Restructuring the problem of Global Warming Mitigation: Climate Protection vs. Economic Growth as a false Trade off

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Abstract

The project asks how to derive and then promote a balanced portfolio of climate policies and technologies currently under discussion as efficient means to avoid ('mitigate'), or at least limit, global warming. Thereby, the agenda responds to the emerging consensus within the climate research community that anthropogenic greenhouse gas emissions – such as generated during combustion – would induce global warming with serious potential consequences. The ongoing climate debate about how much global warming should be mitigated serves as a starting point. While 'climate environmentalists' opt for strict emission reductions, influential economists proposed – at least at the beginning of the project – that the requested reductions would severely hamper the world economy. The 'metamethod' of the project disentangles the deterministic and normative arguments of the debate. Within that setting, the methodology of the project displays two main characteristics. Firstly, robust deterministic knowledge about the climate system and the energy technology sector is captured by mechanistic models. This 'deterministic branch' would allow us to represent the effects of greenhouse gas emissions on global warming as well as the effects of investment decisions on the competitive advantage of renewable sources over greenhouse gas emitting technologies. Secondly, the project distills the present line of normative settings involved in the climate debate – what impacts of global warming on the one hand, and of strict emission reduction targets on the other hand, are acceptable. A further normative issue is how to decide, under present-day uncertainties that modulate our knowledge, about the causal links from potential political actions to their impacts. The approach of the project is to search for climate policies that would observe the minimum requests of each of the two major disputing 'camps' and to thereby maximise the chance for societal consensus. The minimum request of the 'environmentalists' is to guarantee that global warming shall not transgress 2°C. The minimum request of economists is that welfare loss due to climate protection should be somewhat below 1%. As a primary result, the project has qualified the systems dynamics, enabling the identification of investment paths that are likely to observe the minimum requests of both parties. Key transdisciplinary challenges of the ongoing project are as follows: distilling the major epistemic (knowledge on systems dynamics) and major normative arguments, and alleged disagreements, as the two are intimately entangled within economic theory; finally, keeping track of assumptions and desires of major players to ensure that the project's stylised solutions will in fact catalyse a societal consensus.

Background

The project attempts to tackle the alleged trade off between global warming mitigation and economic growth that has continually been proclaimed in the scientific as well as the public debate over the last years. While environmental NGOs tend to focus on the former aspect, most large energy suppliers are more concerned with the latter. Furthermore, both points of view are strongly supported, if not shaped, by members of the climate and economic research communities, while the engineering community is split depending on whether they work on renewable or non-renewable sources. Due to the importance of fossil fuels in discussions of climate change, geologists also have a strong impact on the debate about the costs of climate protection, and are themselves divided into two camps. One camp predicts that the extraction of conventional fossil fuels will reach a maximum within a decade; the other camp claims that fossil fuels will remain cheap and abundant for the rest of this century. The latter view is strongly supported by the majority of economists who argue that price signals will induce substitution processes so that potential bottlenecks in the extraction of conventional oil can be overcome. If fossil fuels are relatively cheap and abundant, then the costs of mitigation are relatively high because any limits set on CO_2 emissions effectively devalue assets invested in the fossil fuel sector. The specific role that researchers play within the debate on climate policies is characterised by a delicate entanglement of target knowledge and systems knowledge arguments. Hence, a significant proportion of resources within our project is devoted to clarifying not only the validity, but initially, the category of those arguments.

Furthermore, our assessment requires the integration of various disciplinary paradigms: while the natural sciences strive to extract the key dynamic mechanisms of the system under study, and attempt to be as neutral as possible regarding normative settings, economic growth theory traditionally proclaims to illuminate which future paths (in our case, which investment paths) should be chosen to maximise welfare. As we will outline in the following sub-section, this seeming clash of an 'objective' versus a 'normative' discipline is easier to tackle than is achieving a balanced view of the uncertainties involved in the individual disciplines together with the further complications caused by looking at issues from the engineering perspective. We have to clearly state that any attempt to comprehensively compare the validity of results derived by various disciplines goes beyond the scope of any individual project and rather represents a long-term enterprise. However, we strive to make the assumptions upon which our assessment is based as explicit as possible, while at the same time trying to develop schemes that either bypass pertinent uncertainties or shift the burden of reducing those uncertainties from the research community to powerful market based institutions. We emphasise that these market based institutions have to be embedded in a broader regulatory framework enabling not only economic but also social and ecological sustainability.

In the course of our project we have found it necessary to massively invest in several of the disciplines involved *before* we could use their results for integration: each community had defined its own priorities, which were not optimised for later integration.

Finally, we attempt to integrate social attitudes by striving for new solutions that satisfy the minimum claims of the mitigation side while leaving global welfare roughly untouched, thereby satisfying requirements for a conservative welfare function as proposed by opponents of strong mitigation measures. We represent the minimum mitigation conditions by the requirement that global warming remains within the 'climate window' defined in WBGU (1997): the increase of global mean surface temperature shall not transgress 2°C (compared to its pre-industrial value) and the rate of change shall stay below 0.2°C per decade if large-scale ecosystem or climate system disruptions are to be avoided. The significance of this climate window has been renewed in WBGU (2003). We frequently check the potential of our iteratively substantiated solutions for consensus by informally contacting various opposing stakeholders.

On 16th February 2005, the Kyoto protocol, that for the first time implements an emission cap for carbon dioxide, was put in operation. However, the emission reduction achieved by this framework represents only a small fraction – markedly below 10% – of the reductions necessary to achieve the climate window. Therefore, at present, a 'post-Kyoto regime' is under heavy negotiation. Our project shall contribute to the development of a powerful 'post-Kyoto regime' resulting in significant, yet politically realistic mitigation measures.

The climate debate

The overwhelming majority of climate scientists expect that the Earth's mean surface temperature will increase in response to anthropogenic emissions of greenhouse gases in ways unprecedented over tens of thousands to millions of years. More specifically, in 2001 the Intergovernmental Panel on Climatic Change (IPCC) established as a scientific consensus that the temperature would rise between 1.5 and 6.2°C (Houghton et al., 2001) by the year 2100. This rather large temperature spread is due in roughly equal parts to the considerable uncertainty in intrinsic properties of the climate system and to the span of future greenhouse gas emission scenarios. The latter implies that climate policies would in fact have a strong influence on the extent of global warming. In fact, several global players such as governmental bodies, NGOs and energy suppliers (e.g. the European Commission, 2000; in a somewhat relaxed form also BP 2004) have stated that global warming must be constrained to an upper limit of 2°C to avoid potential massive, or even irreversible, impacts. Although an increasing number of statements have been made in the past few years asking that significant measures be taken to mitigate global warming, a consensus on which options may facilitate an ambitious climate goal has not been established. Typically, individual options such as massive implementation of solar power or life-style changes are considered as either economically inefficient (Lomborg, 2004; Nordhaus and Boyer, 2000), impractical in engineering terms on a large scale, or politically implausible (Lomborg, 2004). At the same time, supporters of these measures disseminate numbers suggesting an enormous potential for mitigating global warming.

Our project aims at clarifying these somewhat contradictory and non-integrated assessments of mitigation options. We expect that an intelligent mix of options rather than one optimal solution will facilitate mitigation (of massive global warming) and analyse the following major options accordingly:

1. Transformation of the worldwide energy system to renewable energy sources
2. Enhancement of energy efficiency
3. Carbon capture and sequestration (CCS)

We aim to determine for the economically optimal mix of investment streams for these options. The optimisation is performed under the boundary condition that the WBGU climate window (as defined above in 'Background') is observed. For our optimisation, *business as usual* (in particular usage of fossil fuels) is treated as a fourth option. While the first two options have some tradition within the political debate on a decadal time-scale, carbon capture and sequestration is only now entering the public discourse. The latter technology suggests leaving the infrastructure based on fossil fuels intact, while extracting carbon dioxide from the stream of effluent gases emitted from large point sources such as power stations, and compressing, transporting and injecting it into geological formations (Edenhofer et al., 2005a; Held et al., 2006).

Such an assessment is typically called *integrated* as several options are analysed in a joint manner, and several disciplines are involved: climate science (for the impact of emissions on global mean temperature), engineering and economics.

The procedure outlined so far would qualify as an integrated assessment, according to the state of the art. However, we would like to take seriously the fact that major deterministic properties involved in the analysis (such as the climate dynamics) are uncertain, and ask for policy recommendations that are *optimal under uncertainty*. In a formalised setting, the latter is the topic of decision theory. Furthermore, as various mitigation options are characterised by significant potential for undesirable side-effects typically not represented in economic terms, we plan to nest our economic investigations into a qualitative risk assessment using the terminology of risk classes (WBGU, 1998).

Finally, we would like to extend the analysis further towards the actual needs of climate policy. First, our recommendations shall take the view of present-day global actors (such as the EU, the US, India, China, NGOs, corporations) rather than the view of a single global planner (such as a fictitious world government). Second, the social optima derived from such economic analyses still do not tell much about how policies shall be implemented in the existing economic system, and in particular, which financial instruments would induce the desired development at the private enterprise level. Our project aims at developing such financial instruments that shall bridge the gap between abstract policy recommendations and the room for maneuvering that actual policy makers have.

For these reasons, our project involves representatives from climate science, economic growth theory, systems theory and statistics. We import engineering expertise from external partners. Research progress is informally communicated to the German Federal Ministry of Economy, to the Ministry of the Environment, to German energy suppliers and to the NGO Greenpeace. We attempt to shape the scientific information such that a societal consensus on a mitigation policy can be catalysed on rational grounds, and attempt to distill the deterministic from the normative issues involved.

The first iteration of an Integrated Assessment

How do we position ourselves as interdisciplinary researchers within the fields spanned by the climate–economy debate? As a key motivation for our project we comply with the above mentioned statements by the climate community on anthropogenic emission induced global warming. While we accept their systems knowledge on the expected climate dynamics in the sense of a most plausible range of behaviours, we note that the last IPCC report suppresses major sources of uncertainty. We will come back to this issue in the following sub-sub-section. Furthermore, the goal of limiting global warming to 2°C arises from a composite of both systems and target knowledge: the former refers to the impacts of global warming while the latter states that those impacts ought to be avoided. Although the relevant systems knowledge is less certain than the link between emissions and global warming, we still regard the accumulated evidence as sufficient to continue on that basis. In fact, the 2°C target has been further supported in a symposium held in 2004 (European Climate Forum, 2004). Finally, we find the normative position that aims at avoiding those impacts to be highly plausible.

For these reasons, to design a first iteration of assessment we restrict our exploration to those paths that are compatible with the 2°C climate window, noting that our analysis may adjust to lower or higher targets once more comprehensive knowledge on impacts of global warming are produced in the future. We even comply with the stricter climate window that also restricts the *rate* of warming to 0.2°C per decade (WBGU, 1997). By observing such a strict climate window we expect to win over the stakeholders in the climate and environmental communities to the stylised compromise we attempt to derive.

Bruckner et al. (1999) have argued that on the basis of the precautionary principle one must simply derive the funnel of emission paths that fall within the climate window (as they did), and that analysing the costs of corresponding climate policies should be a secondary priority. However, commercial use of coal, oil and gas since the end of the 18th century has tied industrial society so closely to increases in anthropogenic greenhouse gas emissions, that wealth and carbon dioxide emissions due to the use of fossil energy have become almost synonymous terms. Therefore, anyone demanding a reduction of greenhouse gas emissions in the name of the precautionary principle with regards to the climate system provokes fears about whether, and how soon, a zero-emissions capitalist economy is possible. This is exactly the reasoning used by some economists in the past, calling upon an 'economic precautionary principle' and warning against 'excessive climate protection' (Nordhaus and Boyer 2000).

In order to also win over the stakeholders within the economic community for our stylised compromise we adopt their main tool of evaluation: cost-benefit analysis (CBA). Before we make explicit the way in which we comply with their tradition, and the way in which we deviate, we would like to briefly sketch CBA in its standard form.

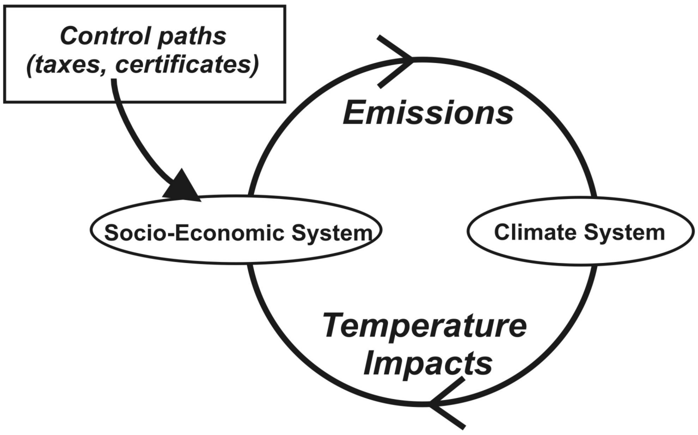

Figure 1: Cost-benefit analysis (CBA) as the standard tool within environmental economics that is supposed to deliver optimal control paths over the coupled economic and climate dynamics.

As Figure 1 shows, three information bases are fed into the CBA: a first module describes the dynamics of the climate system, a second module represents the dynamics of the economy and the third module includes instruments such as taxes and certificates used to achieve control paths. The economy influences the climate system via emissions, which in turn, through an increase in global mean temperature, induces damage to the economic system. The aim is now to determine future emissions in a way that yields an optimum balance between costs of CO_2 avoidance and of climate damages. The amount of emission reduction is therefore determined simultaneously with the policy instruments (taxes, certificates) that should be applied for achieving the calculated emission target. CBA attempts to integrate complex knowledge (meaning here: 'not easy to see through at the negotiation table') on climate and, economic dynamics by a method of weighting goods – based on an intergenerational order of preferences, along with ancillary dynamic conditions – so that a consistent 'social optimum' is derived. This optimum, however, can only be determined with the help of an evaluation function – it is usually assumed that the utility function of present and future generations can be derived exclusively from per-capita consumption. Thus, standard CBA presumes the predominant liberal economic paradigm preference order: absolute (monetary) calculability. This ensures CBA a high degree of compliance with the economic model dynamics it tries to incorporate, and has eased its access to the political level so far.

When asking about integration of disciplinary paradigms one should note that CBA accomplishes such integration by a subtle cut in the way it represents the socio-economic sphere. At the level of aggregation that is required by the problem-setting, it defines some economic system dynamics that are the emergent, quasi non-normative behaviours of a system made up from multiple actors, each potentially optimising according to their individual welfare functions. However, by interpreting historical developments on decadal to secular scales, economic growth theory extracts such an economic deterministic kernel (left ellipse in Figure 1) for the purposes of CBA. That kernel can then be coupled to further deterministic dynamics such as the climate dynamics (right ellipse in Figure 1). The joint systems dynamics is then treated as a boundary condition for intertemporal optimisation via control paths (rectangle in Figure 1) according to the economic welfare function.

We follow this standard approach in the sense that we adopt the ‘predominant liberal economic’ welfare function; one that does not respect non-monetary categories such as moral or aesthetic qualities. That way we maximise support from the present day economics community. However, in contrast to our analysis, standard CBA does not utilise the concept of a climate window. Instead, it monetarises global warming damages and optimises without being restricted by a climate window. We deviate from standard applications of CBA because of our impression that the necessary systems knowledge (coupled economic/climate) as to future impacts of global warming beyond the climate window, is inadequate for such an analysis at present. Also, the auxiliary assumptions in climate models (in particular for the older, more established ones) are generally oriented towards *current* climatology; we therefore expect that they, in general, underestimate the potential for abrupt climate changes on the continental or even global scale (Schellnhuber and Held, 2002) when operated beyond the climate window. Protagonists applying CBA often use damage functions based on even smoother input–output relations and hence overestimate the relative costs of mitigation. By restricting our optimisation to the climate window (‘cost-effectiveness analysis’) and conservatively (from the point of view of mitigation sceptics) disregarding warming damage costs, we bypass those conceptual traps.

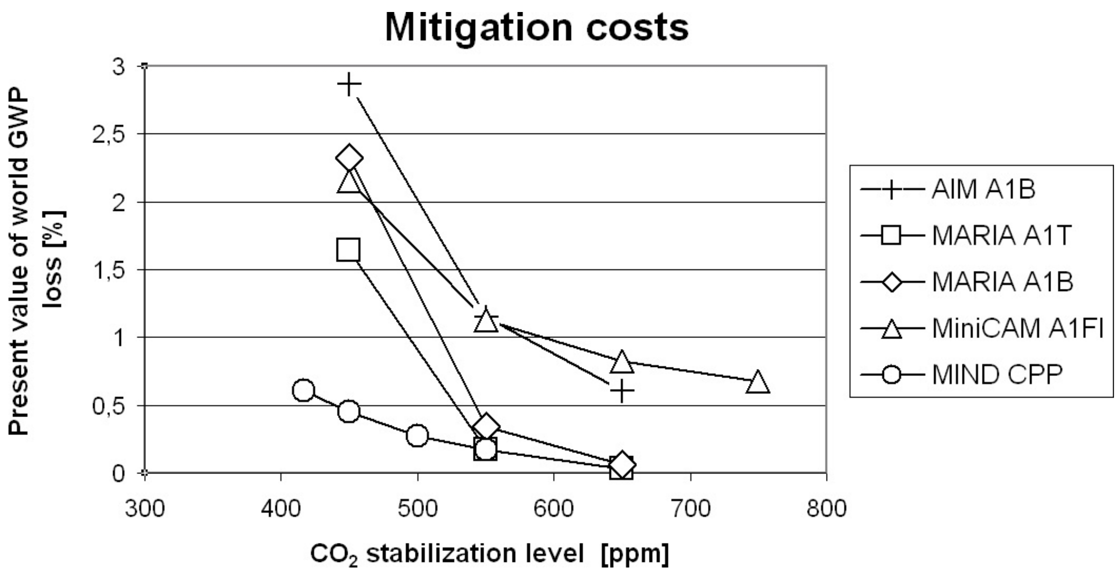

Figure 2: Discounted economic costs of climate protection until 2100 for a climate protection path (CPP) in the model MIND (developed in this project), compared to other macroeconomic models (such as AIM, MARIA, MiniCAM for emission scenarios A1B, A1T, A1Fl that observe, among other items, stabilisation levels as indicated; see Edenhofer et al. 2004 and Morita et al. 2000). A stabilisation level of 400 ppm – as against higher levels – allows the system to stay within the climate window, assuming the most plausible of the uncertain climate system parameters. Our model suggests drastically lower costs of significant mitigation than other models do, due to the endogenisation of technological change.

We involved a further deviation from standard CBA of the climate problem that refers to the economic systems knowledge: in standard analyses technological change is modelled 'exogenously', i.e. by a fixed rate (typically of 1% per year). That way, newer technologies (renewable sources) will by definition always lag behind their well-established counterparts (fossil fuels) in terms of cost-efficiency, no matter how much one would invest in the former. In our model we cured this apparent defect by explicitly 'endogenising' technological change to be driven by investment decisions. First results (Edenhofer et al., 2005a) show that the conclusions of traditional CBA need to be revised quite fundamentally: induced technological change drastically reduces the costs of climate protection (see Figure 2) to a level that seems acceptable within economic circles. Subsequently, the climate window requirement can be met by a change in investment strategy. The results of this first iteration indicate that the often proclaimed trade off between global warming mitigation and economic welfare is a mere construct of deficient modelling and that, quite to the contrary, policies are possible that would satisfy both mitigation protagonists as well as sceptics.

Towards a practical and robust assessment

In the following we would like to outline why these results must be further substantiated as well as extended, and which preliminary, although not yet integrated, results we have obtained along those lines so far.

1. While we eliminated a major source of uncertainty in climate systems dynamics by using the climate-window approach, significant further uncertainties were not tackled in our first iteration. Among those is the sensitivity of the climate system to greenhouse gases. Not only do different state-of-the-art climate models predict diverging warming trends when driven by the identical emission path (as mentioned in our introductory paragraph), but any climate model also contains several uncertain tuning parameters. The effect of the latter was not tackled in the last IPCC report. To close that gap, several research groups undertook *Bayesian learning* on *climate sensitivity*. (Bayesian learning represents a branch of statistics that synthesises a posterior belief on an uncertain entity out of subjective prior knowledge and new objective information. Within the paradigm of standard decision theory, the so derived posterior belief represents an optimised basis for taking rational decisions (Berger, 1985). Climate sensitivity encapsulates most of the uncertainty in climate predictions that are conditioned on a prescribed path of carbon dioxide concentration. It is defined as temperature response after increasing the atmospheric content of carbon dioxide from 280ppm to 560ppm.) Bayesian learning on climate sensitivity then resulted in roughly twice as large an upper limit for climate

sensitivity per model (Stainforth et al., 2005) than that stated in the IPCC report for the whole group of models. This result would be important since it implies great difficulty assessing climate policies as one can no longer define a 'safe' upper limit of emissions. We performed such a Bayesian analysis ourselves, and included paleoclimate information from the period of the last glacial maximum, which displays a much better signal-to-noise ratio than the weak warming signal of the 20th century. Preliminary results (Schneider von Deimling et al., 2006) show that the range for climate sensitivity published in the last IPCC report can be re-established, this time on much more objective grounds. Uncertainty about climate sensitivity could be further reduced if fluctuation properties of the climate system are also taken into account (Held and Kleinen, 2004).

2. On the economic side, in future work major uncertain parameters will be subjected to Bayesian learning, replacing the current best guess values. As a final goal, stylised decisions on optimal paths under joint climate/economic uncertainty can be derived. In this context, another innovation appeared as necessary: Bayesian methods imply a somewhat automated weighting of potential futures that we regard as helpful, since a purely subjective assessment of the 'high-dimensional space of futures' would be too demanding. However, Bayesian methods require the inclusion of subjective, prior, expert knowledge on the uncertain entities. As the modelling effort itself constitutes a form of expert knowledge, we basically consider that drawback as acceptable. Nevertheless, the Bayesian approach will meet its limitations if an expert has few *a priori* preferences for concurring parameter constellations due to a lack of experience. In this case, the Bayesian method subtly suggests to the analyst, apparently firm information, which, however, underestimates and plays down (from the point of view of a pessimist) the probability of generically critical regimes. Modern approaches to imprecise probabilities (Kriegler and Held, 2005; Held and Schneider von Deimling, 2006) offer a valuable compromise between the Bayesian approach and overly conservative, hence mostly non-informative interval methods.

3. An Integrated Assessment that aims to take into account the whole portfolio of avoidance options, including carbon capturing and sequestration (CCS), requires taking one more step back. We consider it impossible that any modelling effort will ever be able to take into account all possible impacts of mitigation measures. The diverse options should therefore be pre-evaluated by applying qualitative metacriteria. Environmental chemistry has developed an interesting proposal for avoiding the problem of a highly complex chain of impacts (Scheringer, 1996): one proposal for the pre-evaluation of environmental chemicals is to draw upon their spatial range (which can be measured rather easily) as a metacriterion. The existing minimal statistical-deterministic knowledge – that is, that substances diffuse at certain rates – is optimally used and transformed into practically relevant knowledge. First considerations indicate that this concept could constitute an important building block for a semi-qualitative analysis of CCS options.

4. Regionalisation should be conducted in a way that identifies potential conflicts of interest and possible compromises between important emitters: main actors like Europe, China, India, USA, corporations, and NGOs should be included in semi-qualitative modelling. First attempts to systematically incorporate issues of distribution and justice systematically into CBA were undertaken by Uzawa (1995 and 2003). In this context it will become necessary to assess whether standard economic modelling requires fundamental changes in order to maintain coherence between differing orders of preferences in the optimisation of CBA, within the optimisation and preference order based economic modules. A main issue will be to explicate and relate historical and future orders of preference. Practically, such preference orders will have to be established iteratively because actors are likely to become aware of their own preferences only in the context of calculated 'optima' with an asserted value.

5. Finally, one cannot be content with taking all possible uncertainties into account; one also has to aim at reducing them, at least in part. Here 'one' refers to the view of one of the actors named above; for example, Europe as represented by the EU Commission. This reduction can be achieved by granting research funds, but we would also like to urge that market forces, the most powerful actors in the current world theatre, be considered in integrated assessment efforts: Edenhofer et al. 2004 make proposals to transfer parts of the – regionally manageable – risks onto the beneficiary of a certain energy technology. By so doing, liability does not remain only with the state, but is shared substantially by the company that is actually making profits. Market instruments can contribute to taking into account the public's desire for environmental safety in manifold ways – maybe in a more democratic and efficient way than an indispensable environmental agency alone could ever achieve.

Implementation

Our project has been defined as an enterprise of analysis rather than implementation. Moreover, it would be premature to report to what extent our project has been responsible for the implementation of climate policy, which is in a very early state. Nevertheless, environmental diplomats, policy makers and NGOs are very aware of the fact that the future of the Kyoto process depends on setting up a reasonable accompanying architecture ('KyotoPlus'). Members of our project are involved in these discussions and we can report the kind of debates our project is already influencing:

- Together with other research institutes like FEEM (Fondazion Eni Enrico Mattei, Milan), DIW (Deutsches Institut für Wirtschaftsforschung, Berlin) and the Tyndall Centre, Norwich, we have founded the Innovation Modelling Comparison Project (IMCP). Within this project we launched a modelling inter-comparison exercise to improve the understanding of how technological change determines mitigation costs and mitigation strategies in different modelling frameworks. It turns out that induced technological change reduces mitigation costs substantially (Edenhofer et al., 2006; Giles, 2006). We are now exploring the implications of these results for a 'KyotoPlus Architecture'. The German Environmental Protection Authority and the EU Commission are at present supporting follow-up projects assessing new ideas for a climate policy regime beyond 2012. The proposition that, costs of climate protection are overestimated by models without taking into account technological change has attracted the interest of different stakeholders, such as the Duma, the CEO of BP, large electricity suppliers in Germany, NGOs and journalists.
- Members of our project have been involved in high level debates about the regulatory framework of CCS and about the promotion of renewable energies. In our project we are now starting an in-depth analysis of climate and energy policy instruments.
- The research agenda of a major proportion of the climate research community will reflect an intensifying of attempts to assimilate paleoclimate information, as we do (PMIP, 2006). This could further substantiate the desirability of avoiding most risky engineering-type mitigation options (Keith, 2000).
- We promote imprecise probabilities within decision theoretical analyses of the climate problem; this will result in improved climate policy recommendations, as the current downplay of extreme events will be replaced by more adequate representations of uncertainty.

Recommendations

This chapter sketched our transdisciplinary project on the integrated assessment of global warming mitigation options. The project began by observing that the debate about climate policies seemed to be somewhat stuck between opposing views, which were substantiated by a misleading admixture of normative settings and systems science arguments, with the latter often implemented below disciplinary standards. For those reasons the pool of potential climate protection policy paths to which most opposing views could subscribe was yet to be scanned in an appropriate way. We showed that this could be achieved by a series of improvements at the disciplinary level, combined with some serious disentangling of systems versus normative arguments. After two years, we then identified policy paths with the desired property. At present, we modify these paths to make them robust under uncertainty and potential side-effects of mitigation measures. In follow-up projects we will incorporate a frequently observed demand by stakeholders into our analysis and replace the one single fictitious global optimiser perspective with that of interdependent actual global actors. We regard this as a way to address, in a stylised manner, what incentive schemes could attract the main emitters to join a KyotoPlus policy regime observing binding warming mitigation targets.

- One could ask in what sense is our approach transdisciplinary? The answer lies in the very fact that we develop stylised solutions to the climate problem that have a fair chance of catalysing political decisions in favor of the very decision paths we derive. Our impression is that such catalysis is not unlikely for the following reasons: we integrate paradigms of opposing actors in such a way that any of those actors views the boundary conditions of the field in which he or she is a stakeholder (economy or climate) as being represented in a scientifically sound way. At the beginning of our project, the two authors, in some sense represented the first iteration of a stakeholder dialogue: one of us was in touch with the – often implicit – normative background of climate scientists, while the other understood the normative assumptions underlying standard economic theory and influential economists. Therefore, within our framework, we have been able to identify pathways that at least satisfy the minimum requests of those opposing groups of actors. Our iterative informal stakeholder dialogues ensure and successively qualify these aspects.

- To what extent could our experiences be transferred to other transdisciplinary projects? Starting with a theoretically trivial, however practically most demanding item, we addressed a publicly debated science–policy issue whose solution had been hampered by approaches too much oriented along disciplinary lines – and from that we distilled one single researchable question to be answered within three years. We tried to work with the simplest rather than the most advanced representations of the involved fields whenever possible, e.g. worked with the most reduced climate model in the first iteration of our analysis.
- At the same time we advanced disciplinary fronts when necessary, such as endogenous economic growth or upper limits of climate sensitivity. For that, a profound disciplinary background or at least a supportive environment proved crucial.
- Before bringing the disciplines together the team leaders had to develop a joint language across disciplines in order to decide which categories and terminologies would enable the disciplines to interact. A deep understanding of the conceptual foundations and limitations of the involved disciplines, proved far more crucial than is usually the case when tackling standard disciplinary research questions.
- Finally, iterative informal stakeholder dialogues provided a key to whether we adequately represented the preferences of conflicting actors in our analysis and whether we in fact made significant statements about decision options – and not on a

too stylised quantity – a decision maker really had at their disposal. An evocative example of the latter point is that it seems much more influential in the climate policy debate to formulate our results in terms of investment strategies rather than desirable emission paths.

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