Bringing down the costs of climate protection - Lessons from a Modelling Comparison Exercise

Submission to Stern Review on the Economics of Climate Change

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1. Introduction

If and when the costs of mitigating greenhouse gas emissions are high, climate policy faces a difficult trade-off between climate protection and impact on economic growth. In a separate submission to the Stern Review (Grubb et. al. 2005) we have argued that treating this trade-off purely as a cost-benefit-analysis where avoided marginal damages are pitted against the costs of climate protection may not be the most productive framing for several reasons. Many of these reasons are concerned with the scale of uncertainties combined with the inertia and irreversibilities in both economic and natural systems. Another important dimension that we noted is the impact of technological change, and in particular, the potential impact of policy decisions upon the nature and cost of future technological options. That is the focus of this submission.

The risks around climate change form the principal rationale behind an emerging political consensus within Europe, which implies that global mean temperature should be prevented from rising faster than 0.2°C per decade and above 2°C relative to pre-industrial levels – an ambitious formulation of the challenge. Such constraints are seen as necessary if dangerous perturbations of the climate system are to be avoided in the next decades. Otherwise impacts such as an increased probability of extreme weather events, disturbances of the global water circulation, loss of biodiversity, or sudden shifts in monsoon dynamics become much more likely. This requirement has been adopted as the guardrail of the German Scientific Advisory Council on Global Change (2003, p. 107), which emphasized its importance again in its latest survey.

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As indicated, the deep uncertainties make it very hard to evaluate the target in a formal cost-benefit sense, but some economists argue that it is overambitious if mitigation costs, avoided damages and the adaptive capacity in dealing with climate change are taken into account properly. In particular, the mitigation costs are considered to be relatively high compared to some estimates of monetary damages. However, if induced technological change (ITC) has the potential to reduce mitigation costs, then the "risk premium" for containing disturbances to the earth system to this degree may be far more affordable, and the trade-offs with other policy goals far less onerous.

We are not in a position to undertake a comprehensive social cost benefit analysis that also comprises a proper estimation of damages and adaptive capacity. This submission focuses on the impact of ITC to reduce mitigation costs within cost-effective mitigation strategies, reporting the main results from a major international project to explore the modelling and implications when technological change is modelled endogenously in global energy-economy models:

Section 2 summarises the project
section 3 discusses the findings on mitigation costs,
section 4 examines the technological contributions to different stabilization scenarios,
the final section discusses implications for future research.

2. The Innovation Modelling Comparison Project (IMCP)

The IMCP has attempted to explore the potential of ITC in a modelling comparison exercise. The IMCP aims to look at the quantitative impact of induced technological change (ITC) on the economics of stabilizing carbon dioxide emissions at different levels. Initiated by Michael Grubb and John Schellnhuber, the IMCP was motivated by the conviction that endogenous technological change[3] (ETC) is vital in modelling economic dynamics on the long time scales required in climate policy analysis. It was designed to assess the state-of-the-art of endoge-

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[3] We differentiate *endogenous* and *induced* technological change: We call technological change *endogenous* (ETC) if its pathway 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.

nous technology modelling across a wide diversity of approaches, and to consider the potential implications for atmospheric stabilisation.

Following an open call for participation and a year's work programme, ten models of different model types have been analysed including Optimal Growth Models, Energy System Models, Simulation models and Computable General Equilibrium (CGE) models. A full description of the project, the underlying theoretical issues, a comprehensive synthesis of results, and the individual papers have been accepted for publication in a Special Issue of the Energy Journal (Edenhofer et. al. 2005e). This submission focuses upon highlights from the Synthesis report (Edenhofer et. al. 2005c).

3. Induced Technological Change and its impact on Mitigation costs

Some of the theoretical literature about ITC Induced Technological Change (Nordhaus 2002, Weyant/Olavson 1999) has been ambiguous about its impact on the costs of mitigation, partly on theoretical grounds associated with "crowding out" of R&D between sectors. The ten models participating in the IMCP span a considerable range, but at the highest level results can be summarized as follows:

a) Induced technological change reduces the mitigation costs
b) Mitigation costs increases with stricter stabilisation levels despite ITC
c) The "typical" IMCP model derives mitigation costs below 1 % of gross world product if stabilisation levels of 450-550ppm are achieved.
d) The costs differ between the different model types. However these differences comes more from the different assumptions about backstop-technologies and end-of-pipe technologies than from the model type itself.

The rest of this section addresses the cost dimensions, the subsequent section examines the strategies the models adopt in response to stabilisation constraints.

a) Induced Technological change reduces mitigation costs

Figure 1 summarises mitigation costs, as a percentage of gross world product (GWP), in different models for different stabilisation levels. This is 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.

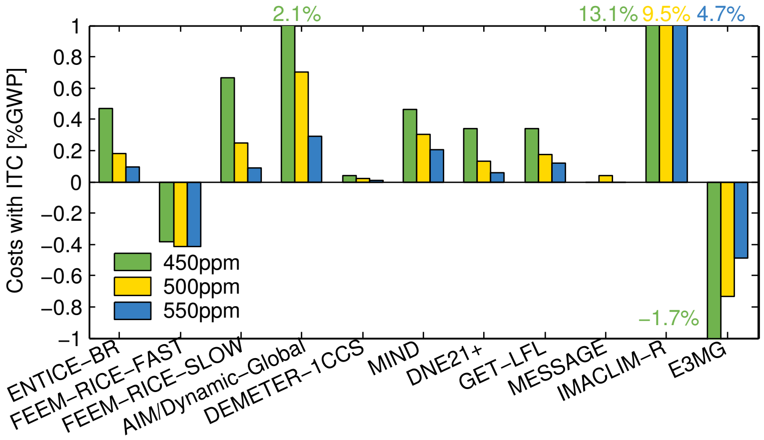

FIGURE 1. *Mitigation costs as a relative loss of gross world product.*

In some models the costs are relatively low because of a small gap between emissions within the business-as-usual scenario and the admissible emissions within the stabilization scenario and not because of a strong impact of ITC on the costs. Consequently, so-called baseline effects have a strong influence on the results. In order to reduce this baseline effect on mitigation costs, we compare scenarios with ITC switched on and off, thus looking at the relative effect of including ITC. This allows us to isolate the effect of ITC by ensuring that all other boundary conditions and parameters remain constant. We find that ITC reduces mitigation costs in all models (for more details see Edenhofer et al. 2005c).

In Figure 1 two models (E3MG and FEEM-RICE-FAST) show negative costs, i.e. gains from implementing climate policies. In the case of E3MG this originates in the Keynesian treatment of demand-side long-run growth, assuming increasing returns to production and underemployment of labour 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 higher growth originates from their second-best baseline scenario.

b) With stricter stabilisation levels, the mitigation costs increases despite of Induced Technological Change.

Nearly all models in Figure 1 conclude that more ambitious climate protection goals lead to an increase in mitigation costs. Note that this is not a trivial statement. With learning-by-doing mitigation costs could in principle decrease if lower stabilization targets are imposed. However, the modelling teams participating 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 externalities.

Only few models achieve a feasible solution when faced with a stabilization target of 400ppm (DEMETER-1CCS, MIND, FEEM-RICE, and GET-LFL). This stabilization level is required when the 2°C target is to be achieved with a relatively high probability (Hare/Meinshausen 2004). Many models cannot derive a feasible solution for 400ppm due to 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 behaviour.

c) The "typical" IMCP model derives mitigation costs below 1 % of gross world product

Although the total span of results in Figure 1 is very wide, three models are of a predominantly exploratory nature, i.e. their intent is not to give a best estimate but to explore extreme or very constrained conditions. The three models are: First, IMACLIM-R, which explores the role of the transportation sector under the assumption that the energy and transportation sector are inflexible and externalities of investments in physical capital are biased against energy efficiency. Second, AIM/Dynamic-Global limits the portfolio of mitigation options to investments in energy saving capital, hence emissions cannot be decoupled from economic growth in the long-run. These two models arrive at the highest costs in this study. Third, there is FEEM-RICE-FAST exploring the possibility of extremely "fast" technological change, which then results in benefits of climate protection rather than climate protection costs. Moreover, E3MG is fundamentally different from the remaining models because it adopts a Keynesian rather than a neoclassical point of view,[4] in which the investment and innovation consequences of tighter stabilisation targets lead to net economic benefits within the energy system.

These cases – two at the high cost end, and two that generate net economic benefits - illustrate interesting phenomena but are not representative of the more central and probable views. The remaining set of seven models generate cost estimates that range from 0.04% to 0.66% costs / loss of discounted GWP over the Century. The mean costs among these remaining models are 0.39, 0.16, and 0.1 percent, for 450ppm, 500ppm, and 550ppm stabilization, respectively. If we abstract from the two energy system models that do not report costs in terms of GWP, the numbers hardly change to 0.41, 0.16, and 0.1 percent, for 450ppm, 500ppm, and

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[4] We do not mean to imply that either point of view has more claim to be true.

550ppm stabilization, respectively. These last numbers average over 4, 5, and 4 models, respectively.

Notwithstanding the considerable uncertainties about model structure and other assumptions, our best estimate is that – taking into account the impact of market conditions upon technological change - the costs climate protection to levels as low as 450ppm CO2 are unlikely to exceed one percent of GWP.

4. Mitigation strategies and ITC for different stabilization scenarios

Within IMCP we have extensively analyzed the characters of mitigation strategies. The crucial results are:

a) In the participating models, induced technological change works more towards decarbonization rather than reducing energy intensity.
b) Backstop Technologies (mostly modelled as renewable energy technologies) are crucial for achieving a low emission and low cost equilibrium.
c) Some models show extensive use of CCS as temporary solution. Carbon Capturing and Sequestration (CCS) as an end-of-pipe technology allows in some models a welfare improving postponement of the diffusion of the backstop technology.
d) Some models incorporating backstop technologies and carbon capturing and sequestration show a path dependent behaviour.

a) The Role of Decarbonization

The stacked bars in Figure 2 show the amount of CO_2 savings in the 550ppm policy scenario from the baseline cumulated over the century. Additionally, colours indicate how much reductions in carbon intensity, energy intensity, and output (GWP) contribute to these savings.

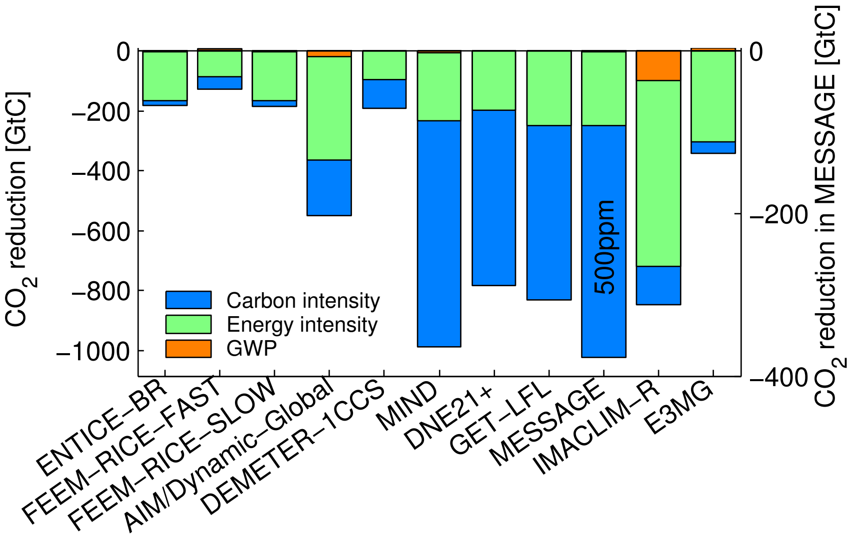

FIGURE 2. *Cumulative CO_2 reduction for the 550ppm stabilization scenario 2000-2100. CO_2 reductions are attributed to reductions in carbon intensity, energy intensity, and gross world product using decomposition analysis.*

The necessary carbon dioxide reductions for complying with low stabilisation target differ strongly among models. The cumulative reductions necessary to comply with a 550ppm concentration cap range from ~116GtC to ~988GtC (in FEEM-RICE and MIND, respectively), implying great differences in the challenge that such reductions pose for an economy.[5] We stress that models tend to agree on the maximum allowable cumulative CO_2 emissions for a given stabilization scenario: averages among models for cumulative CO_2 emissions are 582, 780, and 916GtC for 450, 500, 550ppm stabilization scenarios, respectively. The corresponding standard deviations are 79, 86, and 110GtC. The differences in Figure 2 stem mainly from different CO_2 emission paths in the baseline: cumulative CO_2 emissions in the baseline range from 860 to 2000GtC, mean 1392, with a standard deviation of 392GtC. To account for such baseline effects, we will base our analyses on measures that are as much as possible relative to this 'mitigation effort'.

b) The Role of Backstop Technologies

The whole process of decarbonisation within the IMCP models is mainly driven by the implementation of backstop technologies. In accordance with the literature, we define a backstop

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[5] An obvious collary from these numbers is that emission reductions are necessary to meet even the 550ppm policy goal despite the presence of ETC in the baseline.

technology as a carbon-free technology the usage of which is not restricted by scarcity of non-reproducible production factors. What makes backstop technologies so important in carbon abatement?

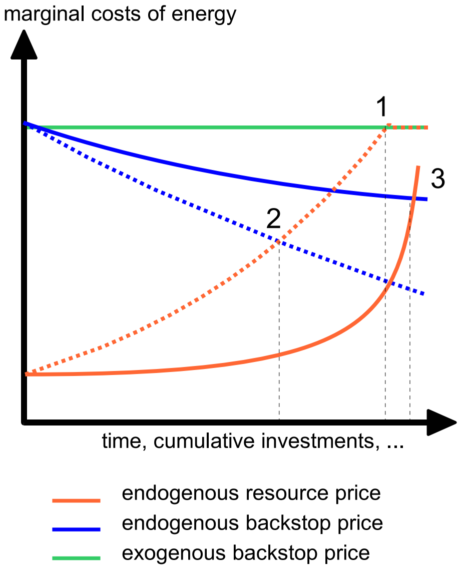

FIGURE 3. *Different formulations of backstop and fossil fuel sector*

In Figure 3, we sketch model behaviour given two different assumptions about backstop technology. The price of energy from a fossil resource is indicated in orange. An exogenously set price for energy from the backstop technology is indicated in green. In contrast, the price of energy from a backstop technology is given in green for the case where it is set exogenously, and plotted in blue in case of an endogenously determined backstop price. Solid time paths indicate business-as-usual, and slashed paths 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 level (intersection 1). There is no intersection with the business-as-usual path.

In case of the backstop technology being explicitly modelled, i.e. backstop capacity is being build up and the 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 on, indicating that investments are being made in anticipation of the later competitiveness. Intersection 3 illustrates, that this may even be the case in 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 reduce mainly energy intensity to achieve climate protection goals. Those models that do incorporate carbon-free energy from backstop technologies are of the second type discussed above (ENTICE-BR, AIM/Dynamic-Global, DEMETER-1CCS, MIND, GET-LFL, DNE21+, MESSAGE-MACRO, and E3MG), i.e. rather than prescribing an exogenous price, the backstop technology is endogenously comprised in the model. Within these models decarbonization is the predominant mitigation strategy.

Figure 3 also helps to understand the role technological change in the resource extraction sector. Similar to technological change in case of the backstop technology, it can 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 decrease the competitiveness of the backstop technology and therefore increase the opportunity costs of climate protection. It may be worthwhile to 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. 2005b). 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.

c) The role of Carbon Capturing and Sequestration

Among the participating models, five explicitly incorporate the option to prevent CO_2 emissions from fossil fuel combustion by capturing and storing it (DEMETER-1CCS, MIND, DNE21+, GET-LFL, and MESSAGE-MACRO). Figure 4 shows how much CO_2 is captured in different scenarios, accumulated over the century.

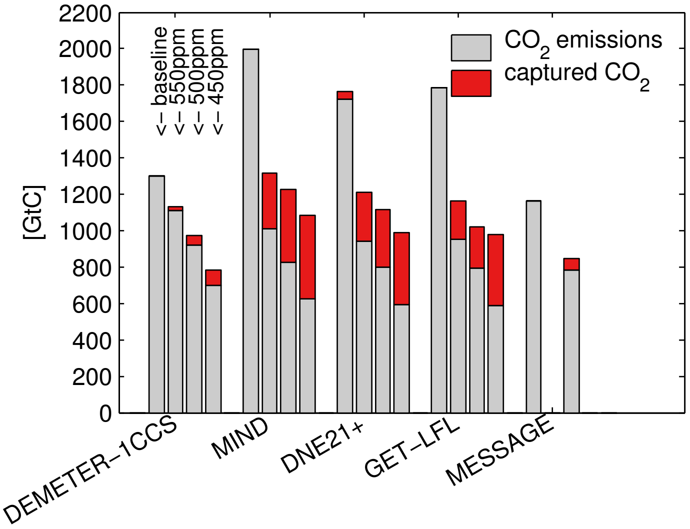

FIGURE 4. *Captured CO_2 and total CO_2 emissions. The figure summarizes usage of the CCS option in the baseline and two policy scenarios as a share of total amount of CO_2; CO_2 that is not captured is emitted.*

As one would expect, Figure 4 shows that the more challenging the climate policy target is, 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 presence of climate policy. DNE21+ is an exception to this rule, 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 fraction of the difference of emissions in baseline and policy scenario.

Two more features contribute to the temporary nature of CCS which is captured in the model MIND: Easily available storage sites are subject to scarcity[6], and MIND models CCS including leakage from storage sites at a fix rate (i.e. the same percentage leaks from the storage

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

site in each time period), implying that CCS does not prevent but only strongly delay 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[7]. 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, Edenhofer et al. 2005a 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 is low, (d) the capacity of deposits is increased and (e) the costs of the fossil fuels are decreased. Furthermore, the effect of a high price for the backstop technology and a low learning rate for it are beneficial.

d) Path Dependency

Within some models the carbon price peaks and declines afterwards. This confirms what some technical change analysts have presupposed: Experience from learning-by-doing or the reality of sunk costs introduce a path dependent scenario development, and thus marginal cost 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. To conclude, some models exhibit a behaviour where the transformation process toward a low emission society is irreversible.

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[7] GET-LFL includes CCS in combination with energy production from biomass. The above argument abstracts from this special case.

5. Implications from the IMCP

In our analysis we identify the crucial economic mechanisms that drive technological change. This modelling comparison exercise demonstrates that the following features of ITC are crucial for determining mitigation costs and strategies:

a) Assumptions about long-term investment decisions
b) Backstop and end-of-the-pipe technologies

a) 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. 2005d). 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 large 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 behaviour makes 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-behaving 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 ingredients for the transformation of the energy system. Therefore, the primary focus for Kyoto beyond 2012 should be the design of policy instruments allowing for long-term investments.

b) 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.

Over the last decade the debate has been focused mainly on the learning-by-doing potential of backstop technologies. However, it turns out in this study that this is only one side of the coin. The other side for 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 modelling efforts need to include a more realistic representation of endogenous technological progress within the fossil fuel sector.

c) Hints for a future research agenda

This modelling comparison exercise takes a first step in assessing the quantitative impacts of ITC on mitigation costs and mitigation strategies. The quantitative impact of ITC is isolated by imposing ceteris paribus conditions, i.e. endogenous technological is induced by climate stabilization targets in a setting where boundary conditions and parameters remain unchanged. Furthermore, in IMCP we have harmonized the baselines of gross world product for the next two decades.

Many of our insights were due to this approach. We think it would be worthwhile to expand this effort in two ways: On the one hand, future model comparisons could refine the harmonization of the participating models to a baseline of central variables (capital stock, investments, bias in technological change) and parameters in order to minimize baseline effects. On the other hand, 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 and could therefore be subject to future model comparisons, e.g. regional spillovers. Moreover, while this study restricted policy intervention to imposing stabilization levels, i.e. setting policy goals, 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 also for a formulation of an agenda improving further modelling design: First, we have explored some reasons for the gap 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 for developing a coherent framework incorporating intertemporal, intersectoral and interregional effects of induced technological change. Second, as it has turned out in IMCP, assumptions about long-term investment behaviour have a strong impact on mitigation costs and strategies. Therefore, experiments with different assumptions about long-term expectations and long-term flexibility of investment behaviour would be a 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 backstops and/or end-of-the-pipe technologies. We argue that technological change in the fossil fuel sectors is complementary to this, but has not received as much attention. There is significant technological change e.g. in the resource extraction sector with a potentially big influence on the opportunity costs of climate protection. Moreover, the potential of ITC in overcoming the fallacies of international cooperation is widely unexplored and deserves further research. A better understanding of the underlying dynamics may therefore improve the design of climate policy.

There is an ongoing debate about the design of climate policy. Recent discussions have cast some doubt about the time consistency of cap and trade systems. Some authors argue that cap and trade systems have to be complemented by purposeful R&D strategies in order to make cap and trade systems time-consistent for private actors. This debate has to be put in broader perspective about the role of cap and trade systems when ITC plays a crucial role. It is a clear message from IMCP that backstop technologies and also to a certain extent end-of-pipe technologies are crucial for reducing the costs of mitigation. However, cap and trade systems alone cannot induce the required technological change because the required investments in backstop and end-of-pipe technologies are highly uncertain. Therefore, additional policy instruments such as Green Energy Certificates and feed-in-tariff systems have to be considered complementary to cap and trade systems. The discussion about a regulatory framework for CCS is at an infant state. However, the risk of leakage from geological sites requires an adequate regulatory framework. The Carbon Sequestration Bond(CSB) proposal by one of the authors (Edenhofer et. al. 2005a) explore one way to deal with such risks because cap and trade systems are only necessary but not sufficient for inducing the social optimal amount of CCS.

The IMCP results suggest that innovation – much of it endogenously arising in the economic system in response to credible signals and incentives – can greatly lessen the trade-off between climate protection and economic growth. ITC has already started its career and will play a leading part in the drama called “How to bring down the costs of climate protection.”

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