$. In calibrated real-world models these elasticities typically lie between 1 and 8 (Bernstein et al. 1999). To enhance the comparability of calculations with different ρ^A we selected the share parameters s^{dom} and s^{for} such that for all ρ^A the export ratio is about 30 percent in the Nash equilibrium. For 2005, the WTO has estimated the ratio of exports in goods and commercial services to GDP as 29 percent (WTO, 2007, 30).

Parameters in the climate module are based on literature values, giving us a 3°C temperature increase by 2100, and a 7.5°C increase by 2200 in the business as usual, i.e. without climate change damages and without any cooperation between regions. Nordhaus and Yang (1996) estimate a similar temperature increase of 3.06°C in 2100 for their market scenario.

The damage function was chosen such that in Nash equilibrium damages in 2100 are 6 percent. We chose this relatively high value (compared to damages ranging from 0 to about 5.5 percent across regions in RICE with a global average of about 3 percent) to account for Stern’s (2007) estimation that “[business as usual] climate change will reduce welfare by an amount equivalent to a reduction in consumption per head of between 5 and 20 percent.”

Within the mitigation option, parameters ψ and *iekm* were selected such that optimal abatement (the social planner solution) reduces the temperature increase in 2100 by 0.6°C. In Nordhaus and Yang (1996), cooperative behavior reduces global temperature in 2100 by 0.22°C.

Parameter	Symbol	Value
Pure rate of time preference	ρ	*0.01*
Income share capital	β	*0.35*
Labor productivity growth	gr	*0.023*
Rate of autonomous emission intensity reduction	ν	*0.01*
Initial labor	l_0	*1*
Initial labor productivity	a_0	*1*
Initial capital stock	k_0	*34*
Share parameter, domestic	s^{dom}	*see text*
Share parameter, foreign	s^{for}	*see text*
Armington elasticity of substitution	ρ^A	*0.975*
Effectiveness of investments in *km*	$iekm$	*5.0*
Abatement cost exponent	ψ	*0.2*
Ocean biosphere as CO₂ source	β^P	*0.47*
Atmospheric retention factor	B	*1.51e-3*
Radiative temperature driving factor	μ	*8.7e-2*
Temperature damping factor	α^P	*1.7e-2*
Ocean biosphere as CO₂ sink	σ^P	*2.15e-2*
Initial concentration	$conc_0$	*377*
Initial temperature	$temp_0$	*0.41*
Initial cumulative emissions	$cume_0$	*501*
Damage function coefficient	$dam1$	*0.02*
Damage function exponent	$dam2$	*1.5*

Table 2: Parameter values.

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Chapter 5

Research cooperation and international standards in a model of coalition stability[*]

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Research cooperation and international standards in a model of coalition stability

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Abstract

Suggestions on international cooperation in climate policy beyond 2012 include substituting or complementing international environmental agreements (IEA) with technology oriented agreements (TOA). We look at the impact of TOA on environmental cooperation in the framework of coalition stability. Using a numerical model, we analyze the differences of several TOA and how they interact. We find that participation in and environmental effectiveness of the IEA are raised less effectively when the TOA focuses on mitigation technology rather than augmenting productivity, which is due to the former having an effect on all actors via emissions, whereas effects of the latter are exclusive to research partners. For the same reason, we find that restricting the effects of R & D cooperation is credible only in case of productivity. Technology standards may fail to foster participation when they are restricting members and non-members alike, and may suffer from inefficiencies. However, when implemented as a complementary instrument, these disadvantages did not apply. Separately negotiated technology standards may hence facilitate participation in an IEA without adding to its complexity.

Key words: Coalition Formation, International Environmental Agreements, Issue Linking, Non-cooperative Game Theory, R & D Spillovers, Technology Standards

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1 Introduction

Achieving full cooperation in a self-enforcing international environmental agreement (IEA) is difficult when the underlying game presents the actors with a dilemma: while global cooperation is socially optimal, it is often better for a number of players to act as free-riders, i.e. enjoying the benefits of other players' abatement efforts

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without reducing their own emissions. Consequently, it is a standard result in non-cooperative game theoretic models that voluntary participation in environmental cooperation alone tends to be low (see for example Carraro and Siniscalco, 1992, and Barrett, 1994, or the more recent Finus et al., 2006, and Carraro et al., 2006).

By introducing additional incentives, the structure of the game may be changed making cooperation easier to achieve. These incentives range from positive incentives such as side payments, permit allocation, and issue linking to negative incentives such as reciprocal measures, financial penalties, and trade restrictions (Barrett and Stavins, 2003), see Wagner (2001) for an overview of incentives to stabilize international environmental agreements. In this paper, we focus on linking environmental cooperation to a technology oriented agreement (TOA).

1.1 Issue Linking

The unfavorable incentive structure in climate change mitigation is due to the public good character of a stable climate. Enjoying a stable climate is non-rival, and there are no means of excluding anybody from doing so, hence the possibility to free-ride.

Issue linking attempts to improve the incentive structure by linking the provision of the public good to an exclusive access to a club good (Carraro, 1999). When the attractiveness of the club good outweighs the incentive to free-ride, the dilemma is overcome. Possible candidates for such club goods are technology oriented agreements. De Coninck et al. (2007) provide an overview of TOA stressing out the potential role of TOA in addressing the free-riding incentives in climate protection negotiations.

Among the TOA, in particular the spillovers from R & D agreements have the qualities of a club good (non-rivalry and excludability). Previous issue linking modeling studies have analyzed the potential of spillovers to raise participation in international cooperation. In these studies, cooperative research and development creates spillovers concerning production costs (Carraro and Siniscalco, 1997; Botteon and Carraro, 1998), profit (Katsoulacos, 1997), energy efficiency (Kemfert, 2004), productivity and emission intensity simultaneously (Buchner and Carraro, 2006), and marginal abatement costs (Nagashima and Dellink, 2008).

1.2 Potential of spillovers

Research and development is known to have spillovers. Griliches (1992), for example, reviews a number of empirical studies which estimate social and private rates of return to R & D. Griliches concludes, “R & D spillovers are present, their magnitude may be quite large, and social rates of return remain significantly above private rates.”

Research partnerships may facilitate these spillovers. There are numerous reasons for cooperative research, ranging from costs minimization to strategic considerations. In particular, the list of reasons includes internalizing spillovers, e.g. learning from partners, transfer of technology and technical knowledge, and increasing efficiency and synergies through network, as well as exploiting the non-rivalry of knowledge, e.g. by sharing R & D costs (Hagedoorn et al., 2000). Of course, raising the spillover intensity is not a policy instrument at the disposal of governments. But by encouraging research partnerships spillovers might be fostered indirectly.

Existing governmental policies aimed at encouraging cooperative R & D focus on providing legal frameworks as well as financial support, noteworthy the EU Framework Programmes on Research and Technological Development (FWP). Aimed at industry as well as universities and research laboratories, the FWP offer financial support of up to 50 percent of the total joint research costs but require the research partnership to include members from at least two EU countries (Hagedoorn et al., 2000), i.e. the FWP are a prime example of boosting international research cooperation.

1.3 Potential of international standards

Contrary to R & D spillovers, international standards do not promise to lessen the dilemma by raising payoffs in the participating regions. They are therefore not suited to be issue-linked to an environmental agreement in the way of R & D, rather, they could complement an environmental agreement. For example, Edmonds and Wise (1999) propose a standard requiring carbon capture and storage for new electricity power plants and for synthetic fuels from coal. Barrett (2003) suggests complementing technological R & D with an agreement on international technology standards. These standards provide a market pull incentive to commercialize the results of cooperative R & D. Participation in such a technology standard may be spurred by the following incentives (Farrell and Saloner, 1987; David and Greenstein, 1990; Barrett, 2003):

- Standards induce *network externalities*: the higher the number of participants in a standard, the larger the benefits of adopting the standard.
- Standards protect their participants from *lock-in* in technologies that are then abandoned.
- Standards help reduce costs when *economies of scale* can be exploited.

Additionally, a minimum participation clause and trade restrictions against non-participants can be implemented to further strengthen these incentives (Barrett, 2003): Network externalities and scale effects increase with participation, hence minimum participation guarantees a minimum extent of these incentives. And combined with a trade ban against non-compliant players, minimum participation ensures a growing market for the new technology as well as a shrinking market for old technology, reinforcing the fear of being locked into an abandoned technology. Barrett (2003) argues that these incentives make the adoption of technology standards much easier than raising participation in an environmental agreement.

Barrett's (2003) proposal is intended as a substitute for an emissions abatement agreement with the advantage of a better incentive structure. Whether these incentives suffice to provide effective environmental protection has been challenged (Philibert, 2003, 2004; de Coninck et al., 2007). The usefulness of technology standards as a complementary policy instrument is however undisputed.

1.4 Coalition formation

The formal analysis of self-enforcing international environmental agreements in non-cooperative game theory was pioneered by Barrett (1991a,b) and Carraro and Siniscalco (1992, 1993), and has recently been reviewed in Finus (2008).

The incentive of issue linking, which is the focus of this paper, has been studied using conceptual and empirically calibrated models. Carraro and Siniscalco (1995, 1997) investigate linkage of environmental cooperation to cooperation on R & D in a static three-stage game showing that linkage indeed furthers participation. Botteon and Carraro (1998) extend this analysis adding heterogeneity based on empirical data to this model. While this renders the model intractable, they confirm their earlier findings numerically: participation in the IEA rises with spillover intensity including full cooperation of five out of five players.

Katsoulacos (1997) questions the approach of having one entity decide upon both, environmental and technological cooperation, arguing that the decision to cooperate on technological R & D is taken by firms, not governments. Consequently, his model distinguishes firms deciding on spillover levels and governments deciding on R & D subsidies aimed at encouraging spillovers. The analysis is restricted to two countries, which can be shown to enter joint cooperation on R & D and environment if the gains from subsidies are large enough.

Kemfert (2004) explores the effects of issue linking in a CGE model calibrated to the GTAP database (McDougall et al., 1998). The scenarios include cooperation on energy efficiency R & D as well as trade barriers against non-cooperating countries. In this model, introducing R & D cooperation has a strong effect on the incentive to participate in an IEA. With R & D cooperation, all four of the negotiating countries want to join the IEA, compared to none in the base case, i.e. full cooperation is internally stable. [1]

Buchner et al. (2005) apply a multi-actor optimal growth model to questions of issue linkage. They limit their analysis to a selected set of coalitions, in particular the coalition of Kyoto signatories plus the United States, and explore the effect of linking R & D cooperation to environmental cooperation on the incentives for the United States to join the Kyoto signatories. It turns out that, given sufficiently high spillovers, such an agreement does indeed become stable. They note, however, that making R & D cooperation dependant on environmental cooperation is not credible, i.e. Kyoto signatories prefer to cooperate on R & D with the United States even if the latter act non-cooperatively on emission abatement.

Nagashima and Dellink (2008) use the STACO model to explore the effects of technology spillovers on the stability of coalitions. They focus on spillovers in mitigation technology, and model these through changes of the marginal abatement cost curve. They observe that spillovers have a positive effect on the abatement effort, but the number of participating regions is only increased by one beyond the business as usual maximum participation of six out of twelve regions. This finding proves robust against a variation of the intensity of spillovers and the way spillovers affect the marginal abatement costs curves, as well as the choice of the indicator for the state of technology. Thus, the authors conclude that technology spillovers do not substantially increase the success of IEA.

All issue linking studies cited above find that issue linking with spillovers has positive effects on participation in the IEA. But the extent of this positive effect varies, ranging from complete success in stabilizing full cooperation (Botteon and Carraro, 1998; Kemfert, 2004), to merely marginal increases of the coalition size (Nagashima and Dellink, 2008). The models differ in a great number of ways and it is unclear which modeling assumptions give rise to these differences in model results. Most authors acknowledge that the intensity of spillovers is an important determinant, but given the state of the literature, it is difficult to provide a sound empirical basis for the choice of spillover intensity. Variation of this key parameter, as studied in Botteon and Carraro (1998) and Nagashima and Dellink (2008), reveals the sensitivity of this key assumption, yet the selected values for spillover intensity cannot be compared across models. Furthermore, the sources of spillovers differ between models. The implication of the kind of spillover, e.g. whether related to productivity as in Botteon and Carraro (1998), or related to mitigation technology as in Nagashima and Dellink (2008) has not been studied.

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[1] Coalitions are internally stable when no member has an incentive to leave. We define this formally below.

1.5 Novelty

We go beyond existing studies by comparing spillovers that arise from two different research sectors, productivity and mitigation technology, showing that the effectiveness of spillovers depends on the type of knowledge that spills over. The reason is that, unlike in the case of productivity R & D, progress in mitigation technology has an external effect via its impact on emissions, making it easier to achieve high levels of cooperation by linking to productivity R & D. These results on participation carry over to similar conclusions about the impact of IEA on environmental effectiveness and global welfare. In order to increase the comparability of spillover intensity, we estimate the gains from spillovers in terms of additional consumption.

Furthermore, the effect of spillover from cooperative R & D has so far only been investigated in isolation from international technology standards. We complement spillovers by technology standards and explore the interdependence of the two, as well as the scope of technology standards to stabilize coalitions by themselves. We find that cooperative R & D and technology standards are mutually reinforcing in their positive effect on international cooperation. By themselves, technology standards have almost no effect on participation in the IEA. The remainder of this paper follows the usual three steps definition of the model (Section 2), results (Section 3) including some sensitivity analysis (Section 4), and conclusions (Section 5).

2 The Model

We approach the assessment of coalition stability, research cooperation, and international standards in a multi-actor optimal growth model, which is a common modeling framework for the economy-climate stock pollutant problem in general (e.g. Nordhaus and Yang, 1996; Kypreos and Bahn, 2003; Bosetti et al., 2006) and also in coalition stability analyses (e.g. Eyckmans and Tulkens, 2003; Buchner and Carraro, 2006). In particular, it is appropriate for the long economic time horizon required for an integrated assessment of global warming (Edenhofer et al., 2006). Furthermore, intertemporal utility maximization of a representative agent gives macroeconomic models a firm micro-foundation and makes them suitable for welfare analysis (Turnovsky, 2000, pp. 3).

2.1 Model Equations

Preferences

Within this framework, each region i is modeled following Ramsey (1928) as a maximizer of its intertemporal welfare W_i. Here, we chose the utilitarian welfare function with an instantaneous utility function U, $U' > 0$ and $U'' < 0$, and per capita consumption c_{it}/l_{it} as an indicator of well-being. Parameter ρ denotes the pure rate of time preference, $-\eta$ is the elasticity of marginal utility, and l_{it} the size of the population.

$$W_i = \int_0^\infty l_{it}\, U(c_{it}/l_{it})\, e^{-\rho t}\, \mathrm{dt} \tag{1}$$

$$U(c_{it}/l_{it}) = \frac{(c_{it}/l_{it})^{1-\eta}}{1-\eta} \tag{2}$$

Technology

Each region produces a single good using Cobb-Douglas technology F from capital k_{it} and exogenously given labor supply l_{it}, which is subject to labor enhancing technological change $\tilde{a}_{it}$. Parameter β is the income share of capital.

$$F(\tilde{a}_{it} l_{it}, k_{it}) = (\tilde{a}_{it} l_{it})^{1-\beta} k_{it}^{\beta} \tag{3}$$

Capital is made up from past investments, in_{it}. New ideas that contribute to labor productivity a_{it} in country i are a function of the funds invested in R & D, ia_{it}. Parameters $\lambda \leq 1$ and $\Phi \geq 0$ describe effects of researchers “stepping on tows” and “standing on shoulders,” respectively. Parameter ξ_a is a scaling parameter. This knowledge production function is proposed in an empirical study by Jones and Williams (1998) and has been applied in integrated assessment in Edenhofer et al. (2005, 2006).

$$\frac{d}{dt} k_{it} = in_{it} \tag{4}$$

$$\frac{d}{dt} a_{it} = \xi_a \, (ia_{it})^{\lambda} \, (a_{it})^{\Phi} \tag{5}$$

Labor productivity $\tilde{a}_{it}$ encompasses the accumulated knowledge of region i (a_{it}) as well as eventual spillovers from other regions. In the base case we assume no spillovers between regions and simply set $\tilde{a}_{it} = a_{it}$. When R & D spillovers are modeled, we use a weighted aggregate of labor productivity in all regions. This approach is also used in the empirical literature on R & D spillovers, for example in Griliches (1992).

$$\tilde{a}_{it} = \sum_j \varepsilon^a_{ij} a_{jt} \tag{6}$$

Griliches (1992) interprets ε_{ij} as the “economic and technological distance” between i and j where large values of ε_{ij} indicate “closeness”. We always set $\varepsilon^a_{ii} = 1$, and in the base case $\varepsilon^a_{ij} = 0$ for $i \neq j$. Values of $\varepsilon^a_{ij} > 0$ indicate spillovers and are discussed below.

Climate Dynamics

We model greenhouse gas emissions e_{it} as a by-product of economic activity (y_{it} below in Equation 16). Emission intensity of production decreases exogenously with ei_t at an annual rate of dr but may be additionally decreased by investing in a mitigation stock km_{it}. Mitigation km_{it} reduces emission intensity σ_{it} with diminishing effectiveness described by $\gamma < 1$.

$$e_{it} = \sigma_{it}\, ei_t\, y_{it} \tag{7}$$
$$ei_t = \exp(-\nu t) \tag{8}$$
$$\sigma_{it} = (1 + \tilde{km}_{it})^{-\gamma} \tag{9}$$
$$\frac{d}{dt} km_{it} = \xi_m im_{it} \tag{10}$$

Parameter ξ_m determines the effectiveness of investments im_{it}. As before in the case of productivity, we allow for spillovers but set the spillover intensity ε^m_{ij} to $\varepsilon^m_{ij} = 0$ ($i \neq j$) in the base case and $\varepsilon_{ii} = 1$.

$$\tilde{km}_{it} = \sum_j \varepsilon^m_{ij} km_{jt} \tag{11}$$

To account for the stock pollutant character of global warming, we include a stylized model of the climate system (Petschel-Held et al., 1999). Parameters of the climate system are defined in Appendix A. The total stock of atmospheric greenhouse gases ce_t grows due to the instantaneous emissions of all countries

$$\frac{d}{dt} ce_t = \sum_j e_{jt} \tag{12}$$

and is linked to the greenhouse gas concentration $conc_t$ according to

$$\frac{d}{dt} conc_t = B\, ce_t + \beta^P \sum_j e_{jt} - \sigma^P (conc_t - conc_0) \tag{13}$$

The concentration, in turn, determines the change of global mean temperature $temp$ by

$$\frac{d}{dt} temp_t = \mu \log(conc_t / conc_0) - \alpha^P (temp_t - temp_0) \tag{14}$$

For a detailed description of the climate equations and their parameters we refer to the original publication.

Adapted from Nordhaus and Yang (1996), temperature changes cause climate change damages, destroying a fraction $1 - \Omega_{it}$ of economic output:

$$\Omega_{it} = 1/(1 + dam1_i (temp_t)^{dam2_i}) \tag{15}$$

$$y_{it} = \Omega_{it} F(k_{it}, l_{it}) \tag{16}$$

The physical budget constraint closes the economy.

$$y_{it} = c_{it} + in_{it} + ia_{it} + im_{it} \tag{17}$$

2.2 Coalition Formation

Coalition formation is modeled as a two stage game. In the first stage, a membership game is played, i.e. regions choose whether to become members and henceforth act cooperatively on emission abatement with the other coalition members, or to remain individual entities as non-members. In the second stage, the emission game, non-members and the coalition (acting as one player) determine their emissions indirectly by deciding on their consumption and investment behavior.

Coalition Stability

Among all possible coalitions, we consider *stable* coalitions in the sense of *internal* and *external stability* of D'Aspremont and Gabszewicz (1986). Coalitions are internally stable if no member has an incentive to leave the coalition ($W_i|_S \geq W_i|_{S\setminus\{i\}}$ for $i \in S$), and externally stable if no non-member has an incentive to join ($W_j\big|_S > W_j\big|_{S\cup\{j\}}$ for $j \notin S$). The coalition is thus self-enforced by economic incentives.

R & D Cooperation and Issue Linking

When applied to the provision of a public good, the motivation for issue linking is to offset the incentive to free-ride on the non-excludable benefits of the public good by the incentive to gain access to an (excludable) club good (Perez, 2005). We adopt this view for our paper by identifying the coalition of regions dedicated to cooperation on emission reduction with a club of regions that shares spillovers from R & D.

Spillovers become a *club good* of the coalition S (a subset of the set of all regions N) via the spillover intensities ε_{ij} in Equation 6 or Equation 11, which compute the weighted sums of productivity and mitigation, respectively. We set only spillover intensities ε_{ij} for $i, j \in S$ to non-zero levels. This restricts spillovers to coalition members. In contrast, if spillovers of cooperative R & D within the coalition are a *public good*, spillovers extend to all regions, in which case we can set ε_{ij} for $i \in S$, $j \in N$ and $i \neq j$ to positive values. We use the public good case when we test credibility of the club good assumption.

International Standards

As argued in the introduction, standards on the technology level exhibit incentives that foster a broad adoption of such standards on their own right. In this study, we are interested in the effects of an existing standard on participation and issue linking. Therefore, we assume that the decision of adopting the standards has already taken place, i.e. this decision is exogenous to our model. [2]

We implement international standards by requiring a reduction of endogenous emis-

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[2] Adoption of the international standards may be viewed as a third stage game of the coalition formation game taking place before the membership game: Players meet to decide on the adoption of standards first, then, based on the (possibly partial) standards agreement, go on to decide upon membership in the environmental agreement, and finally decide upon emission strategies. In this setting, our assumption is that the outcome of the first stage is adoption of standards by *all* players. This is also a welcome reduction of the computational burden (i.e. we only explore two out of nine possible outcomes of the first stage: full adoption and no adoption at all).

sion intensity σ_{it} by a fraction θ of the business-as-usual emission intensity, i.e. the non-cooperative equilibrium intensity σ_{it}^{NE}.[3]

$$\sigma_{it} \leq (1-\theta)\,\sigma_{it}^{NE} \tag{18}$$

In effect, this implements a performance standard, which we use to approximate the effect of technology standards.[4] The implicit assumption is that a broad adoption of technological standards aimed at low emissions technologies will translate to low emission intensity on the macro-economic level. While this is plausible, it is clearly desirable to check this assumption in a model with the necessary technological detail in the future.

3 Results

For our analyzes, we run the following experiments: To assess the impact of spillover intensity and the stringency of standards on stable coalition size, environmental effectiveness, and welfare, we systematically vary θ as well as ε_{ij}^{a} and ε_{ij}^{m} for $i,j \in S$, with the coalition S ranging from the empty set to the set of all players (see Equations 6, 11, and 18). For exploring the credibility of threatening exclusive access to spillovers we additionally need to vary ε_{ij}^{a} and ε_{ij}^{m} for $i \in S$ and $j \in N$.

3.1 Participation in Environmental Cooperation

The first experiment looks at the effect of spillovers on coalition formation. We plot the size of the largest stable coalition (participation) for different spillover intensities.

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[3] To avoid numerical infeasibility of the model, we implement a smooth transition from no standards to the full level of standards in early years of the simulation.

[4] The literature distinguishes equipment standards (particularly technology standards) and performance standards. The positive effects of technology standards cited in the introduction (network externalities, no lock-ins, economies of scale) are often due to the ability of these standards to enforce compatibility. Performance standards are technology-neutral. This characteristic is likely to increase their cost-effectiveness when applied to emission reduction but they lack much of the positive incentives of equipment standards (Barrett, 2003, Ch. 9).

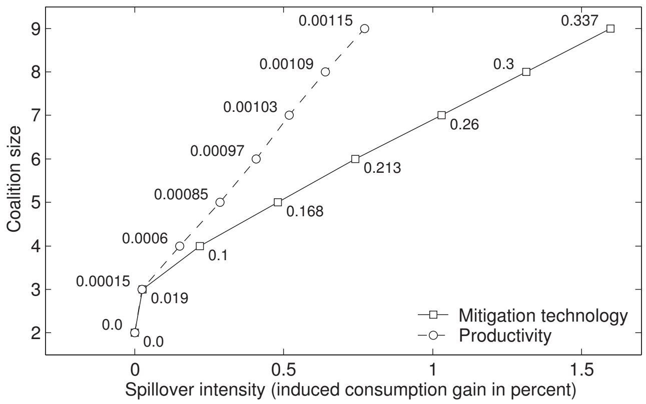

Figure 1. Participation (size of the largest stable coalition) as a function of spillover intensity. Spillover intensity is measured as *induced consumption gain*, i.e. the increase due to spillovers in discounted consumption for the respective coalition size, relative to the no-spillovers case (see also Footnote 5). The values of spillover intensity parameters ε^m and ε^a are given next to the data points.

Cooperative R & D

To make spillovers of knowledge in mitigation technology and productivity comparable, we use *induced consumption gains* on the x-axis. Spillovers are manna from heaven compared to an economy without spillovers, and the additional payoff due to the same parameter value of the spillover intensity of productivity, ε^a, or mitigation technology, ε^m, may vary. The induced consumption gain is the additional consumption due to spillovers for the coalition under consideration and thus a proxy for its intensity.[5]

In Figure 1 we observe the following: First, participation is low in absence of spillovers. This is in line with the literature and confirms that players in this model are indeed facing a dilemma, i.e. the incentive to free-ride is large enough for players to act non-cooperatively. Second, for both kinds of spillovers participation rises with spillover intensity. Again, this is in line with the literature. For high spillovers, full cooperation is supported. Third, participation rises more rapidly in the case of productivity cooperation. This is the case in terms of parameter values, which are smaller by a couple of orders of magnitude, as well as, more importantly, in terms of induced consumption gains.

To understand why productivity R & D is more effective in raising participation, we take a closer look at how spillovers raise participation, i.e. create incentives for larger stable coalitions. In particular, we take a look at payoffs received inside and

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[5] Technically, we take the difference of consumption paths with and without spillovers, discounted using a 3 percent discount rate. We convert to percentages of discounted base case consumption. We prefer a consumption based metric to a welfare metric to make the order of magnitude of the necessary spillovers easier to grasp.

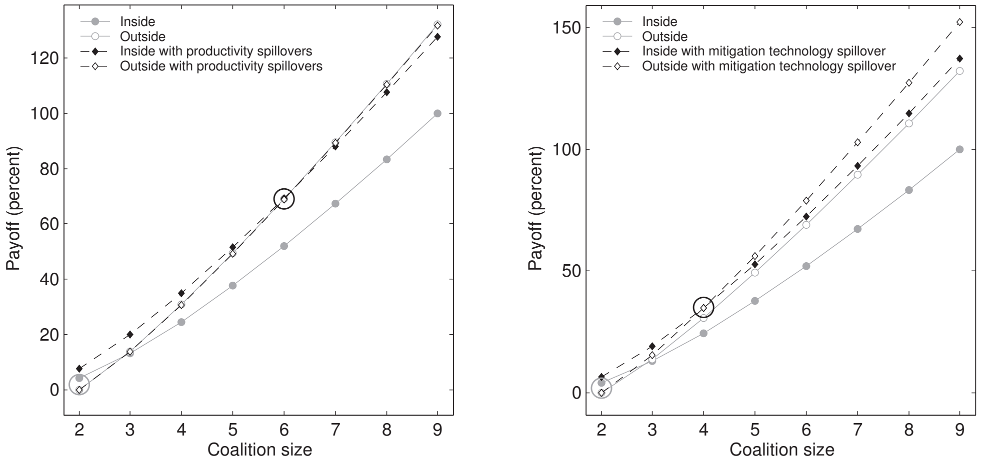

Figure 2. Payoff inside and outside of a given coalition. The figures compare the *inside payoff* received by a member of a coalition of size n (on the x-axis) with the *outside payoff* of a non-member free-riding on the effort of a coalition of size $n-1$. An inside payoff larger than an outside payoff indicates a stable coalition. We show payoffs for the base case without spillovers, and one exemplary case with spillovers, for productivity (left) and mitigation spillovers spillovers (right). The corresponding data points for stable coalitions are circled. Payoffs are given as percentage of the difference between full cooperation and no cooperation without any spillovers.

outside a given coalition, i.e. the *inside payoff* of a player within the coalition of size n versus the *outside payoff* of the same player should she abandon the coalition and instead face the remaining coalition of $n-1$ players as a non-member.

The left graph in Figure 2 shows payoffs for introducing spillovers in productivity, the right hand graph shows results of introducing spillovers in mitigation technology. Both figures show the case of no spillovers and one exemplary level of spillovers to illustrate the discussion; the argument presented holds for all intensities of spillovers considered in this study.

Without spillovers the payoffs both inside and outside any given coalition rise with the size of the coalition. Inside the coalition the payoff rises because the emission externality is increasingly internalized. Outside the coalition, players free-ride on the abatement effort of the coalition, which becomes increasingly more ambitious as participation rises and thus the benefit of free-riding increases. The curves of inside payoff and outside payoffs intersect before coalition size 3, marking a coalition of 2 as the largest stable coalition.

What changes when spillovers are introduced? Spillovers are restricted to coalition members only, therefore in case of productivity the outside payoff curve remains unchanged. Member payoffs increase with spillovers, thus shifting the inside payoff curve upwards and tilting it to the left because spillovers affect larger coalitions more strongly: there simply are more players benefiting from them. In

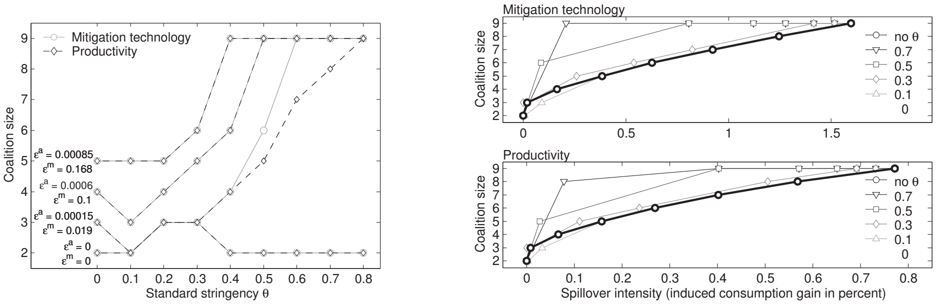

Figure 3. Effect of international standards. The left figure shows the effect of standards on participation for selected spillover intensities. The figures on the right shows the effect of standards on the spillover-participation relationship analogous to Figure 1.

effect, this moves the intersection of inside and outside payoff curves to the right—participation increases.

Spillovers in mitigation technology shift and tilt the inside payoff curve in the same way, upwards and to the left. However, in contrast to the case of productivity, the outside payoff curve is tilted counterclockwise, too. [6] Whereas productivity of coalition members hardly affects non-members, spillovers in mitigation technology lead to an increased abatement effort by reducing the abatement costs for coalition members. Reduced global emissions, however, have an effect on all players: non-members, too, enjoy these additional emission reductions in form of reduced damages. Thus the positive effect on the inside payoff curve is partially offset by the tilting outside payoff curve—participation is still increased, but less effectively.

Technology Standards

In the following experiments, we combine spillovers with standards, i.e. we introduce standards in a world where simultaneously research cooperation is implemented.

Figure 3 shows participation as a function of the stringency of the technology standard (left). The stringency θ indicates the prescribed reduction of emission intensity relative to emission intensity in non-cooperative equilibrium (Equation 18). Technology standards by themselves (i.e. for $\varepsilon = 0$) have very little impact. Participation remains low with only a temporary increase by one member at $\theta = 0.2$ and

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[6] We do not observe an upward shift of the outside payoff curve the way to inside payoff curve is shifted. It simply rotates around the fixed-point $(2,0)$ because the outside payoff of a coalition of 2 is simply the non-cooperative equilibrium where there are no spillovers irrespective of the spillover intensity parameter. In contrast, the fixed-point of the tilting inside payoff curve is $(1,0)$, which we observe as a tilting and shift upwards in the range of coalition from 2 to 9.

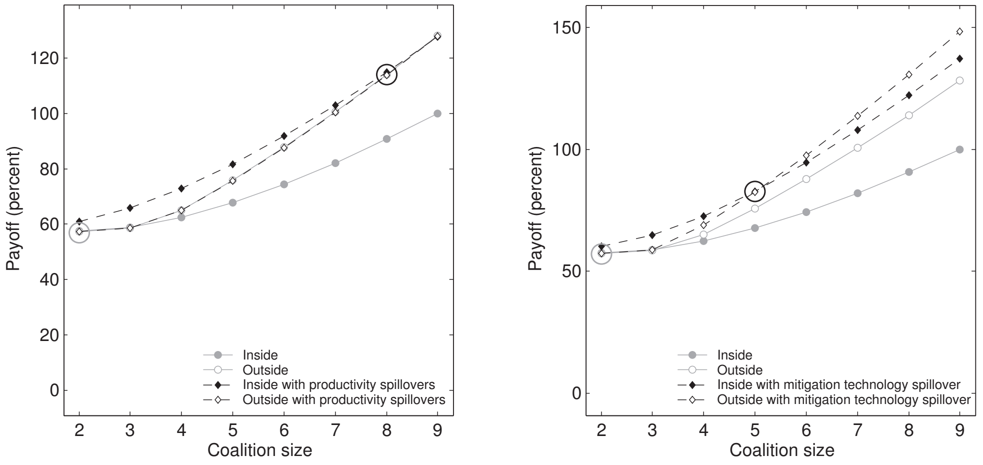

Figure 4. Inside payoff and outside payoff with standards. Analogous to Figure 2, the graphs show inside payoff (received by a member of a coalition of size *n*), which is larger than outside payoff (received by a non-member facing a coalition of size $n-1$) if the coalition is stable. Spillover on the left are in productivity and in mitigation technology on the right. For stable coalitions the corresponding data points are circled. Payoff is scaled to the gap between no cooperation (0 percent) and full cooperation (100 percent) in the base model without spillovers.

$\theta = 0.3$.[7] Only in combination with spillovers, standards raise participation substantially. Likewise, the positive effect of spillovers on coalition size is strengthened by standards (Figure 3, right).

Why do standards hardly change participation by themselves, but they do enlarge stable coalitions when combined with spillovers? Again, we take a look at payoffs inside and outside the coalitions for mitigation spillovers and productivity spillovers (Figure 4).

Standards guarantee investment in abatement beyond the level of Nash equilibrium without standards. Hence, ambitious standards reduce climate change damages and give all players higher payoffs even in non-cooperative equilibrium or in presence

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[7] Without standards, emission intensity is lower for coalition members compared to non-members. With increasing standards stringency, non-members are forced to abate more. The coalition benefits to the extent that coalitions of three instead of coalitions of two become stable. However, due to (a) the small coalition size and (b) the absence of spillovers, emission intensities within the coalition do not differ much from emission intensities of non-members. Hence with the stringency of standards increasing furthermore, there soon comes a point where standards also affect the abatement behavior of coalition members. This lowers the coalition welfare enough to destabilize the coalition of three. Stability of larger coalitions, or coalitions in calculations with non-zero spillovers are not affected in this way, because the emission intensity within the coalition is lower to begin with and is therefore not affected by standards.

of small coalitions. Compared to the case without standards in Figure 2, payoff in non-cooperative equilibrium (outside payoff for coalition size 2) is now lifted half way towards payoff for fully cooperative behavior (50 percent of the gap between no cooperation and full cooperation).

The distance between non-cooperative and fully cooperative solutions has therefore been decreased. In the absence of spillover effects, however, this does not facilitate more participation since the *relative* position of inside and outside payoff curves is not affected, i.e. outside payoff grows more rapidly with coalition size than the inside payoff and soon (at coalition size 3) exceeds it. Spillovers make a difference because, as discussed above, they shift the curve of inside payoffs upwards, thus delaying the interception of the two curves and hence increasing the size of the largest stable coalition.

The argument holds for spillovers in mitigation technology as well as productivity. Again, the latter is more effective in raising participation because here there outside payoff is largely unaffected by spillovers.

3.2 Environmental Effectiveness and Welfare Effects

In the previous section we have seen under which circumstances cooperative R & D and technology standards may raise participation. This section explores the implications of increased participation for environmental effectiveness and for global welfare. We begin the analysis by turning to cooperative R & D.

Cooperative R & D

Figure 5 shows environmental effectiveness relative to socially optimal emission levels in absence of spillovers as the reference point (i.e. 100 percent, whereas emissions from non-cooperative behavior are scaled to 0 percent). Environmental effectiveness increases with spillover intensity in a very similar way to participation (Figure 1), indicating that coalition size is a major determinant and hence a good proxy for environmental effectiveness in this model.

An interesting difference to participation is that environmental effectiveness is exceeded in case of mitigation technology spillovers but not for spillovers of productivity. The reason is that spillovers in mitigation technology decrease abatement costs and therefore a cleaner environment becomes socially optimal.

The impact of mitigation spillovers on environmental effectiveness offsets some of the drawbacks of mitigation spillovers in terms of participation: Figure 1 stressed that achieving full cooperation required larger spillover intensities in case of mitigation technology. This is also true for environmental effectiveness. However, Fig-

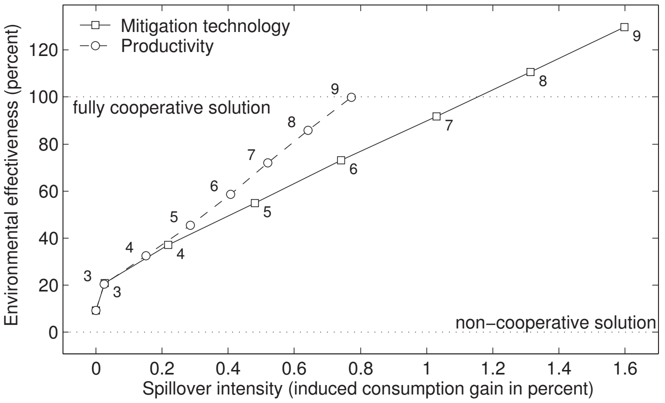

Figure 5. Environmental effectiveness of cooperative R & D. This figure shows environmental effectiveness for stable coalitions, where zero percent is the emission level in absence of spillovers and coalitions, and 100 percent describes socially optimal emissions in an economy without spillovers. Spillover intensity is measured in consumption gain (see Figure 1). We indicate the size of the respective stable coalitions next to the data points.

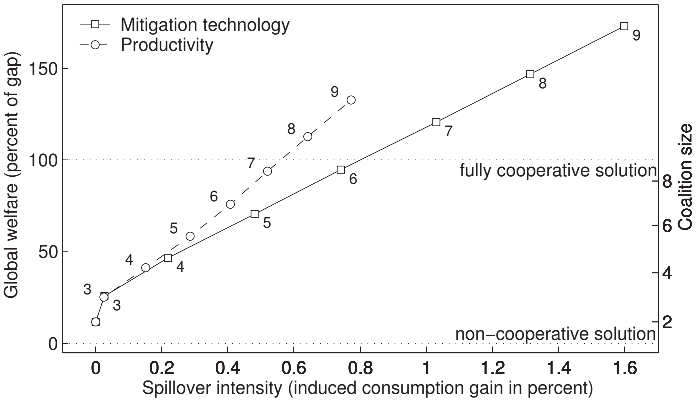

Figure 6. Welfare effects of cooperative R & D. In this figure we show how global welfare of stable coalitions increases with spillover intensity (measured in consumption gain, see Figure 1). Much of the effect is due to rising participation (see Figure 1), hence we indicate coalition size next to the respective data points.

ure 5 shows that the difference in spillover intensity to achieve 100 percent environmental effectiveness is less than the difference in achieving full cooperation. Still, productivity cooperation remains the more effective incentive.

Figure 6 shows the welfare effect of stable coalitions. Welfare is normalized to the non-cooperative behavior (0 percent) and full cooperation (100 percent) in an economy without spillovers. Again, we find a similar picture to participation and environmental effectiveness. Participation, or the degree of cooperation, is also a strong determinant of global welfare. Global welfare exceeds 100 percent of welfare without spillovers for both cases of R & D cooperation, highlighting the fact that spillovers are manna from heaven, i.e. compared to an economy without spill-

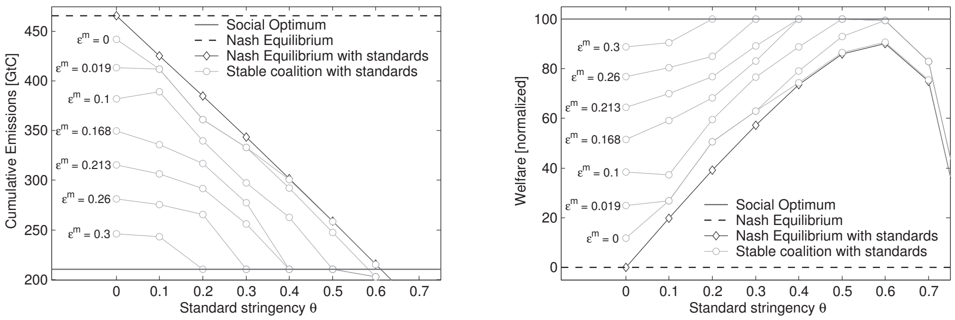

Figure 7. Effects of standards on cumulative emissions (left) and welfare (right). Stable coalitions are induced by spillovers of mitigation technology, the spillover parameter ε^m is included next to the corresponding curves.

overs they provide an additional free income.

Technology Standards

This section explores environmental effectiveness and welfare implications of imposing technology standards. When standards are stringent enough, they might solve the environmental dilemma by themselves irrespective of any cooperation agreements on environment or R & D. We look at the effectiveness and the welfare implications of standards and assess the scope that cooperative agreements have in this setting.

Figure 7 shows the effect of standards on emissions in Nash equilibrium and in case of stable coalitions. When the stringency of the standard is increased, the effect on cumulative global emissions is to bring them down towards their optimal level and below. As cumulative global emissions approach their optimum levels, so does global welfare (Figure 7). However, welfare does not reach its optimum level but starts to fall before emissions reach the optimum. This is due the fact that the timing of emission intensity reduction prescribed by the standards are not cost-effective. It is the inefficiency of standards as a policy instrument manifesting in this figure. This disadvantage of command and control instruments like standards compared to market or price incentive based instruments is well known (see e.g. Requate, 2005). Indeed any of the levels of cumulative emissions in the previous figure could likely be reached at lower costs and higher global welfare if the timing of emission intensity reduction was not prescribed but chosen optimally.

Cooperative agreements on environment and R & D can bridge this gap: Figure 3 includes welfare levels for a number of coalitions that are stable at the given standard stringency due to including cooperative R & D (spillovers) in the agreement. Standards that fall short of enforcing optimal emission levels and are inefficient to begin with, may still be sufficient to induce full cooperation in combination with some spillovers. We observe that often the standards that were necessary to sta-

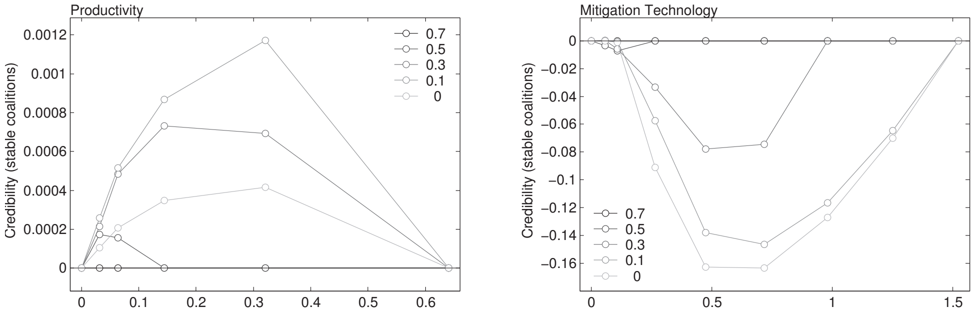

Figure 8. Credibility of restricting spillovers to coalition members. We compute credibility as the difference of coalition members' welfare with restricted spillovers minus the case of spillovers to all regions, hence positive values imply credibility.

bilize full cooperation are exceeded under full cooperation—otherwise standards would distort the optimal solution resulting in below-optimal welfare levels.

3.3 Credibility of Exclusive R & D Cooperation

Restricting spillovers to coalition members is only credible if coalition members are not worse off compared to the case where knowledge is public, i.e. spillovers are unrestricted. Hence we investigate the credibility of exclusive R & D cooperation by comparing it to a scenario where R & D spillovers extend to all regions and not just coalition members. We continue to assume that only coalition members participate in R & D cooperation, i.e. spillovers extend to non-members but not vice versa.

Figure 8 shows whether restricting spillovers to the coalition is beneficial to its members. Values are plotted for different stringencies of standards and only for stable coalitions. In case of productivity we find that threatening exclusiveness is credible for all stable coalitions, and all unstable coalitions as well (not shown). There is no advantage for coalition members in boosting productivity for non-members. Quite the contrary, the increased productivity would entice non-members to produce and pollute more.

Excluding non-members from spillovers of R & D in mitigation technology is almost always a non-credible threat for stable coalitions (Figure 8, right). Coalition members benefit from letting spillovers extend to non-members, because the spillovers add to non-member abatement and further reduce the emission intensity and actual emissions of the non-members. Coalition members then benefit from reduced climate change damages. This is a crucial difference to productivity spillovers that do not have this feedback onto the coalition.

For both kinds of spillovers, credibility approaches zero for small as well as for large coalitions and exhibits a maximum for medium coalition sizes. This depends

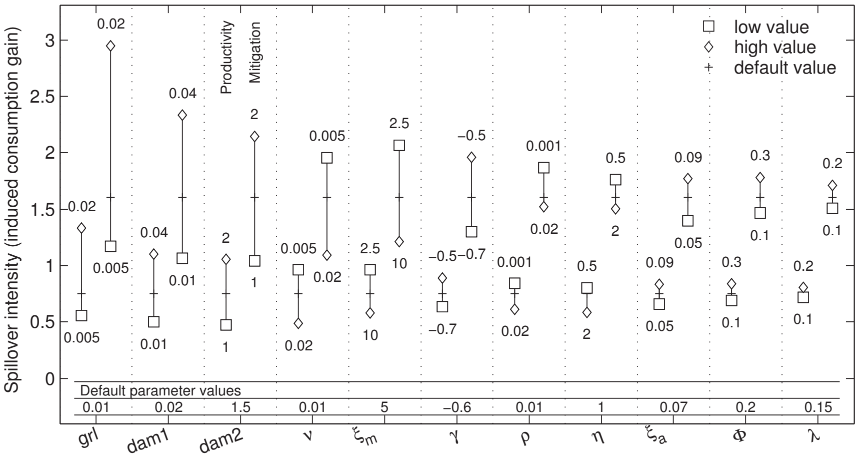

Figure 9. Spillover intensities that support full cooperation. We show the impact of parameter variation on the effectiveness of research cooperation by giving the lowest spillover intensity that induces full cooperation. Results for cooperation on productivity and mitigation are shown side by side for each parameter; numbers above and below data points indicate the low and high values used.

on the extent of spillovers to nonmembers: the smaller coalitions are, the lower the number of players generating spillovers. On the other end of the spectrum, the larger the coalition, the lower the number of nonmembers receiving spillovers.

4 Sensitivity of Key Results

This section explores the sensitivity of key results towards variation of input parameters. Central results of the preceding sections are that TOA may sustain full cooperation depending on the spillover intensity, and that linking to productivity cooperation is generally more effective in raising environmental cooperation than linking to cooperative research on mitigation.

We explore in how far these results continue to hold when parameter values change by running *high* value and *low* value scenarios for key parameters. An assessment of global sensitivities, i.e. a simultaneous variation of all parameters, would be preferable because it accounts for the fact that sensitivity of the results for variation of one parameter will in general depend on all other parameters. We stick with an exploration of local sensitivities to limit the computational burden.

Figure 9 shows results from these low value/high value calculations. Using full cooperation as a reference point, Figure 9 reports the spillover intensity necessary for the grand coalition of all players to be stable. The first message from this figure is that in all variations, either full cooperation was sustained by raising spillover

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intensities or was even achieved at lower spillover intensities. Thus, R & D cooperation proves to be a sufficiently strong incentive for all parameter values in these variations. More importantly though, the spillover intensities necessary to achieve full cooperation via cooperative mitigation research are always higher than in case of the corresponding calculation featuring cooperation on productivity. Hence, our this finding is also robust with respect to our parameter variations.

Table 1 summarizes our choice of high and low parameter values and also reports the impact of these parameter variations on more key results. The difference between cooperation on productivity versus mitigation is measured by the "difference in incentives" in columns 6-7, reported as the difference in spillover intensities that are sufficient to stabilize full cooperation. In Figure 1 this is the distance between the topmost data points of mitigation cooperation and productivity cooperation on the *x*-axis. This difference is considerably affected by parameter changes, mostly in the range of plus/minus thirty percent of the default, yet it is always positive and larger than 0.5 percent, indicating that R & D cooperation on productivity remains significantly more effective than cooperation on mitigation R & D.

Similarly, columns 8-9 show the difference in environmental effectiveness for the same stable grand coalitions from Figure 9. We take the metric of environmental effectiveness from Figure 5, i.e. the numbers in this table measure the difference of the topmost data points in Figure 5 on the *y*-axis. Analogously, columns 10-11 show the impact of parameter variation on the difference in global welfare of grand coalitions, i.e. the distance of the topmost data points in Figure 6 on the *y*-axis. The values in columns 8-11 of Table 1 show that even though parameter variation has a considerable impact, our conclusions remain intact.

5 Summary and Conclusions

We assessed different technology oriented agreements (TAO) in a conceptual model and had to resort to numerical solutions. Naturally, any conclusions from these result about the economy described by the model must be taken with a grain of salt. Nevertheless, the model suggests some rather general differences between the selected TOA, which we summarize in the following.

Cooperative R & D in mitigation technology is less effective because via emissions reductions, spillovers of mitigation technology raise both, the coalition payoff and the free-rider incentive. This feedback of mitigation reduces the positive incentive of spillovers on coalition formation making cooperative R & D that is unrelated to emission abatement a more attractive option for setting incentives for participation.

Contrary to R & D in productivity, R & D in mitigation technology has a positive impact on the environment by reducing abatement costs. Indeed the same level of

Table 1: Parameter values and effectiveness difference. Columns 3-5 list the default, low, and high parameter values. Columns 6-7 report the difference in spillover intensity between cooperation on mitigation and productivity to achieve full cooperation. For default parameters this value is 0.85, the metric for spillover intensity is induced consumption gain, see Figure 1 or Footnote 5. Columns 8-9 and columns 10-11 report the corresponding difference in environmental effectiveness and global welfare, respectively. Here, the default values are 30.0 and 41.5, respectively.

		Parameter values			Diff. in Incentive		Env. Effect.		Welfare Effect	
Parameter	Symbol	Default	Low	High	Low	High	Low	High	Low	High
Pure rate of time preference	ρ	0.01	0.001	0.02	1.03	0.91	24.7	39.6	40.0	44.1
Mare rate of time preference	η	1.0	0.5	2.0	0.96	0.92	25.7	40.3	40.5	44.2
Growth rate of labor supply	grl	0.01	0.005	0.02	0.61	1.62	27.1	41.8	42.6	40.2
Rate of decarbonization	ν	0.01	0.005	0.02	1.00	0.61	47.3	14.5	40.6	41.6
Effectiveness of investments in *km*	ξ_m	5.0	2.5	10.0	1.11	0.63	39.6	22.5	42.1	39.9
Effectiveness of investments in *a*	ξ_a	0.07	0.05	0.09	0.74	0.93	27.1	32.2	41.2	40.7
Stepping on toes effect	λ	0.15	0.1	0.2	0.79	0.91	28.7	31.3	40.3	41.3
Standing on shoulders effect	Φ	0.2	0.1	0.3	0.77	0.94	27.9	32.5	41.3	40.6
Abatement cost exponent	$-\gamma$	0.6	0.5	0.7	0.66	1.07	21.2	43.4	35.4	48.7
Damage function exponent	$dam2$	1.5	1.0	2.0	0.57	1.09	42.6	23.2	42.3	40.0
Damage function coefficient	$dam1$	0.02	0.01	0.04	0.56	1.23	39.5	22.6	41.3	40.8

environmental effectiveness can be reached with smaller coalitions using R & D cooperation in mitigation technology rather than productivity. Nevertheless, the spillover intensity necessary to reach this same level of environmental effectiveness is larger than in case of productivity.

Moreover, our model suggests that restricting spillovers exclusively to the coalition is non-credible in case of mitigation technology. This is plausible because in a world with a global warming problem, it is desirable to let advanced mitigation technology diffuse as much as possible. Overcoming non-credibility due to economic reasons may be possible by means exogenous to this model, for example by commitment (e.g. Houba and Bolt, 2002, Ch. 7), which could be enforced by reputation or eliminating the alternatives. Nevertheless, this is a complication that is absent in productivity spillovers.

This impact of the source of spillovers could be one of the reasons why Nagashima and Dellink (2008) only find small effects of spillovers related to marginal abatement costs, whereas Botteon and Carraro (1998) observe a significant increase of participation up to full cooperation due to spillovers that reduce production costs. [8]

We argued that if technology standards are easier to agree upon than a cooperative environmental agreement, then adopting an agreement on standards may be a helpful first step towards an international environmental agreement. Our model suggests that this works when standards cause emission reductions for non-members but are fulfilled voluntary by coalition members. Here, this is the case only when at least some cooperative R & D is carried out, setting the abatement levels of members and non-members far enough apart.

A combination of technology standards and cooperative R & D is also promising for a second reason. International standards by themselves reduce emissions in a way that is not cost efficient. Combined with cooperative R & D, however, they may induce environmental cooperation to an extend beyond standards, therefore making its inefficiency unimportant.

Limitations

This study aimed to identify general cause-effect relationships in the interplay of TAO and IEA. The simplifying assumptions of (ex ante) identical regions and lack of technological detail facilitated the analysis, but at the same time they reduce

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[8] Of course, the models used in Botteon and Carraro (1998) and Nagashima and Dellink (2008) differs in many respects from this model, among them are: a different modeling framework, heterogeneity of players, and inclusion of transfers within the coalition. The feedback of a stronger abatement effort (due to lower abatement costs) onto non-members ought to be present in the model nonetheless. It is also not clear how the assumed spillover intensities in the different models compare.

the scope of its conclusions for real world policy. Therefore, testing the lessons learnt from this study in models with heterogeneous regions and explicit technology choice would be a step to confirm them and elaborate on their implications.

In particular, we analyzed the interaction of standards and spillovers from a purely macro-economic perspective, arguing that standards come into force due to incentives that are exogenous to the model. Recent integrated assessment models (e.g. Bosetti et al., 2006) resolve some technological detail providing the basis to implement standards on the technology level and allow to explore the scope of the results of this paper in a less conceptual setting.

Moreover, we argued that the spillover extent could be fostered through governmental programs, assuming that this is possible at no additional societal costs. While this assumption is backed by the very idea of R & D spillovers, namely that R & D generates particularly high returns, it does not account for crowding out of other R & D.

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A Parameter Choices

Table A.1 lists our choice of parameters. We restrict this study to the case of symmetric players, hence a calibration to real world regions is out of question. Nevertheless we selected a set of parameters that is plausible in light of the empirical literature. This appendix lists the assumptions we made.

Parameter ξ_a drives endogenous growth. We chose its value such that economic output shows a 2.5 percent annual growth in the first century.

Parameters in the climate module are based on literature values, giving us a 3°C temperature increase by 2100, and a 7.5°C increase by 2200 in non-cooperative equilibrium and business as usual, i.e. without climate change damages.

The damage function was chosen such that in non-cooperative equilibrium damages in 2100 are 6 percent. Within the mitigation option, parameters γ and ξ_m were selected such that optimal abatement (the social optimum solution) reduces the temperature increase in 2100 to 2.4°C.

Table A.1
Parameter values

Parameter	Symbol	Value
Pure rate of time preference	ρ	0.01
Elasticity of marginal utility	η	1
Income share capital	β	0.35
Growth rate of labor supply	grl	0.01
Exogenous rate of decarbonization	ν	0.01
Initial labor	l_0	1
Initial labor productivity	a_0	1
Initial capital stock	k_0	34
Effectiveness of investments in a	ξ_a	0.023
Effectiveness of investments in km	ξ_m	5.0
Abatement cost exponent	γ	0.2
Ocean biosphere as CO_2 source	β^P	0.47
Atmospheric retention factor	B	1.51e-3
Radiative temperature driving factor	μ	8.7e-2
Temperature damping factor	α^P	1.7e-2
Ocean biosphere as CO_2 sink	σ^P	2.15e-2
Initial concentration	$conc_0$	377
Initial temperature	$temp_0$	0.41
Initial cumulative emissions	$cume_0$	501
Damage function coefficient	$dam1$	0.02
Damage function exponent	$dam2$	1.5

Chapter 6

Synthesis and Outlook

The starting point for this thesis is set by two assumptions: first, action to mitigate climate change is necessary, and second, technologies will play a key role in this effort because technology and technological change facilitate the reduction of anthropogenic greenhouse gas emissions. Both assumptions are supported by the latest scientific findings reported in IPCC WG3 (2007). As a consequence, the way technological change is described in integrated assessment models of climate change is of great importance, and a sound understanding of endogenous technological change and its interaction with climate policies is needed.

There is empirical evidence that technological change is induced by policies, but results from previous modeling assessments of induced technological change (ITC) have been ambiguous about the responsiveness of technological change to climate policies and its potential to reduce the costs of mitigating climate change. On the other hand, inducing this kind of technological progress requires a clear climate policy. Stern (2007) concludes: "Without a 'loud, legal and long' carbon price signal, in addition to direct support for R & D, the technologies will not emerge with sufficient impact." The carbon price signal ought to extend globally in order to prevent carbon leakage and achieve efficiency, but according to the literature on international environmental agreements the prospect for global cooperation on climate policy is not bright.

This raises two broad research questions: First, what is the role of ITC for climate change mitigation? And second, if there is a desirable contribution of ITC to mitigation, how can we achieve the global policy that triggers this technological change?

The four papers presented in this thesis contribute to these two questions. The first two papers explore the role of ITC within a single integrated assessment model (Chapter 2) and across a broad range of models in a model comparison excercise (Chapter 3). The remaining two papers address the second question, i.e. achieving a global policy, by looking at the prospect of achieving high participation in a self-enforcing international climate agreement by linking climate policy negotiations to trade sanctions (Chapter 4) and technology-oriented agreements (Chapter 5).

This chapter synthesizes these four papers, proceeding as follows: First, I summarize Chapters 2 and 3 and discuss the role of ITC for mitigation strategies. Then I summarize Chapters 4 and 5 and discuss issue linking. The thesis concludes with an outlook on possible extensions of this work.

6.1 Induced technological change in integrated assessment modeling

In the introduction of this thesis, I broke down the two broad research questions concerning the role of ITC for mitigation on the one hand, and the necessary climate policy regime on the other hand, in four sets of questions. The following sections answer these questions drawing on the insights from Chapters 2–5.

6.1.1 Implications of ITC in the MIND model

The first set of questions focuses on the impact of ITC on the costs and strategies of mitigating climate change.

- What is the impact of ITC on mitigation policy scenarios?
- What is the role of economy wide feedbacks concerning ITC?
- What are the implications of ITC in particular for mitigation costs and mitigation strategies, i.e. the optimal composition of mitigation options?

MIND is a model built for the integrated assessment of climate change and global economic development (Edenhofer et al., 2005a). Its novelty is that it incorporates macroeconomy and energy system, albeit in a stylized way, and endogenous technological change (ETC) throughout the economy.[1] That is, macro-economic growth is driven by ETC, and ETC is also implemented in the energy system sectors. This makes an analysis of MIND well suited to address these question. Indeed, I find that in MIND, ITC has significant impact on both, costs and strategies of mitigation.

In particular, the analysis reveals two "directions" of technological change (Table 6.1). First, there is technological change that permeates the entire economy—this is reflected in a strong impact on the overall macro-economic costs of mitigation policy. This is the case for R & D that augments overall labor productivity or energy efficiency, or ETC in the resource extraction sector, which has impact on the entire economy because of the strong effect of cheap fossil fuel on economic growth in the baseline. And then there is technological change whose impact is specific to a single sector, the energy sector, as evident from a strong impact on the contribution to mitigation options. For example, learning by doing effects for renewable energy and for resource extraction belong to this class of ETC. The competitiveness of mitigation options has a strong impact on the strategy, but their effect on mitigation costs is negligible.

ETC therefore proves to be an influential determinant of mitigation costs and strategies. Costs may rise or fall due to ETC depending on whether "clean" progress (e.g. in renewable energy technology), or "dirty" progress (e.g. in resource extraction technology)

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[1] The concepts of endogenous technological change (ETC) and induced technological change (ITC) are closely related, in fact the two terms are often used synonymously. Here, I use ETC to emphasize the modeling assumption of endogenous (versus exogenous) technological change, and ITC to stress technological change being triggered by climate policy.

	Impact of ETC is . . . macro-economic	sectoral
Macro-economic ETC	labor R & D energy efficiency	
Sectoral ETC	resource extraction	renewables resource extraction

Table 6.1: The scope of ETC in MIND

prevails. The effect of ETC on the competitiveness of mitigation options influences their contributions to overall mitigation.

Moreover, this reveals the importance of economy-wide effects of ETC beyond sector boundaries, and stresses the importance of models that resolve important technological options including their potential of ETC, and account for the economy-wide impact of ETC.

The analysis in Chapter 2 highlighted the importance of including ETC in climate policy models that explore mitigation costs and strategies. The numerical experiments relied on parameter variation, therefore assessing impact of parameter uncertainty for one particular implementation of ETC—but the question how to incorporate ETC in models is far from trivial. On the contrary, among models that include ETC there is a wide variety of approaches taken to describe ETC. I now turn to Chapter 3, which explored the resulting differences in the assessment of ITC.

6.1.2 Implications across models

The variety in ETC implementations and the corresponding variety in the findings about the effects of ITC are addressed in the next set of question.

- How much do integrated assessment models differ in their analysis of ITC?
- What are the underlying reasons for the differences?
- What conclusions are robust across models despite the model uncertainty?

The above set of questions was addressed in a comparison exercise of ten state-of-the-art models of energy, economy, and environment. At the heart of this comparison is the definition of *ceteris paribus* scenarios that aim to isolate and expose the impact of ITC in the various models: policy scenarios that use exogenous technological change (taken from a separate business-as-usual scenario) are compared to scenarios that implement the same policy target, but allow for additional technological change to be induced by the policy. I refer to these scenarios as “without ITC” and “with ITC.”

At the most aggregate level, the impact of ITC becomes apparent in mitigation costs with and without ITC. The analysis reveals that ITC has potential to reduce costs: compared to the scenarios without ITC, mitigation costs are lower in scenarios with ITC, in many models substantially. Average mitigation costs in the participating neoclassical models,

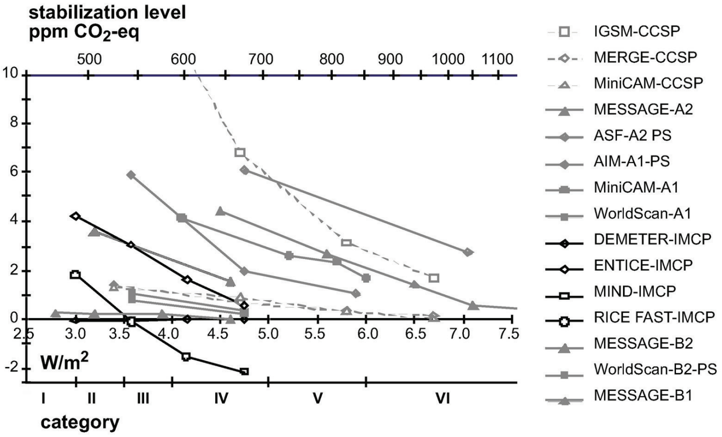

Figure 6.1: Loss of GDP in 2100 in percent. IMCP models use the Common POLES/IMAGE baseline, which is based on SRES scenarios A1B and B2 and assumes "a strong dependence on fossil fuels" (van Vuuren et al., 2003). GDP losses in 2100 for MIND and DEMETER are very close to zero. Source: adapted from IPCC WG3 (2007, Figure 3.25)

excluding those models that explore an extreme scenario (such as energy conservation as the sole abatement option), are below 1 percent discounted GDP (gross domestic product) for the next century. This is low compared to numbers from other models. Figure 6.1 from IPCC WG3 (2007) shows that mitigation cost estimates from this comparison study (denoted as "-IMCP") are at the lower end of a set of state-of-the-art models.

However, the magnitude of the impact of ITC differs greatly, ranging from 90 percent reduction of mitigation costs to models where introducing ITC has almost no effect. Numerous reasons for this variety in model results were identified. Here, I summarize these reasons in three categories: first, baseline effects, second, differences in mitigation strategies, and third, modeling assumptions.

Baseline Effects

The baseline (or business-as-usual scenario) has a strong impact on mitigation costs because it determines the necessary emission reductions. Emission profiles that are consistent with a certain GHG concentration stabilization target are very similar across models because the uncertainty about climate models is relatively small. Contrary, predictions of economic output and associated emissions for the next century vary strongly between economic models. Although an effort was made to harmonize the business-as-usual scenarios of the different models, the remaining differences need to be taken into account when interpreting the results.

Mitigation Strategies

The choice of a mitigation strategy is closely related to the corresponding mitigation costs: when the mitigation strategy constitutes avoiding emissions by reducing the economic output, costs will be high compared to strategies that rely on switching from fossil fuel combustion to carbon free energy sources. Here, mitigation strategies are explored on two levels of aggregation. First, abatement is decomposed along the Kaya identity, i.e. into reductions of economic output, energy intensity of output, and carbon intensity of energy (Kaya, 1990). Second, abating emissions through change in the composition of energy supply are considered, e.g. the usage of energy from renewable sources or utilization of carbon capture and storage (CCS).

Overall emissions reductions are attributed to the factors of Kaya's identity, carbon intensity, energy intensity, and output[2]

$$\text{emissions} = \frac{\text{emissions}}{\text{energy}} \cdot \frac{\text{energy}}{\text{output}} \cdot \text{output}$$

using the refined Laspeyres index method (Sun, 1998). Naturally, reducing output as a means of mitigation is only a last resort as it translates directly into mitigation costs measured as loss of GDP. The analysis reveals that macro-economic models without explicit representation of the energy sector tend to focus their abatement strategy on reductions of energy intensity, whereas energy system models and models that feature an energy sector achieve the majority of their abatement through decarbonization. Reducing carbon intensity becomes particularly important for large reductions of emissions: while many models raise the contribution of carbon intensity reductions for lower levels of GHG concentration stabilization, those models without decarbonization options in explicitly modeled energy systems resort to reducing their GDP. The tendency that carbon intensity reductions become increasingly more important with the level of emission reductions is confirmed by their contribution over time: reduction of energy intensity dominates abatement in early periods of simulation time, but the contribution of carbon intensity reduction is more important in later time periods.

The composition of the energy supply mirrors these trends. Models that focused their abatement strategy on reducing energy intensity and GDP are those that lack options to decarbonize the energy system, or that simply did not resolve the energy sector explicitly. Conversely, large reductions of carbon intensity are implemented through large shares of carbon free energy, e.g. energy from renewable sources, use of CCS, and nuclear power. This implies that mitigation costs as well as strategies ought to be sensitive towards the assumptions about the availability of carbon free energy, e.g. from backstop technologies or end-of-the-pipe technologies—a hypothesis that is confirmed by the analysis in Chapter 2 of this thesis. Among the carbon free energy sources, CCS plays a special role. With respect to the utilization of this option over time, those models that account for rising fossil fuel prices due to resource scarcity show a peak and decline of CCS. This suggests that the competitive advantage of CCS is lost when resource scarcity raises the price of fossil fuels and at the same time alternative carbon free energy sources such as renewable energy become cheaper due to learning effects. Thus, CCS would only be a temporary abatement option.

Modeling Assumptions

Three key modeling assumptions were identified that explain some of the major differences in model results: first, whether a model describes a first-best or a second-best world.

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[2] As population dynamics are exogenous to all participating models, I omit it as a factor in the identity.

Second, the choice of the model type, e.g. energy system model, computational general equilibrium model (CGE), or optimal growth model. Third, assumptions about foresight of economic agents in their investment decisions.

First-best models abstract from market distortions. Therefore, comparing first-best scenarios with and without climate policy exposes the opportunity costs of mitigation. In contrast, in a second-best model a (climate) policy may remove imperfections that distort markets in business-as-usual in addition to implementing climate protection. Second-best assumptions explain the outliers in the comparison that show very low costs or even negative mitigation costs.

The model type often implies a choice of equilibrium concept. The participating energy system models are implemented as partial equilibrium models. They show particularly low costs, which can be due to neglected general equilibrium effects. The participating CGE model is solved recursively dynamic which reduces its investment flexibility compared to models with perfect foresight. This helps to explain the extraordinary high costs in this model. Finally, models in the optimal growth framework demonstrate the effects of full sectoral and temporal flexibility.

The long-term investment behavior of economic agents in the different models is driven by their ability of foresight. Under perfect foresight, the necessary investments may be undertaken early, thus reducing mitigation costs. This is another reason for the low costs reported in optimal growth models and energy system models.

6.1.3 Discussion

The previous sections stressed the importance of technological change in the assessment of mitigation costs and strategies. Endogenous technological change and the implementation of technological detail in the energy sector were found to make potentially important contributions to mitigating climate change at low costs. This is a plausible result. When introducing ETC and a variety of low carbon technologies increase the flexibility within a model to decarbonize the economy, the impact on costs ought to be favorable. However, this raises the question, whether the flexibility of the real world energy system and economy, or rather their inertia and inflexibilities, are sufficiently captured.

Indeed, several models used in this thesis rest on assumptions that potentially overestimate the world economy's flexibility to be decarbonized. These assumptions include modeling the world as one aggregate rather than distinguishing world regions, and focusing on the combustion of fossil fuels in the energy sector as the main driver of GHG concentrations.

The latter neglects that abatement of emissions from, for example, transport or consumption behavior of households may be more difficult to achieve. Indeed, one modeling team cited the explicit transport sector in their model as an important factor contributing to the pessimistic prediction of mitigation costs (IMACLIM-R). Modeling the world economy without regional disaggregation, on the other hand, cannot resolve any inefficiencies that arise from regional heterogeneity. Consequently, the model comparison study recommended extending integrated models towards "hybrid models" comprising detailed energy system models in a macro-economic setting, and to explore the regional effects of mitigation.

Since the publication of Edenhofer et al. (2006a) and Edenhofer et al. (2006b), model development in integrated assessment of climate change has shifted towards such hybrid models (see for example the Special Issue on Hybrid Modelling edited by Hourcade et al., 2006), in particular in new model developments such as the WITCH and REMIND-R models (Bosetti et al., 2006b; Leimbach et al., 2008). Resolving technological detail allows these models to draw on technological and empirical data, giving these models a solid, data based calibration, which before was only available to energy system models. Moreover, both WITCH and REMIND-R feature multiple regions.

The assumption of perfect foresight has a large influence in bringing down costs. Of course, this model assumption overstates the ability of individual economic actors. In this sense, models that assume perfect foresight only conclude that mitigation costs are *potentially* low. However, this result should also be a motivation for policy to implement a stable long-term climate policy and investment environment, which in effect increases the ability of economic actors to take longer time horizons into account. The design of stable mitigation agreements is addressed in Chapters 4 and 5 of this thesis.

6.2 The Prospect of Issue Linking for Global Climate Policy

Chapters 2 and 3 looked at climate policies implemented as global policy targets, in particular maximum carbon dioxide concentrations. They took for granted that policies need to be agreed upon and implemented to achieve these targets by placing the necessary price on carbon, e.g. by determining a distribution of emission allowances and setting up a global carbon market. Establishing a carbon price this way requires global coordination and cooperation but it is known from literature as well as political experience that negotiating such an international environmental agreement is difficult. Chapters 4 and 5 looked at the potential of issue linking to help to build such agreements.

6.2.1 Trade Sanctions

In the introductory chapter, the following questions were raised concerning international cooperation:

- What is the prospect for international cooperation on climate change mitigation?
- How can it be increased by the design of international environmental agreement?
- What is the potential of trade sanctions to increase participation in international environmental agreements?
- What are the effects on environmental and global welfare of trade sanctions on the one hand and increased cooperation on the other hand?
- How can competitive equilibria be computed in models with emission externality, international trade, and tariffs?

To answer these questions, I developed an integrated assessment model of coalition formation. The topic at hand, namely international cooperation to mitigate climate change, requires a modeling framework apt to describe long-term economic development due to the inertia of the climate system. To account for the stock pollutant character of climate change, a dynamic model is needed. And any model discussing the prospect of cooperation needs to describe many actors. Therefore, the model developed for this thesis is a multi-actor optimal growth model. Including international trade and implementing trade sanctions in a coalition model within this framework has to the best of my knowledge not been done before.

The model is calibrated such that global totals of the model outputs like economic output, savings rate, export ratio, emissions, are consistent with real world data. However, actors within the model are assumed to be identical. This limits the applicability of the model to real world negotiation, but facilitates studying the incentives for cooperation in isolation from the distributional effects introduced via heterogeneity of actors.

I show in numerical experiments that introducing trade sanctions positively affects cooperation on international cooperation: When those actors that cooperate on climate protection additionally impose import tariffs on goods from non-members of the coalition, more actors are inclined to participate in the joined international agreement of both, environment and trade, than elsewise. Indeed, participation rises with the tariff rate, reaching full cooperation at some point. How quickly participation rises and at which tariff rate full cooperation is sustained depends on the ease with which taxed goods are substituted with alternatives. Global welfare rises with participation despite the distortions caused by trade restriction. These results proved robust against variation of key parameters. Tariffs therefore seem to be a feasible means of increasing participation.

Moreover, trade sanctions turn out to be a credible incentive in the sense that imposing an import tariff is beneficial to the coalition. This is true as long as the tariff rate is ‘small’ in relation to the substitutability of the taxed good: when goods are easily substituted the losses of reduced trade will exceed the additional income in form of tariff revenues.

Standard approaches to find a competitive equilibrium for traded goods could not be applied due to the market distortions introduced via climate change on the one hand and tariffs on the other hand. This was overcome by extending existing approaches.

6.2.2 Technology-oriented Agreements

The next set of questions explores potential interactions between endogenous technological change and international cooperation. Specifically, it focuses on issue linking of environmental agreements and technology oriented agreements.

- How does ETC help to promote international cooperation on emission abatement?
- What are the roles of different technology oriented agreements (TOA)?
- What is the role of cooperative research and development and technological spillovers?
- In which ways does the type of technology that spills over matter?

- What is the role of international technology standards?

I address these questions by applying the model of coalition formation developed for this thesis. The model was extended by two concepts of technological cooperation: international actors could chose to cooperate on R & D (augmenting either productivity or mitigation) and by doing so benefit from increased technology spillovers, or actors could jointly implement international technology standards.

It turns out that ETC provides a means to increase participation in an environmental cooperation: issue linking of the environmental agreement to cooperative research, which induces increased technology spillovers changes the incentive structure such that more actors sign the linked agreement. The number of participants rises with the intensity of spillovers up to and including full cooperation.

The type of technological knowledge that spills over (either related to productivity or mitigation) makes a difference for the effectiveness of this type of issue linking: cooperation on productivity R & D is unambiguously more effective in raising participation in the agreement, global welfare, and environmental quality. The reason is that the benefit of cooperation is only truly exclusive to the coalition in case of productivity. In case of cooperation on mitigation some of the benefits of cooperation spill over indirectly to non-members via reduced climate change damages. This impact of the source of spillovers helps to understand why previous investigations into this topic came up with mixed results: in Botteon and Carraro (1998) where spillovers are related to productivity high levels of cooperation are sustained through issue linking. Contrary, in Nagashima and Dellink (2008) spillovers are related to mitigation technology and the impact on participation is only modest.

International technology standards are also shown to have a positive effect on coalition formation. By assumption, standards are easier to agree on and implement, and "standards agreements" are accomplished *ad hoc*. The existence of a separate standards agreement alone has very little impact on environmental cooperation. It would, however, significantly increase participation in a linked agreement on environmental and technological cooperation.

This renders a stepwise approach of building coalitions possible: creating a global agreement on technology standards would not (according to this model) solve the climate problem in the sense of inducing increased cooperation in an environmental agreement. It does, however, prepare the ground for a linked agreement on environmental and technological cooperation.

6.2.3 Discussion

Chapters 4 and 5 assessed the impact of linking environmental cooperation to trade sanctions or technology-oriented agreements on the incentives to participate in an international environmental agreement using numeric model experiments. In principle, it would be preferable to derive analytical solutions because of their greater generality. However, showing the stability of coalitions in general is often not feasible, in particular when models include more complex interactions such as spillovers, trade, and tariffs. Relying on numerical simulations enables me to explore these issues in the state-of-the-art framework of optimal growth modeling. Additionally, I can avoid simplistic assumptions during model development, for example, the stock pollutant characteristic of GHG concentrations can adequately be accounted for by using a dynamic modeling setting. Still, it is important to keep the limitations of numerical results in mind when drawing conclusions from model results.

The modeling approach in this thesis takes middle ground between using stylized economic actors and modeling real world actors by calibrating global totals of economic output, GHG emissions, etc. to data. While using identical actors has advantages when investigating the impact of issue linking in general, the analysis would benefit from calibrating all actors to real world regions to additionally estimate the magnitude of these effects.

The model assumes national product differentiation in a single good world to describe the driving forces of international trade. Consequently, when trade sanctions in form of import tariffs are imposed by coalition members, all trade is affected. Realistically though, a trade sanction under World Trade Organisation rules could only target carbon intensive goods. So while the current description of trade suffices to access the scope of trade sanctions in a very general setting, a real world analysis of the approximate magnitudes of gains, losses, and impact on incentives of tariffs would require multiple traded goods.

Furthermore, the exploration of technology oriented agreements includes a first numerical assessment of international technology standards. As discussed in the corresponding chapter, an *ad hoc* agreement concerning the global implementation of these standards is assumed because arguably, their incentive structure makes standards self-enforcing. Naturally, the analysis would be more complete if the decision about an agreement on standards was incorporated into the given model. The necessary model extension would encompass introducing technological dynamics exhibiting the potential for increasing returns to scale and lock-in effects for technologies.

6.3 Outlook and Further Research

The questions and concepts explored in this thesis can be extended in future research in at least three ways: further model comparisons, advanced concepts of coalition stability, and accounting for the large uncertainties, which are pervasive in integrated assessment modeling of climate change.

Model comparisons are established as a tool to assess uncertainty in model structure. The Stanford Energy Modeling Forum (EMF) has pioneered model comparisons for integrated assessment models of climate change, and likewise, Chapter 3 of this thesis used a model comparison to shed light on the impact of induced technological change. Section 3.6.6 suggests to move the comparison of mitigation strategies in IAM down to the level of technological options—this suggestion has been taken up in ADAM (2008, pp. 8–9). Game theoretic models of climate change are not as numerous as their integrated assessment counterparts. But new model developments from recent years, Finus et al. (2006), Bosetti et al. (2006b) and the coalition model from this thesis (Lessmann et al., 2009), have led to a critical mass in models and variability in their predictions (e.g. about the effects of spillovers on participation in different models as discussed in Section 5.5), thus meriting a comparison of these models and the driving forces of their results. Comparing the predicted stable coalition from these model would be a demanding task. Running comparable scenarios in these different models is already a challenge for simple non-cooperative or fully cooperative settings, and the game theoretic setting of stable coalitions adds another layer of complexity: assumptions concerning the concept of stability, number of players, choice of regions, intra-coalitional welfare transfers, etc. would require harmonization. Nevertheless, valuable insights may be gained, e.g. concerning which assumptions are decisive for the incentive to free-ride for different regions in different models.

The concept of coalitional stability used in this thesis, cartel stability, is frequently used in applied analyses of international environmental agreements. It has great intuitive appeal and is readily implemented, partially due to its myopic perspective, e.g. a player abandoning a coalition will not anticipate whether the remaining coalition perseveres, even though this has strong implications for her payoff. In a setting where actors take their economic decision with perfect foresight, this assumption on strategic foresight seems rather limiting. More advanced coalition concepts are discussed in the game theoretic literature, such as Faresightedly Stable Coalitions and the Coalition Proof Nash Equilibrium. To date, these concepts have rarely been applied in integrated assessment models. Furthermore, in case of the cartel stability concept, international environmental agreements are modeled as a one-shot, static game, even though the negotiations on a climate agreement under the UNFCCC seeks to increase participation in future commitment periods. Dynamic games would capture this better than the static approach, indeed non-static concepts have recently been employed: Weikard and Dellink (2008) allow to renegotiate their agreement in several commitment periods, Rubio and Ulph (2007) analyse dynamic membership. Still, modeling dynamic international environmental agreements is in its infancy.

In economic models that span several centuries, uncertainties abound. This is especially true for the estimates of climate change damages, which are an integral part of game theoretic models of climate change because the assumption on damage functions determine the benefits of abatement. The analysis of coalition stability would therefore benefit from additional research on damage functions.

Overall, the studies reported in this thesis suggest that there is indeed potential that ITC may reduce the burden that mitigation requirements will put on the economy. And while there is no final conclusion to the magnitude of the impact of ITC due to the model uncertainty, which remains large, this thesis advanced the understanding of these uncertainties and the underlying reasons for the variability in the results. To exploit a large potential of ITC, a clear carbon price signal is required. This thesis suggests that linking the negotiations on climate policy to trade sanctions or to research cooperations is a feasible way to create incentives that make a cooperative global climate policy more likely. Again, more research is needed to determine the magnitude of the potential of issue linking, but its potential in general has been shown and different issue linking proposal have been characterized with respect to their advantages and disadvantages.

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Statement of Contribution

The four core chapters of this thesis (Chapters 2 to 5) are the result of collaborations in this PhD project between the author of this thesis and his advisor, Prof. Dr. Ottmar Edenhofer, sometimes involving additional colleagues as indicated. The author of this thesis has made extensive contributions to the contents of all four papers, from conceptual design and technical development to writing. This section details the contribution of the author to the four papers and acknowledges major contributions of others.

Chapter 2 This chapter uses the MIND model developed by Edenhofer, Bauer, and Kriegler (2005a). The author's contribution to this chapter is the conceptual design of the research question and the numerical experiments, their implementation and execution, and the subsequent analysis and processing of model results and their visualization in the graphs of the chapter. Discussions and conclusions from these results were written in close cooperation with O. Edenhofer.

Chapter 3 In preparation of this chapter, the author made decisive contributions to the conception and design of the Innovation Modeling Comparison Project, in particular the definition of the baseline and policy scenario. The author coordinated the quantitative comparison of model results by preparing a questionnaire on the details of the model as well as a reporting scheme for model output, and was in charge of correspondence with the modeling teams, particularly for collecting and processing questionnaires and model output. Consequently, all data analysis and visualization in graphs are due to the author. The text of the chapter was written in close cooperation by the author and O. Edenhofer, with revisions by all coauthors of the article.

Chapter 4 The conception of the dynamic model of coalition stability and its application within the theme of issue linking was jointly developed by O. Edenhofer and the author; R. Marschinski contributed to the conception of how to include trade in the model. The implementation of the model and development and implementation of the solution algorithm in GAMS are due to the author. Likewise, all calculations, analysis of model output and graphs for the article were done by the author. Interpretation, discussion, conclusions and the writing of the article text were done in close collaboration with R. Marschinski.

Chapter 5 The research question for this chapter was developed in cooperation with O. Edenhofer. Model development, numerical experiments, their interpretation and discussion, and the manuscript are due to the author.

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Tools and Resources

This dissertation relies heavily on numerical modeling. Naturally, a number of software tools were used to create and run the models, and to process, analyze and visualize the results. This section lists these tools.

Modeling All model experiments performed by the author made use of the General Algebraic Modeling System (GAMS), version 22.7.2 (Brooke et al., 1988) and the CONOPT3 solver, version 3.14S, for non-linear programs (Drud, 1994). The multi-run environment SimEnv, versions 1.15–2.01, was used frequently (Flechsig et al., 2008).

Data Processing Model output was analyzed using The MathWorks' MATLAB, version 6.5 release 13 (MATLAB, 1998) and the NetCDF Toolbox for MATLAB by Charles R. Denham, as well as the statistical software R, version 2.4.0 (R Development Core Team, 2008).

Typesetting This document was prepared using LaTeX 2ε (Lamport, 1994), particularly the pdfpages package (Matthias, 2006), to include Chapters 2 to 5 in their given layouts.

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