Managing the Low-Carbon Transition – From Model Results to Policies

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Model analysis within the ADAM project has shown that achieving low greenhouse gas concentration levels, e.g. at 400ppm CO_2-eq, is technologically feasible at costs of a few percent of GDP. However, models simplify the dynamics involved in implementing climate policy and the results depend on critical model assumptions such as global participation in climate policy and full availability of current and newly evolving technologies. The design of a low stabilization policy regime in the real world depends on factors that can only be partly covered by models. In this context, the paper reflects on limits of the integrated assessment models used to explore climate policy and addresses the issues of (i) how global participation might be achieved, (ii) which kind of options are available to induce deep GHG reductions inside and outside the energy sector, and (iii) which risks and which co-benefits of mitigation options are not assessed by the models.

1. INTRODUCTION

The ultimate goal of the United Nations Framework Convention on Climate Change (UNFCCC) is "the stabilization of greenhouse gas (GHG) concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" (UN 1992). Several studies have indicated that unabated growth of GHGs is expected to result in severe and potentially irreversible impacts on natural and human systems (IPCC, 2007;

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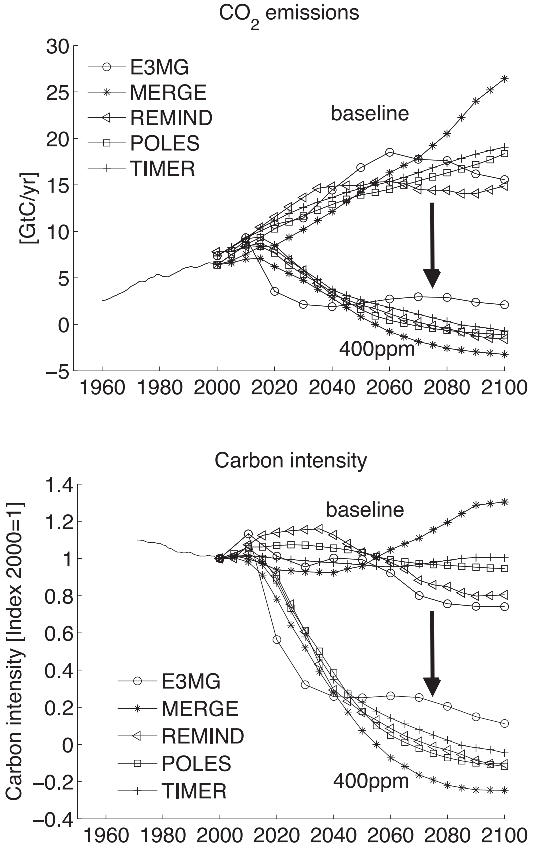
Smith et al., 2009; Lenton et al., 2008). The target, however, that would prevent "dangerous" climate change cannot be determined unambiguously. Here, we focus on a temperature target of 2°C because this target has gained prominence in part of the scientific literature and the policy community as a possible interpretation of the UNFCCC goal (Schellnhuber et al., 2006; Meinshausen et al., 2009). The EU has adopted the objective to limit global temperature increase to 2°C or below relative to pre-industrial levels (1939th EU Council meeting, 1996) and the major global economies have recognised the broad scientific view that 2°C warming ought not to be exceed (Major Economies Forum 2009).

Ensuring a higher than even likelihood of staying below 2°C requires stabilization of atmospheric GHG concentrations of 450 or 400 ppm CO_2 equivalent (CO_2-eq) or even lower, implying a 50% to 80% reduction of CO_2 emissions by 2050 compared to 1990 levels (IPCC 2007). Therefore, the focus of the model comparison within the EU project ADAM presented in this Special Issue (cf. Edenhofer et al., 2010 this Issue) is to explore the feasibility and costs of long-term GHG stabilization at such low GHG levels (450 and 400 ppm CO_2-eq in particular). The results of all participating energy-environment-economy models show that it is technically feasible to attain such targets at costs of around a few percent of GDP for the time horizon of 2000 to 2100 (Edenhofer et al., 2010 this Issue). The results also show that reaching low concentration targets requires large-scale deployment of carbon capture and storage (CCS) - a technology that enters the market between 2020 and 2030 in the models and is responsible for an average of 30% of total emissions reductions up to 2100. A strong expansion of renewable energies is also required with about a ten fold increase in capacity for solar, wind and hydro power, and a five fold increase in biomass use over the whole century. If one of these mitigation options is unavailable or strongly limited, low stabilization becomes infeasible in all considered models. Also, the combination of bio-energy and CCS might be important as it provides the opportunity for removing CO_2 from the atmosphere. In contrast, the effect of nuclear energy as a mitigation option is limited as nuclear already plays an important role in the baseline energy mix and in most models the increase induced by climate policy is not significant.

The models included in the study described in this Special Issue are based on simplifications and make critical assumptions. One important assumption is that emissions can be reduced in all world regions and sectors, and so it is done where it is cheapest. The limited number of studies that focus on the effect of incomplete and delayed participation for low stabilization targets show substantially higher costs, while the most ambitious targets might even become infeasible for long delays (Luderer et al., 2009, Clarke et al., 2009). The models also hardly address policy implementation issues, but instead assume one generic instrument: attaching a uniform price to every ton of carbon emitted. Finally, some models, such as MERGE (Magné et al., 2010 this Issue) and REMIND (Leimbach et al., 2010 this Issue) assume perfect foresight, i.e. investments are allocated so as to maximize inter-temporal social welfare over the century.

Figure 1. Required Change in Emissions and in Carbon Intensity Relative to the Baseline for Achieving a Low-stabilization Target



Energy-related CO_2 emissions (top) and carbon intensity as CO_2 per unit GDP (bottom) in history and model projections for the baseline and 400ppm scenario.

Deep emission reductions are only feasible if suitable policies and institutions are put in place to incentivize the low-carbon transition. This paper reflects on the model results and discusses which institutional conditions are necessary for delivering the emission pathways depicted in Figure 1. As shown in Figure 1, the challenges are impressive: Global emissions need to peak in just one or two decades and have to decline afterwards. While historically carbon intensity has declined very slowly, a steep decreasing trend in carbon intensity has to be induced in the coming years. This requires changes in the energy system at an unprecedented rate accompanied by societal changes; implying a state of urgency for action to realise emission reduction objectives.

The paper is organized as follows: Section 2 addresses challenges and options for realizing global participation in GHG emission reductions. Section 3 discusses options to induce deep GHG reductions in the energy sector, ranging from price and non-price instruments, such as domestic or international GHG pricing and technology policies (e.g. R&D, demonstration plants, etc), to voluntary life-style changes as a further option. In Section 4 land-use change and avoided deforestation are discussed as further mitigation options. As the models neglect many technological shortcomings, the risks of mitigation options - as well as their potential co-benefits - are discussed in Section 5. Knowledge gaps and directions for further research are addressed in Section 6.

2. INCREASING GLOBAL PARTICIPATION

As cost-effective low stabilization requires global emissions to peak and decline in just one to two decades (Figure 1), broad climate policy participation and swift implementation of policies incentivizing emission reductions below business-as-usual trends in all world regions are required by 2020-2030 at the latest (Luderer et al., 2009, Clarke et al., 2009, Metz et al., 2002, den Elzen and Höhne, 2008).[1] All of the models in the ADAM model comparison assume full global participation in climate policy.

Cooperation among all world regions to transform the global energy system at minimum cost is very difficult to achieve. To a large extent this difficulty results from the bargaining of self-interested players over the global mitigation bill. These negotiations are complicated further by large differences between countries with respect to their contribution in creating the climate problem, their current levels of economic development, expected emission trends, and different regional impacts of climate change. Thus, international negotiations are complicated and suffer from the free-rider problem (e.g. Carraro and Siniscalco 1993, Barrett 1999, Lessmann et al. 2009a).

In particular for low stabilization targets, which will cost more than less ambitious targets, it is likely that successful international policy can only succeed if parties consider the policy to be fair (Lange and Vogt 2003, Lange 2006). However, agreement on fair burden-sharing rules is complicated by different perceptions of fairness amongst countries compounding the large differences among countries (den Elzen et al., 2008). Another global cooperation problem arises in providing the substantial amounts of public and private research and development (R&D) expenditure that will be required to develop low-carbon technologies at the required scale (Barrett 2008, Lessmann and Edenhofer, 2009b) (see also Section 3).

Against this background we suggest the following key points are likely to be necessary for a climate agreement aiming at low atmospheric stabilization:

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[1] In view of their small contribution to global emissions and the priority for dedicating resources to poverty eradication, Least Developed Countries should be excluded from substantial early mitigation efforts, in particular where trade-offs with poverty eradication arise.

(i) medium (2020 and 2030) and long-term (2050) global emission budgets to send a very clear signal about the level of policy ambition to stakeholders (business, consumers, local policy-makers, etc.); (ii) rules for sharing the costs of mitigation and technology development among countries that are considered fair by all participants, e.g. regional emission budgets; (iii) financial mechanisms for implementing this burden-sharing regime, e.g. an international emissions trading regime with appropriate national emission budgets, or some equivalent mechanism; (iv) means to foster technology development and deployment, and (v) financial mechanisms to reduce deforestation. Since impacts of climate change are felt most in developing countries, any global climate agreement also needs to include (vi) adaptation measures with corresponding technological and financial transfers.

In consideration of the aforementioned distributional concerns and associated barriers to global agreement, which factors can enable agreement on an effective low stabilization policy regime? In addition to parties acting on the basis of global responsibility, there are options that may function even under more self-interested (rational) behavior of countries.[2]

First, transfer schemes (e.g. allocation in international emissions trading, or explicit financial transfers) enable side-payments to be made by those with a higher willingness to pay for climate mitigation subsidize emission reductions to countries with a lower willingness to pay, thereby enabling more ambitious global reductions than achievable through non-cooperative efforts. Clearly, such international transfer schemes are not easy to establish.

Second, package deals, often referred to as 'issue linking' in the literature, tie the setting of mitigation targets with other international policy issues, for example the joint development and exclusive sharing of technologies. Such package deals may also involve 'grand bargains' across policy areas, for example linking climate negotiations with those of trade and agricultural negotiations, or representation in international financial institutions (Perez 2005).[3] To involve developing countries early in climate policy, linkages between (sustainable) development policy and climate policy are probably needed (Metz et al., 2002). This can for example be achieved by mainstreaming climate policy in various non-climate domains and related international frameworks and agreements beyond the UNFCCC such as development and poverty reduction policies, disaster reduction and sectoral policies (Kok and de Coninck 2007; Kok et al., 2008).

Third, trade sanctions for non-participating countries (in particular OECD countries) have been analyzed as a means to increase global participation in a climate agreement. While these can be effective devices in theory (e.g. Barrett 1997, Lessmann et al. 2009a), they raise significant problems if introduced in

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[2] For game theoretic analyses of the issue see e.g. Carraro and Siniscalco, 1993, Barrett, 1994, Wagner, 2001 surveys the literature, while Finus 2008 summarizes recent findings and challenges.

[3] The EU's engagement for Russian accession to the WTO in compensation of Russia's ratification of the Kyoto protocol represents a prime example of such a package deal across policy domains.

practice. One-sided introduction of tariffs may give rise to counter-tariffs, potentially unleashing a vicious cycle in international trade policy.

Fourth, co-benefits of emission mitigation and possible synergies between development and climate-change policies such as economic growth, alleviation of poverty, energy and food security, health and local environmental protection can play an important role in facilitating the implementation of climate policies (Bradley and Baumert 2005; Halnaes and Garg 2006; OECD 2005).

Fifth, parties may act on the basis of the risk of wide spread climate impacts or even catastrophic climate change which would not only impact particular countries but are likely to have global consequences (e.g. Lenton et al. 2008).

Finally, a sense of moral responsibility is possibly one of the most important preconditions for enabling low stabilization targets. This may take various forms. On the middle ground between a concept of human action driven by pure self-interest on the one hand and selfless altruism on the other hand, reputation and prestige at international and domestic level may be an enabling factor for striking and complying with an ambitious international agreement (Finus 2008).

Given the urgency of emission reduction for achieving low stabilization targets, non-governmental forms of international cooperation will also be important. This could, for instance, include technology agreements between large companies, city-level initiatives etc. While such initiatives may in the short-term be more flexible than complex international negotiations and can act as an important complement to a global policy framework, in the longer term it is hard to imagine that such "fragmented" regimes alone could achieve the ambitious reductions required for low stabilization targets in a cost-efficient way (Hof et al., 2009).

3. DIFFERENT OPTIONS TO INDUCE CHANGE

Transitions to low-carbon societies can be achieved in different ways such as putting a price on GHG emissions, and implementing technology policies that include non-price regulation. Also, more "bottom-up" voluntary lifestyle changes can contribute to reducing emissions. This section discusses the three options of GHG pricing (3.1), technology policies (3.2) and lifestyle changes (3.3) as complementary levers to achieve substantial and rapid decarbonization required by low stabilization.

3.1 Putting a Price on GHG Emissions

Putting a price on GHG emissions is an economic standard prescription for addressing the negative externalities of greenhouse gases. In fact, a price on carbon is the only climate policy instrument implemented in the models within the ADAM model comparison, and as these models (except for E3MG, see Barker and Scrieciu, 2010 this Issue) do not account for additional market imperfections, this is sufficient to achieve emissions reductions in line with the imposed climate policy constraints in a cost effective manner.

A price on GHG emissions has two main effects. First, economic agents will adjust their operations and investments by reducing the use of GHG-intensive technologies. Second, a GHG price sets an incentive for developing and introducing low-carbon products and processes to replace existing technologies. The strength of GHG prices lies in achieving these objectives while economizing on the need for information gathering by economic agents and regulators, e.g. regulators do not need to pick certain technologies as 'winners' as a GHG price is inherently technology-neutral. Still, there can be other reasons such as market imperfections and technology risks that suggest the need for additional policy instruments. We discuss these issues in the following sections.

Two economic instruments can be used for GHG pricing. The Pigovian approach suggests implementing a tax reflecting the social costs of emissions (Pigou 1920). Emission taxes, however, can cause serious problems associated with the extraction of fossil resources demonstrated by the green paradox (Sinn 2008; Edenhofer and Kalkuhl 2009). If there is no consistent and credible pricing policy, increasing emission taxes leave room for strategic behavior of resource owners who fear a devaluation of their resource rents by future climate policy. In the end, climate policy has to ensure that a cumulative global GHG emission budget will not be exceeded by burning fossil fuels and releasing other greenhouse gases. Irrespective of how this GHG budget will be determined, the price of emissions has to increase over time to reflect the increasing scarcity of the atmosphere. However, the political process of determining and implementing emissions taxes suffers from many uncertainties in mitigation costs, climate damages, international negotiations and public acceptance. Due to these uncertainties in emission pricing, resource owners may expect fast increasing taxes and accelerate extraction (Sinn 2008). There are some proposals for tax designs that reduce the incentive to accelerate extraction, such as a declining or only slowly increasing GHG tax or an individual stock-dependent resource tax for each resource owner (Edenhofer and Kalkuhl, 2009). These proposals mainly depend on whether the regulator is able to assure a credible commitment about the future tax path. In contrast, individual stock-dependent resources taxes will be unattractive due to high information requirements as well as high transaction costs.

In any case, an effective policy instrument has to send price signals to firms and investors. This implies that there is an institution which is committed to ensure that the cumulative GHG carbon budget will not be exceeded. A tradable permit scheme under fixed emission budgets would be an effective policy instrument allowing a price signal to be sent based on well-defined property rights. Under this condition, the owners of fossil fuels can only defend their rents if they invest in carbon-free technologies.

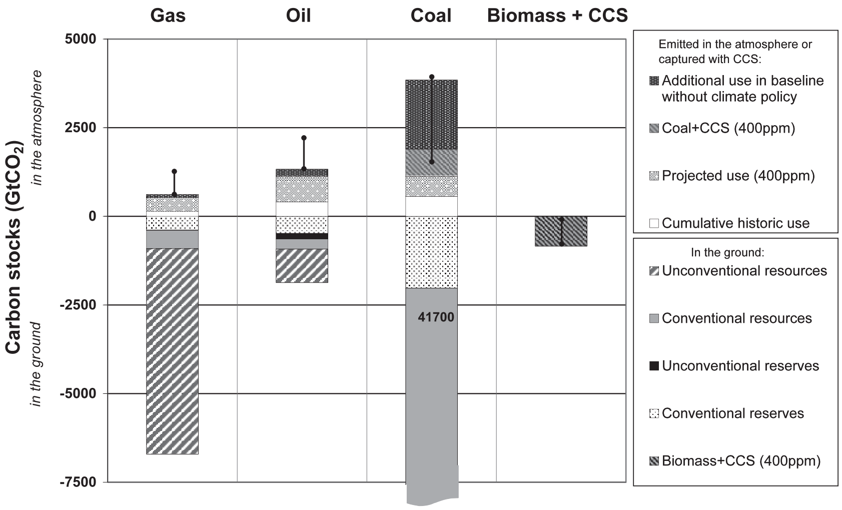
This is illustrated in Figure 2. There is a stock of fossil resources and reserves underground which can be used for fueling the economy. The CO_2 related to the burnt fossil fuels can only be deposited in the atmosphere or underground in geological formations by CCS technology. Both deposits are limited in case we pursue a climate policy. Figure 2 displays underground reserves and resources, and their usage in the baseline and 400ppm scenarios. For coal, even in the absence of climate policy, clearly not all reserves and resources are used by 2100. In contrast, all conventional oil and gas reserves are extracted and used in all models in both the baseline and mitigation case. However, with climate policy, oil and gas resources are extracted more slowly at lower prices, while for coal a significant part is left underground.. In the 400ppm scenario only 1334 $GtCO_2$ from coal can be used instead of 3380 $GtCO_2$ in the baseline case.

A cumulative carbon budget has to be controlled over time, as the available amount of carbon in fossil fuels clearly exceeds the total carbon that can be emitted under climate constraints. The institution that would manage the carbon budget under these conditions might allow for banking or borrowing, and it might define intertemporal exchange rates for the permits – in any case, it has to ensure intertemporal optimality. It is widely accepted that a statically efficient emission trading scheme needs to comprise all relevant sectors and regions. However, intertemporal optimality is likely to be more demanding, and identifying suitable institutional and organizational arrangements to implement dynamically efficient and environmentally effective low-stabilization policy is a primordial research task complementing low-stabilization modeling.

Concerning the discrepancy of modeling exercises and real-world development of policies, it is worthwhile considering the sectoral, regional and temporal scope of climate policies. With respect to sectoral scope, the cap-and-trade system adopted by the European Union (European Emission Trading System - EU ETS) has operated since 2005 and covers only approximately 40% of European GHG emissions, focussing on the energy sector and CO_2 emissions. Aviation and some process-related emissions of non-CO_2 gases will be included in the future (EU Commission 2008, 2009). This is one example where policy implementation may differ from the instruments explored in models, and arguably be less cost effective. Thus, it should be welfare-improving to integrate the transport and building sectors to cap-and-trade systems. In addition, land-use and land-use change related emissions amount to approximately a third of global anthropogenic GHG emissions (see Section 4). Integration of these sectors into trading systems is considerably more challenging, but represents one important option to control global GHG emissions.

Broad regional participation is a crucial condition for achieving low stabilization targets (Luderer et al., 2009, Clarke et al., 2009, Metz et al., 2002). Most of the proposals to broaden participation include various types of international financial instruments. Such policies can also help to mitigate concerns over carbon leakage stemming from regionally asymmetric GHG prices (Houser et al. 2007). International financial mechanisms, either based on explicit financial transfers or global carbon markets, seem to be a pre-requisite for achieving low stabilization targets in order to achieve reductions wherever they are available at lowest cost. At the same time, the financial flows can represent a

Figure 2. Carbon Stock of Fossil Energy Carriers in the Ground (Negative Values) and Released to the Atmosphere (Positive Values)



Estimates of carbon stocks in the ground are taken from BGR (2009), the cumulative historic carbon consumption (1750-2004) from Boden et al. (2009), and estimated future consumption (2005-2100) for the baseline and the 400ppm scenario are from REMIND-R (Leimbach et al., 2010 this Issue). The other models of the ADAM model comparison give a qualitatively similar picture with an overall range for the use of fossil fuels in the baseline of 450-1086 $GtCO_2$ for gas, of 932-1765 $GtCO_2$ for oil, 968-3506 $GtCO_2$ for coal (indicated by the vertical lines). Biomass with CCS ranges from 0-840 $GtCO_2$. Fossil energy stocks are converted to carbon dioxide emissions by using emission factors from IPCC (2006). Reserves refer to what is extractable with today's technologies at current energy prices, as compared to resources which refer to the total amount regardless of the technology or the economic realization. Conventional oil and gas resources or reserves are extractable with the classical extraction methods in opposite, e.g., to oil sands that are unconventional.

major political challenge because of their potentially large volumes. In order to set up international policy schemes in the short-term (to achieve a peak in global emission in one to two decades) different routes are possible. These include tax systems with explicit financial transfers (e.g. Nordhaus 2008), an extension of the Kyoto Protocol approach (Hahn and Stavins, 1999), or architectures linking the monitoring of regional decarbonization efforts with international compensation schemes (Verbruggen 2009).[4] As an alternative or complement, in order to achieve fast-track changes and to underpin the broader multilateral approaches, one could also think of linking more limited, regional systems like the EU ETS with potentially emerging systems in the United States and other OECD countries (Victor 2007, Tuerk et al. 2009, Flachsland et al. 2009a,b). No matter which

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[4] See Aldy and Stavins (2007) which offers an overview of post-2012 climate policy approaches.

policy framework is chosen, it is vital to ensure that aggregate policy targets (e.g. caps in emissions trading systems) are set at a level of ambition in line with low stabilization trajectories.

It has been argued above that intertemporal optimality is vital for an efficient climate policy. The optimal extraction pathway might follow a modified Hotelling rule that defines optimal intertemporal GHG price trajectories considering technological change, climate system dynamics and extraction costs of fossil resources (see e.g. Farzin, 1996; Sinn, 2008). But in addition to issues of optimal intertemporal pricing, it is vital that the carbon budget is also perceived as credible by all relevant parties. If they suspect that announced ambitious climate policy will not be implemented, e.g. when costs of mitigation start to rise or in time of economic hardship, they will not start investing in low-carbon technologies and research and development activities as they will not expect an appropriate return on their investment (Requate, 2005; Montgomery and Smith, 2007). Therefore, other instruments such as technology standards, patents, technology deployment programs, and setting long-term targets by law to stabilize expectations as envisaged by the UK Climate Change Bill (de Groot and de Jong, 2008) can constitute important additional elements of the low stabilization policy portfolio. More generally, there are a number of market imperfections relevant to low stabilization, giving rise to the need for technology policies that complement GHG pricing.

3.2 Technology Policies

As elaborated in the previous section, pricing emissions is an effective instrument to realize near-term emissions reduction potentials and to provide incentives for technology development if reduction targets are considered credible. This means that policies need to ensure investment security by providing indicative reduction trajectories and showing commitment. Because of additional market imperfections, however, GHG pricing alone is not sufficient, and additional regulation is required. At the same time, non-price regulation runs the risk of introducing significant inefficiencies due to information asymmetries. Hence, a well-designed mix of GHG pricing and other regulatory instruments is required to address the full range of market imperfections and ensure a cost effective policy outcome.

There are several reasons why non-price regulation should complement GHG pricing:

- The positive effects of introducing new technologies are not limited to the innovating firm, because technology development typically also creates benefits for others, e. g. in the form of *knowledge spillovers*. Without policies addressing these externalities explicitly, private agents tend to under-invest in innovation (Jones and Williams, 2000).
- Investors expect high returns on investment, thus working with time horizons that are much shorter than those implied by an ‘ethical’ long-term perspective.

Currently, from a static perspective, additional investments in many low-carbon technologies are not profitable, even with GHG pricing, when the technologies are at the beginning of their learning curves. Learning curves are an additional market failure which is not automatically cured by a carbon price. The investments required to achieve social optimal learning might justify subsidies for learning technologies in order to *stimulate learning* (Stern, 2007; Ch. 16.2).

- There are large *uncertainties* concerning the future development of energy and climate policy, availability and prices of fossil fuels, as well as the speed of innovation in low-carbon technologies. In this context, the credibility of climate and low-carbon technology policies plays a pivotal role. Risk aversion and the threat of stranded investments could result in a strong tendency to delay investments (Patino-Echeverri et al., 2009). Non-price policies such as long-term targets may help to reduce uncertainty.
- *Infrastructure requirements* of a low-carbon energy system are markedly different from those of a conventional energy system. Large-scale deployment of variable renewable sources of power, as envisaged by most model-based low-stabilization scenarios requires different and highly performing electricity grids for adjusting regional fluctuations of production. Government regulation or even investments into this infrastructure will be important to open up routes to alternative energy systems. CCS, the other major mitigation option in the power sector, will require large scale new infrastructure, in particular a pipeline network at a scale similar to existing gas transport infrastructures, besides further infrastructure requirements concerning the storage capacities.
- The lifetime of most infrastructures is very long – and in many cases, one foresees today that particular technologies cannot be part of a low stabilization scenario, for example new fossil fuel power plants without CCS. Given *lock-ins,* i.e. the long-term consequences of investment decisions, regulation could help bring long-term considerations forward, for example by banning new fossil-fuel based power plants without CCS after 2020.

The previous considerations all provide a case for non-price policies in addition to GHG pricing to facilitate the transition towards a low-carbon economy. In order to ensure sufficient technology development, these policies need to be targeted at the different stages of the innovation chain, ranging from basic research and development to market introduction and the setup of suitable infrastructure.

A central insight from ADAM model comparison and other model-based studies of climate mitigation strategies (Luderer et al. 2009; IEA 2008a) is that no single technology or energy source will suffice. Rather a large portfolio of technological options is required to achieve the low-carbon transformation.

At early stages of technology development, public R&D funding plays an important role. The knowledge created by R&D exhibits the characteristics of a public good, and thus tends to be underfunded. Despite the increasing challenges of meeting the growing global energy demand and mitigating climate change, public energy R&D funding in OECD countries has remained at a rather low level compared to the early 1980s. Historically, the major share of energy R&D spending went to large-scale non-sustainable technologies such as fossil fuels and nuclear power (IEA, 2008b). Funds need to be redressed towards crucial low-carbon technologies such as renewables and CCS and overall volumes need to be increased in order to deliver a diverse and effective portfolio of low-carbon options. Policy-makers have to strike a delicate balance between supporting promising developments whilst avoiding the temptation to prematurely pick winners. In view of network effects, it is essential to consider path dependencies and avoid the risk of lock-ins. Policy-makers should also critically review the direction of R&D investments. The actual breakdown of R&D investments is often very different from the options chosen by models as part of their mitigation portfolio. For instance, while energy efficiency and CCS play an important part in emission reduction in most models, they represent only a minor share of R&D budgets.

Given the premise of this paper, i.e. the need for low stabilization and peaking within the next 10-20 years, acceleration of market-implementation of low-carbon technologies needs to be a key focus of technology policies. In general, the more advanced the stages of development and deployment, the larger the role of private investors and the impact of GHG pricing. For complex and large-scale approaches, such as CCS or centralized power production using concentrating solar power (CSP), demonstration projects can prove viability and reduce risks and can thus be an important intermediate step towards commercialisation.

To reduce uncertainty, governments need to provide a stable framework of incentives. Deployment incentives are important to promote learning and facilitate learning in specific niches. Examples of deployment incentives for renewable energy technologies complementary to GHG pricing are price (e. g., feed-in tariffs) and quantity instruments (e.g., renewable quotas) (Stern, 2007, Ch. 16.6.). Such market introduction programs can be an ample tool for increasing the market share of new technologies and in reaching cost-reductions through experience learning and economies of scale. Experience, such as the renewable energy law in Germany, suggests that price-based mechanisms are important in achieving growing deployment at moderate societal costs. This is due to (i) the possibility of discriminating between different renewable supplies and allowing for a balanced qualification (Verbruggen and Lauber, 2009), thus avoiding the producer's rents in excess of the marginal costs of producing electricity from a particular source (Jacobsson et al., 2009), and (ii) the long-term price guarantees that effectively reduce investor's risks (Butler and Neuhoff, 2004). Technology policy can also include command-and-control measures, such as efficiency standards for buildings and vehicles.

Besides instruments that unfold the potential at the domestic level, technology policy also has an important international dimension. Due to the common public good character of technological innovation, there could be an incentive for countries to free-ride on the effort of others. On the other hand, first mover advantages tend to incentivize unilateral national technology policy. The inadequacy of technology policies currently implemented in the industrialized world indicates that the tendency to under-invest in the common good of technological innovation prevails over the first mover advantage. Engaging jointly in R&D and coordinating national R&D efforts via dedicated technology action plans should therefore be a priority for the international climate policy agenda as it helps in sharing the costs among countries as well as the risks associated with the development of new technologies required for low stabilization.

Achieving low stabilization will require rapid deployment of low-carbon technologies in developed and developing countries alike. Developing countries need to switch to a low-carbon growth path without going through carbon-intensive development stages first. Central barriers for such 'technology leapfrogging' are (i) lack of support for technology transfer from industrialized countries, (ii) inadequate financial incentives for deployment and legal frameworks in receiving countries, (iii) insufficient absorptive capacity in receiving countries, and (iv) large capital needs of low-carbon technologies (IPCC, 2000). For an international climate policy regime to be successful, it will be essential to implement technology transfer in an integrated framework that addresses these barriers.

3.3 Life-style Changes

Most models tend to focus only on technological changes as a way to reduce emissions. However, voluntary lifestyle and value changes (e.g. changes in dietary patterns, choices in transport modes) can have a significant impact as well. In economic terms, voluntary lifestyle changes are (exogenous) changes in consumer preferences. As such, they are logically distinct from changes in consumption patterns driven by modified relative prices due to GHG pricing or regulation. In the latter case, consumer preferences remain unchanged and consumption changes are incentivized by an economic policy adjusting relative prices. In the former case, consumers voluntarily alter their valuation of products due to the insight of the problematic consequences of consuming GHG intensive products. Ultimately, both mechanisms lead to changes in consumption decisions, but for different reasons.

Changes in lifestyle and values may also increase public acceptance for the necessary changes implied by a low GHG society in a more general sense, including for example the large-scale introduction of new technologies, or political acceptance of consumption losses resulting from ambitious climate policies.

To enact lifestyle changes consumers need to be aware of the emissions contents of the products they consume (e.g. via product labelling), willing to reduce these emissions, and have alternatives at hand. Product labelling, awareness raising campaigns and public discussions are policy instruments to enable voluntary lifestyle changes. At the same time, care seems expedient to avoid the inception of new moral pressures and related processes of social exclusion, as well as a loss of legitimacy of climate policies if people feel offended by calls for lifestyle changes they feel would touch upon sensitive aspects of personal identity.

When aiming at very low stabilization scenarios, it appears very unlikely that voluntary changes in lifestyles alone will be sufficient to drive global decarbonization. However, if people find that adopting less GHG-intensive lifestyles is not costly to them, climate policy could theoretically be more effective and less costly in the real world than suggested by models that do not include lifestyle change. One standard argument in favour of GHG pricing over policies aimed at inducing voluntary lifestyle-changes is that GHG pricing economizes on the information (e.g. comprehensive product labeling) that is required to achieve substantial changes in consumption and investment patterns (Nordhaus, 2008). Another argument is that unlike policies aimed at enabling voluntary adjustment of private consumption patterns, public policies such as cap-and-trade provide certainty about the achievement of policy objectives.

Hence, it appears that while voluntary lifestyle changes will not be sufficient to achieve low stabilization, they can play an important role in reducing the perceived cost of the ambitious mitigation programs that will be required.

4. NON-ENERGY SECTOR MITIGATION POLICIES

Most of the models used in ADAM model comparison focused only on GHG emissions and mitigation options from fuel combustion and industrial emissions. However, GHG emissions from non-energy sectors contributed 35 % to global anthropogenic GHG emissions in the year 2000 (IPCC, 2007). The IMAGE model as part of the ADAM model comparison shows that low greenhouse gas concentration cannot be achieved without reducing GHG from non-energy sectors, especially agriculture and land use change (van Vuuren et al., this Issue 2010a).

4.1 Agriculture and Bio-energy

Agriculture accounts for approximately 14% of total global anthropogenic GHG emissions (5.1 to 6.1 Gt CO_2-eq p.a. in 2005, Smith et al. 2007b). For most agricultural sources, a range of low cost mitigation options exists. However, mitigation is mostly restricted to a proportion of the emissions (e.g. methane emissions from cows). Moreover, implementation of agricultural GHG mitigation is limited by institutional, social, educational and economic constraints (Smith et al. 2007a) – in particular due to the rather diffuse nature of the sector. Measures to overcome these barriers are crucial for a climate change mitigation strategy in agriculture. Due to potentially high transaction costs (especially in non-Annex I countries), an expansion of emissions trading and other financial instruments to the agricultural sector may not be the most efficient way to fully use the available mitigation potentials. Emission reduction could be more successfully driven by other climate and non-climate policy instruments such as the European Nitrate directive and as an integral part of a wider approach for promotion of sustainable agriculture and rural development. Bio-energy also plays an important role as discussed in a paper in this Special Issue by van Vuuren et al. 2010b (this Issue). Overall, one may deduce that in addition to bio-energy specific policies (as currently formulated), a more integral approach to land use is probably needed to prevent the so-called indirect impact of bio-energy use.

4.2 Deforestation

Agriculture is the main driver for tropical deforestation (Geist and Lambin 2002). Tropical deforestation (as high as about 150,000 km^2 per year during the 1990s) accounted for at least a quarter of all anthropogenic carbon emissions in the 1980s and 1990s (Fearnside, 2000; Malhi and Grace, 2000; Houghton, 2003) and almost 20% (8 $GtCO_2$ p.a.) of current total GHG emissions (Stern, 2007). Avoided deforestation is often found to be a low-cost mitigation option compared to energy-related abatement. Halving emissions from the forest sector by 2030 would cost between $17–28 billion per year with mean carbon prices of 16$ per ton CO_2 (Kindermann et al. 2008). However, implementation of this potential is rather complicated, partly because of different interests of stakeholders. Historically, in several countries, existing policies aimed at avoiding deforestation failed to provide much incentive. The most important drivers of deforestation are agricultural expansion, infrastructure extension and wood exploitation (Geist and Lambin, 2002). In most cases, these drivers work together and are based on underlying factors such as political, institutional and economic factors. Climate policy should provide an additional incentive to avoid deforestation. Essential elements would be (i) improved local governance, (ii) removing perverse subsidies for logging, (iii) increase agricultural yields from existing agricultural areas and (iv) provide economic incentives for local farmers. Several proposals have been tabled on how to implement and frame policy instruments that provide incentives to reduce deforestation and degradation in a future international climate policy framework. These could for example, be integrated into the global GHG market or form a separate fund.

5. IMPLICATIONS OF RISKS AND CO-BENEFITS OF MITIGATION TECHNOLOGIES ON THEIR IMPLEMENTATION

Climate economy models routinely implement mitigation technologies without taking into account the entire suite of associated risks and co-benefits in their assessments. Each mitigation technology comes with its own set of opportunities, drawbacks and uncertainties. Technology choices matter not only in terms of the carbon balance, but also in view of their non-climate related co-benefits as well as shortcomings and risks. Replacing conventional energy technologies with alternative ones can have a positive impact, such as improving air quality and enhancing energy security. On the other hand, certain options (e. g. biomass, nuclear) bear new risks of adverse impacts. While co-benefits can obviously provide an important incentive in implementing low-concentration scenarios, the associated shortcomings and risks could slow down transitions. Developing a broad technology portfolio is of key importance to be able to limit known risks and hedge against uncertainties.

Decision makers and the public have to be informed about the hazards and the risks to be able to make consolidated decisions about specific technologies. None of the models analysed in this Special Issue specifically address the risks and co-benefits of various technologies over their lifetime. Therefore we will briefly discuss these issues here. The potential hazards are listed in Table 1. More specifically, we discuss bio-energy and deforestation policies, as bio-energy was seen to play an important role for low stabilization (Edenhofer et al., 2010 this Issue) and emissions from deforestation account for a large share of total emissions.

5.1 Bio-energy

The simulation models suggest modernized bio-energy systems will be important contributors to future sustainable energy systems. However, as large-scale energy crop production will increase the competition for land, water, and other inputs, they may create conflicts with other sustainability aspects, such as food security, land-use emissions, deforestation, water use and biodiversity loss (e.g. Farrell et al. 2006, Searchinger et al. 2008, van Vuuren et al., 2010b this Issue). First, bioenergy expansion will have mixed impacts on poor population in urban and rural areas, as it puts an upward pressure on food prices, raises land values, and potentially increases rural employment (Goldemberg 2007). Second, to estimate the net contribution of bio-energy in a sustainable energy mix one needs to include CO_2 emissions from fertilizer production and application, biomass conversion and trade. Furthermore, in tropical developing countries there is an additional pressure to convert forests and peat lands into cropland. Forests are a major storage of carbon, so there is a potentially adverse impact when forest carbon is released for the purpose of bio-energy production. In addition, under increasing scarcity of productive land the growth in food and bioenergy demand may only be accommodated by agricultural intensification (Smeets et al. 2009), which implies more fertilizer use and higher N_2O emissions. Third, large-scale bioenergy production may affect water scarcity and quality, which are highly dependent on particular crop needs. In many regions, additional irrigation for bio-energy will further intensify existing pressures on water resources. Worldwide, agriculture accounts for roughly 70% of global freshwater use, but in the future an increasing share will be needed for industrial and household uses. Finally, large-scale bioenergy production will have negative consequences for biodiversity. Degradation of natural areas will reduce valuable habitats and ecosystem services from complex ecological systems (Groom et al. 2008).

Table 1. Different Mitigation Options and Their Associated Unresolved Challenges and Potential Societal Hazards

Mitigation options	Unresolved challenges not assessed in the models	Societal hazards
CCS	Leakage of storage; monitoring costs; warning systems; Emissions from transport; Potential competition with geothermal energy	Abrupt release of large amounts of CO_2; Ground instabilities, triggering of seismic activity; Contamination of groundwater; Impact of drilling operation at sequestration site (acidification)
Nuclear	Disposal of waste; Water pollution due to uranium mining	Proliferation and terrorism, especially with fast breeder; Long-term active waste; Severe accidents
Wind and solar energy	Integration into electricity grid; Fluctuations and variability of demand and supply; Large upfront investments required for technological learning	
Wind offshore	Offshore-parks near coastlines could compete with other purposes (fishery, navigation, military, tourism, maritime conservation)	
Bioenergy	Food security; Co-emissions of N_2O, indirect CO_2 emissions from land-use change; Biodiversity impacts	Famines; Irreversible loss of biodiversity
Geothermal energy	Groundwater pollution; Possible release of greenhouse gas emissions trapped deep within the earth	Drilling and cracking can possibly trigger seismic activity; Possible subsidence blow out while drilling
Carbon-cycle management options	So far not assessed at all in integrated assessment models (e.g. biochar production, atmospheric scrubbing, wood burial)	Very dependent on the specific option
Geo-engineering options (influencing the radiative balance by altering the albedo)	Not assessed at all in integrated assessment models (e.g. production of stratospheric sulphur aerosols, space mirrors, cloud seeding)	Often associated with high and unexpected impacts; Unknown effects on regional climate; Does not resolve ocean acidification; Most techniques are unproven

5.2 Avoided Deforestation

In addition to storing carbon and acting as sinks for atmospheric CO_2, externalities of avoided deforestation are believed to be positive and high, as forests provide many other services. They are home to 350 million people around the world and about 60 million indigenous people are almost wholly dependent on the forest in terms of wood, fuel, shelter, medicinal plants, foods and many other services for communities (World Development Report 2004). Forests guarantee the protection of biodiversity, as primary forests are often more diverse than secondary forests or plantations (Barlow 2007). Such diverse ecosystems are more capable of adjusting to changing environmental conditions like climatic change, and they are likely to provide future benefits from new plants which are irrevocably lost through deforestation. Furthermore, forests regulate local and regional climate and enhance the conservation of soil and water.

However, including REDD (Reducing Emissions from Deforestation and forest Degradation) in a global mitigation strategy involves substantial challenges and risks. There is no guarantee that carbon stored by forests is permanent, as climate change, fire and chainsaws can quickly destroy past achievements in forest protection. Furthermore, it must be ensured that deforestation and associated emissions are not merely shifted from one region to another. Hence, at the national level, well-performing governance structures as well as monitoring and enforcement mechanisms, are prerequisites for the functioning of REDD. This includes well-defined property rights. Without clear entitlements to land and carbon certificates, REDD could present a high risk for the poor as they might be evicted or cannot profit from emission-related financial payments. Furthermore, poorly defined property rights and land tenure issues might result in open-access forests that are overexploited. At the very least, there need to be binding arrangements for assessing and negotiating benefit distribution.

6. BRIDGING THE GAP BETWEEN MODEL RESULTS AND POLICIES

The models surveyed in this Special Issue explore energy-economic scenarios for achieving low stabilization targets of 400ppm CO_2-eq atmospheric GHG concentrations. Model results suggest that reducing emissions in line with a 2°C target is feasible at a maximum cost of a few per cent of discounted global GDP, but very challenging (cf. Edenhofer et al., 2010 this Issue); a drastic decrease in carbon intensity is necessary. Moreover, besides broad participation, a wide range of technologies and further options for decarbonisation will be needed. The models presented in this Special Issue provide initial answers to the questions of the costs and technologies with which low mitigation targets can be achieved. However, they do not say anything about the policy regime required to implement the low stabilization mitigation scenarios. This article has indicated the scope of options that are available to achieve low stabilization, including GHG pricing, technology policies, non-energy sector policies, and voluntary lifestyle changes. With view to the short time-frame for achieving a peak and decline in global emissions, a sense of political urgency is necessary for realizing low stabilization climate policy scenarios, and a wide range of policy options need to be considered and implemented.

Further research is required in many areas. Prominent knowledge gaps and directions for further research include:

- Combining long-term models that cover all sectors and GHGs with insights on governance and institutional issues.
- Identifying a climate policy instrument mix comprising GHG pricing and non-price regulation policies that are consistent across sectors, regions and time.
- Further assessment of bio-energy options, because biomass plays an important role for mitigation in the energy sector but may lead to co-emissions from deforestation and agricultural intensification. It may also affect other sustainability goals such as food security especially in ambitious low stabilization scenarios.
- Further exploration of scenarios by integrated assessment models with only partial participation and/or not including the full portfolio of technologies. This includes analysis of delayed climate policy participation, as started, for example, by Clarke et al. (2009) or Luderer et al. (2009), and extended evaluation of technology failures. It also includes analysing the robustness of the results against crucial model assumptions like biomass or CCS potentials, which was a particular focus of the ADAM model comparison.
- Evaluation of the risks and the identification of crucial bottlenecks for all technologies, including renewable energy sources, to enable a full assessment of the adverse and positive impacts of all technologies.

To overcome these gaps in knowledge, the stimulation of an iterative process and a dialogue between modelling teams, policy analysts and stakeholders is needed. Integrated assessment models provide visions about the future and show possible ways for solving the climate problem. But as indicated in this paper, pure model analysis is insufficient to address the full range of economic, political and risk management issues raised by low stabilization. Therefore, model solutions have to be assessed in a public debate where the necessary mitigation options and their associated risks and co-benefits are discussed. Only by bridging the gap of knowledge between stylized model results and political realities will a low stabilization pathway have a chance of becoming reality.

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