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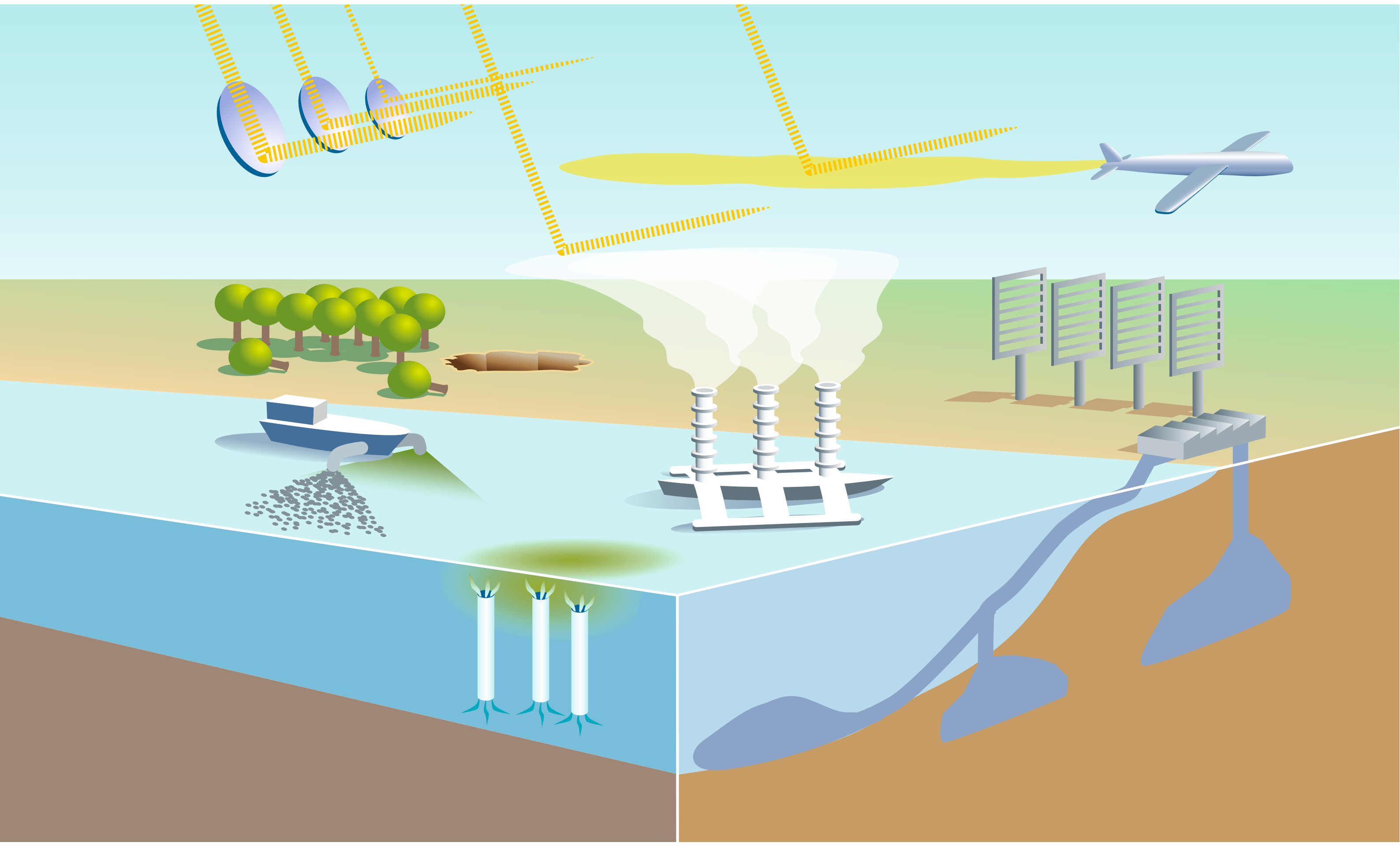
# Large-Scale Intentional Interventions into the Climate System?

## Assessing the Climate Engineering Debate



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Editors:

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# Preface

Overcoming climate change is one of the core challenges of the 21st century. At first glance, climate engineering appears to offer a new way out. The associated technologies have been attracting increased attention in recent times, particularly at an international level. However, climate engineering is still a long way from large-scale testing, let alone implementation. It is extremely difficult to reliably assess the processes under discussion—not least due to their novelty, the extent of ecological intervention they entail, and their far-reaching political and economic consequences. The question of whether climate engineering could or should complement climate protection measures and endeavors to adapt to climate changes that are no longer avoidable is as yet unanswered.

Climate engineering raises numerous questions of fundamental importance: Which proposals are scientifically realistic? Can they be technically implemented, and how effective are they likely to be? What interactions and side-effects (e.g., in the climate system) are to be expected? How far do the efficiency advantages of individual measures go in a comprehensive macroeconomic consideration? Will climate engineering become an endurance test for society and international relations? Is selective intervention in the Earth system ethically acceptable or justifiable?

The German Federal Ministry of Education and Research (BMBF) believes that, in addressing these questions, we need to act with foresight, rely on scientific findings and take a wide range of perspectives into consideration. For this purpose the BMBF has, as a first step, appointed an independent team of scientists to collate current knowledge on climate engineering, assess it on the basis of their scientific expertise, and clearly indicate contentious issues and gaps in knowledge.

This report is pioneering in its thematic scope and interdisciplinary approach. It provides a well-founded knowledge base and guidance for public debate and political decision-making regarding climate engineering. It will also contribute to stimulating international debate on climate engineering.

At the same time, there can be no question that we must unreservedly devote our abilities and resources to reducing $CO_2$ emissions and adapting to inevitable climate change. These areas will continue to be given priority in the BMBF's research funding.

Despite the differentiated analysis and broad range of topics addressed in this report and the complementary individual reports, many questions remain unanswered. The purpose of further, more in-depth research into climate engineering is not to prepare for the use of the associated technologies; instead it should be clearly designed to increase our ability to assess this topic. This requires not only the development of scientific theories and models, but also an examination of socio-economic issues, taking into account the potential for social and international conflict associated with climate engineering. This is a discussion that politics must not seek to avoid.

*Dr. Georg Schütte*
*State Secretary at the Federal Ministry of Education and Research (BMBF)*

# Editors' Foreword

Climate engineering—a collective term for large-scale technical interventions into the Earth's climate system—is an increasingly debated option in the fight against anthropogenic climate change. As the definition implies, any application of climate engineering has potentially global effects: climate and ecosystems would be changed across the world, affecting the environments of entire societies. For this reason, a purely scientific or economic analysis of the topic falls seriously short, precisely because climate engineering affects so many environmental media, societies, and areas of human life. Accordingly, only an interdisciplinary approach that also extends to the social factors involved can ensure a satisfactory analysis of the topic.

This is why the German Federal Ministry of Education and Research (BMBF) commissioned the present interdisciplinary exploratory report on climate engineering in the spring of 2010. The report has been elaborated by a consortium consisting of six project teams from different scientific disciplines. The coordination work was done by Wilfried Rickels, Gernot Klepper and Jonas Dovern at the Kiel Earth Institute. To manage the collaboration between the project teams and link the various aspects of the climate engineering debate, the report uses argument maps organizing the links between all arguments and theses relevant to the debate on the pros and cons of researching and deploying climate engineering. These argument maps were developed by Gregor Betz and Sebastian Cacean (both of the Karlsruhe Institute of Technology) based on their analysis of the structure of the debate on climate engineering as conducted in academic publications and social discourse.

Any assessment of climate engineering must be founded on the technical interrelations of its application along with the physical and biochemical reactions it initiates in the Earth's climate system. These aspects were examined for the report by Jost Heintzenberg (Leibniz Institute for Tropospheric Research), Thomas Leisner (Karlsruhe Institute of Technology and University of Heidelberg), Ulrich Platt (University of Heidelberg), Corinna Hoose (Karlsruhe Institute of Technology), and Andreas Oschlies (IFM-GEOMAR). Gernot Klepper and Wilfried Rickels (both of the Kiel Institute for the World Economy) analyzed the costs and economic effects of the various technologies. Aspects of the public perception of climate engineering and ways of involving the public in the discourse on climate engineering were investigated by Ortwin Renn, Nadine Brachatzek, and Sylvia Hiller (all of the University of Stuttgart). To this end, the team also organized a Delphi group to collect expert opinions. Alexander Proelß (University of Trier) and Kerstin Güssow (University of Kiel) analyzed the aspects of international law that are relevant due to the global character of climate engineering. Finally, issues connected with intergovernmental cooperation and the international regulation of climate engineering were evaluated by Michael Zürn and Stefan Schäfer (both of the Social Science Research Center Berlin).

The project partners consulted and networked with each other at a total of four workshops held at different stages of the project in Berlin, Bonn, and Kiel. We would like to thank all the project partners for their exceptionally cooperative and productive collaboration, as well as the Project Management Agency at the German Aerospace Center (DLR) and the project supervisors at the VDI Technologiezentrum and BMBF.

The present work was the first comprehensive report on the subject of climate engineering published in Germany. It has now been translated into English by the authors together with Katherine Houghton, Andrew Jenkins, David Keller, Paul Kramer, and DELTA International CITS GmbH. Due to the broad interdisciplinary approach of this report, it provides a more comprehensive discussion of the subject than the previous reports that have influenced scientific and political debates so far. We hope this report will serve to provide a broad, well-established basis for the political opinion-forming and decision-making process and also for communicating the subject to the public.

*Wilfried Rickels, Gernot Klepper and Jonas Dovern*

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# Executive Summary

CLIMATE ENGINEERING: LARGE-SCALE INTENTIONAL INTERVENTIONS INTO THE CLIMATE SYSTEM

"Climate engineering" (CE) encompasses technologies designed to remove the causes of anthropogenic climate change and to treat the symptoms associated with it. The former are referred to as carbon dioxide removal (CDR) technologies because they reduce $CO_2$ in the atmosphere, the latter as radiation management (RM) technologies because they directly influence the radiation budget and hence the temperature. CDR technologies draw upon biological, chemical, or physical processes to cause the ocean or the terrestrial biosphere to absorb atmospheric $CO_2$ or directly store it geologically. RM technologies reduce the Earth's short-wave solar radiation input, enhance its reflection, or increase long-wave thermal radiation to space.

STATE OF THE DEBATE ON CLIMATE ENGINEERING

Research and public debate on climate engineering are still in their early stages. The public at large is almost totally unfamiliar with climate engineering, so the debate takes place within a small circle of predominantly academic participants plus a few representatives from the business community, non-governmental organizations (NGOs), and governments. Research on climate engineering began with very general considerations about how to manipulate the Earth's radiation budget. Today, it also focuses specifically on the implementation and application of suitable technologies. Research to date has revealed that CDR and RM technologies differ greatly, not only in terms of their mode of operation, efficiency, and side-effects, but also in terms of their social implications. Accordingly, they need to be assessed in different ways.

DIMENSIONS OF THE DEBATE ON CLIMATE ENGINEERING

The current debate on climate engineering is far more complex and variegated than the majority of academic publications would appear to suggest. To understand the complexity of research into and use of climate engineering, it is first necessary to collect, structure, and relate the very different arguments that have been advanced for and against climate engineering. In support of its use or operative readiness, three main arguments are usually presented: (i) CE technologies are more efficient than conventional emission control; (ii) without CE technologies ambitious climate targets could not be achieved; and (iii) CE technologies are necessary as an emergency option, should there be hazardous anthropogenic interference with the climate system as referred to in the United Nations Framework Convention on Climate Change (UNFCCC).

In addition to reservations about the effectiveness and economic efficiency of such technologies, arguments against the use of climate engineering include those centering on risk ethics and fairness plus a variety of other fundamental (e.g., religious) arguments. Hence it is claimed that the operational readiness of any CE technology should include the investigation of all consequences associated with it. Others argue that CE research has harmful side-effects and violates ethical and legal principles (such as the "polluter-pays" principle). In addition to normative assumptions, all these arguments are based on empirical premises that can, in principle, be scientifically tested. Scientific results can thus inform the CE debate, but they cannot be the sole basis of a decision for or against climate engineering.

INTENTIONAL AND UNINTENTIONAL CONSEQUENCES OF CE TECHNOLOGIES AND THEIR PREDICTABILITY

To assess the intentional consequences of CE technologies, it is vital to know what targets their effectiveness is to be measured by. What types and degrees of anthropogenic climate change should actually be compensated for? And how quickly should these climate changes be corrected? Measured against the objective of a comparatively rapid reduction in average global temperature, some RM technologies appear to be more effective than others. However, if we set our sights on other consequences of climate change such as shifts in precipitation patterns or changes in oceanic acidification, we find that these technologies are less or not effective. Moreover, we must bear in mind that lasting temperature reduction via the use of RM technologies requires continued use of these technologies over very long periods, because the concentration of greenhouse gases and especially of $CO_2$ will only decrease very gradually by natural means. Only if RM deployment were complemented by a decrease in the concentration of $CO_2$ would it be possible to discontinue their use at an earlier stage without causing a sudden rise in temperature. So a reversal of climate change and with it the long-term correction of anthropogenic climate changes can only be achieved through CDR technologies, which, however, do not allow for rapid temperature reduction.

To evaluate the unintentional consequences or side-effects of a CE technology, it is important to consider the material and energy flows affected by the technology and the extent to which this happens. Fundamentally, it can be said that the risk of unintentional consequences is greater, the larger the scale of the technology used, the more sensitively the material cycles affected react, and the longer these cycles are influenced by the technology in question. The deployment of RM technologies represents an additional intervention into the radiation budget with the aim of compensating for the greenhouse gas-induced reduction of long-wave radiation via the corresponding reduction of short-wave radiation. Little research has yet been done to find out how the high-feedback system Earth will react to such compensation and what fundamental side-effects may arise in the climate system, in other material cycles, and in the biosphere. Accordingly, RM technologies in general are expected to have a greater potential for producing unpredictable side-effects than CDR technologies. The potential side-effects of individual CDR technologies result predominantly from the ability they have to influence material cycles. Biological cycles are assumed to be those most severely affected. However, feedback processes (e.g., as a result of a change in the Earth's albedo) may also cause CDR technologies to trigger unpredictable meteorological side-effects.

Though further research may be able to reduce or even eliminate some of the uncertainties regarding effectiveness and side-effects, the complexity of the Earth system makes it difficult to predict all the effects and side-effects of CE technologies, particularly at a regional level. So ongoing research endeavors involving model calculations and field trials will not result in risk-free climate engineering. These general considerations also apply of course to anthropogenic climate change. Its global and particularly its regional effects are difficult to predict in detail. This means that decisions on climate policy will continue to involve trade-offs between a number of different risks and uncertainties.

### THE ROLE OF FIELD TRIALS

Sooner or later, the improvement of our understanding of CE technologies will necessitate large-scale field trials that come very close to an actual application of the technologies. Such field trials should be accompanied by comprehensive monitoring programs. Even if we assume the best possible design for large-scale trials, unequivocal identification and quantification of the effects and side-effects of particular technologies would take many years or even decades. In the course of a field trial extending over such a long period, apparent effects and side-effects unrelated to the application of the technology would also occur. The conduct of such a large-scale trial without the occurrence of significant social and political impacts must be considered one of the major challenges of climate engineering.

### THE INTERNATIONAL LEGAL FRAMEWORK

Given the largely transboundary effects of most of the technologies concerned, the legal permissibility of climate engineering is determined primarily by the provisions of international law. International law has not as yet instituted any standards that would generally and comprehensively regulate research into, or the use of, climate engineering. Nevertheless, there are individual treaties that are applicable to CE technologies. Treaties dedicated to specific problems are very broadly worded, with the express intention of being comprehensive enough to cover future developments not actually referred to specifically in the treaties themselves.

We have no binding definition of climate engineering under international law. In legal terms, no specific consequences have been attached to the distinction between RM and CDR technologies. Instead, the question of whether climate engineering is legal needs be assessed separately for each individual CE technology with regard to international treaty law and customary international law. However, what we can say specifically against the background of the requirements of the UNFCCC is that there is, first of all, no general ban on climate engineering under international law. Second, detailed analysis of the individual CE technologies supports the conclusion that CDR technologies tend to attract fewer legal objections than RM technologies. Third, the vast majority of CE technologies require due regard to be given to the existing rights and territorial integrity of other states. This is why there is a rebuttable presumption that purely unilateral CE action is not in accordance with international law. Fourth, particularly with regard to RM technologies, legal assessment depends above all on how the phenomenon of conflicting environment-related objectives will be handled in the future. Given the current degree of scientific uncertainty, any decision on the pros and cons of CE research or its use inevitably requires that a balancing of the risks involved be carried out, provided of course that specific CE technologies are not prohibited in international law.

Against this background, it is important for the risk-balancing process underlying any decision to be carried out in a legitimate and transparent way. To this end, the general obligations imposed by customary international law to inform potentially affected states, to conduct consultations, and to carry out environmental impact assessments in the context of the specific or potentially pertinent treaty must be applied in light of the specific features of the CE technologies in question and be effectively implemented.

### POTENTIAL FOR INTERNATIONAL CONFLICT

Emission control can only be effective when it is carried out within the framework of an agreement between a large numbers of states. By contrast, some CE technologies can be readily implemented, both technically and financially, by a single state or a small number of states. This might conceivably lead to international conflicts. The promise of a quick and highly effective technical solution (particularly one involving RM technologies) that can be carried out by one or a small number of states, is held out by precisely those technologies that give reason to expect particularly vehement politicization and large-scale social and political resistance, with potentially far-reaching consequences for the UNFCCC process. Against this background, international coordination of climate engineering appears desirable, notably with a view to avoiding international social and political conflicts.

The institutional integration of research on, and possible implementations of, CE technologies into an international regime would provide a sound basis for bringing about adequate social acceptance at the international and transnational level. Such integration would also favor the coordination of all measures pertaining to climate policy by linking climate engineering to existing environmental regulations. Requirements for institutional integration are (i) international coordination of research and technical evaluation, (ii) creation of an independent supervisory authority, (iii) definition of international norms and rules, (iv) comparability of emission control and CE deployment, (v) coordination of research to deal with the slippery-slope problem, and (vi) a definition of terms for phasing out the use of climate engineering.

### COSTS OF CE TECHNOLOGIES

At present, our knowledge of the costs generated by different CE technologies is rudimentary and bedeviled by major uncertainties. Estimates of these costs are primarily limited to the operating costs of individual CE technologies, while for the majority of these technologies explicit estimates of the research and development costs involved in attaining operational readiness and the capital costs associated with their use quite simply do not exist. Furthermore, these estimates disregard economies of scale and price, which are likely to occur if CE technologies are implemented on a large scale. Finally, we still have no studies dealing with the overall economic costs arising from side-effects of the use of CE technologies. Despite the uncertainties about the side-effects resulting from our limited understanding of the Earth system, it is fair to assume that the economic costs will increase with the magnitude of CE deployment and that the associated economic, political, and social impacts will also increase accordingly.

While the costs of CDR technologies are assessed on the same basis as the costs of $CO_2$ emission control and thus allow for direct comparison, this is not the case with RM technologies. If RM technologies were used to compensate anthropogenic radiative forcing, they would have to be sustained over very long periods. Hence, even in the case of very low annual costs, the cumulative costs of RM technologies might exceed the costs of emission control or CDR technologies. Currently, we have no comparative analysis of different emissions and compensation scenarios that takes into account such long-term factors and the feedback effects of RM technologies on natural $CO_2$ uptake. Accordingly, assessments can only be made on the basis of investment expenditures and annual operating costs. Assessment of the costs accumulating over time is not feasible.

### EFFECTS OF CLIMATE ENGINEERING ON EMISSION CONTROL

Economic analyses on aspects of climate engineering come to the conclusion that the use of CE technologies is generally accompanied by a decrease in emission control if emission reductions are more costly than the application of CE technologies for a given target. Given the limitations of our current knowledge on the economic costs of climate engineering, we cannot confirm that this is genuinely the case. In fact, a number of studies indicate that already CE research itself, can be expected to result in a lower level of emission control. These studies argue that the risks of sudden climate change can best be averted by RM technologies, so that maintenance of especially intensive emissions control is no longer necessary.

### PUBLIC DEBATE

The prospect of the availability of climate engineering leading to less intensive emission control efforts is also a concern in the public debate on the subject. Analysis of reader opinions and blogs indicates widespread concern that the use or availability of climate engineering will make climate change appear less threatening, thus slackening the pressure on politicians to control emissions and/or promote renewable energies. But studies show that the reverse case may also occur: Efforts to control emissions might increase among the general public because this would be seen as a lesser evil compared with climate engineering.

There are indications from sociological studies that CE critics would act in a more environmentally friendly way if there were progress in the development of CE technologies, while CE advocates would tend to have a more carefree attitude towards greenhouse gas emissions. However, the extent to which a rising level of awareness of CE technologies in society would lead to a general change in attitudes towards climate protection is currently unclear. Similar game theory-based considerations could also apply to the analysis of international relations. This line of reasoning is not restricted to CE deployment. It also applies to CE research, since decisions on CE research and decisions on the range of emission control to be used cannot be made in isolation.

### COMMERCIAL CONTROL OF CE DEPLOYMENT

One general risk in the development of new technologies is that researchers or their sponsors may pursue their own interests and promote the technology they are investigating or sponsoring even if the application of this technology does not seem objectively necessary. The fear that CE research might become self-sustaining is frequently expressed in public debate. However, the vast majority of CE technologies do not currently seem to have any commercial application. Commercial applications would only arise if the appropriate incentives were created via government regulation. If there were relevant markets (as for $CO_2$) or if regulatory provisions were made regarding the implementation of climate engineering, it would be incumbent on the relevant jurisdiction or the authorities supervising competition to limit the extent of commercial control.

### IRREVERSIBILITY OF CE TECHNOLOGIES

In principle, every kind of CE technology can be discontinued without serious consequences if the technology is phased out smoothly and gradually. The precise conditions under which this is possible depend on the extent to which the Earth system has been influenced by the CE technology itself. Given that it is possible to securely store carbon, the use of air capture, for example, would affect relatively few material cycles in comparison with RM technologies. We can legitimately assume that the use of the majority of CDR technologies could be discontinued without having too great an influence on the Earth system. If RM technologies were phased out too quickly or were subject to unscheduled disruption over a lengthy period of time, this could trigger rapid climate change that might even be more intense than it would have been without the prior use of RM technologies. However, discussion of the potential reversibility of CE interventions into the climate system should also bear in mind that untrammeled $CO_2$ emissions would probably lead to equally irreversible changes.

### NECESSITY FOR AN INTEGRATED APPROACH

Irrespective of the role individual CE technologies may play in future climate protection, it is obvious that the discussion revolving around CE technologies and research into them cannot be considered in isolation. The assessment of CE technologies alone, for example, depends on the extent to which other climate protection measures are being implemented. Recent research findings indicate clearly that greater attention must be paid not only to the various anthropogenic influences on the radiation budget, such as greenhouse gas or aerosol emissions, but also to changes in land use and associated economic and social interactions. Political decisions on climate protection should therefore consider all anthropogenic influences on the climate. In other words, an integrated climate policy should also encompass the various effects of anthropogenic aerosol emissions and anthropogenic surface changes on climate, whether they are caused by

CE technologies or represent side-effects of economic development.

We can safely say that further research into the Earth system is not only a prerequisite for a better understanding of the intentional effects of CE technologies but also for the quantification of their side-effects. This knowledge is essential for research into the individual cause-effect chains on land and in the oceans. A better understanding of these effects could then serve as a basis for the legal, economic, and sociological analysis of the advantages and disadvantages of CE technologies. Initial analytic studies have gone some way toward indicating the potential societal implications of the use of, and even research into, CE technologies at a qualitative level. But the actual extent of these implications is still largely unknown. These studies also indicate that that CE technologies and CE research are expected to have implications on national and international emission control policies. It is therefore also important to assess the significance of these implications in quantitative terms.

The natural impacts of climate change and the social contexts of international efforts toward effective climate protection have been accorded high priority in research. The same cannot be said as yet for climate engineering. However, research has revealed that climate engineering and emission control cannot be considered in isolation from one another. The fact that climate engineering is receiving greater academic and societal attention makes it increasingly important to investigate all aspects of climate engineering, including its interaction with emission control. Knowledge of the side-effects of CE technologies, in particular their ecological, economic, and social dimensions, is still insufficient for us to draw conclusions about the role of climate engineering in an integrated climate policy strategy designed to comply with the 2° C target.

# 1 Introduction

## 1.1 Intentional interventions in the climate system: Climate engineering

The term "climate engineering" (CE) covers technologies that are expressly used to reduce the concentration of $CO_2$ in the atmosphere or to directly influence the Earth's radiation budget with a view to mitigating or offsetting anthropogenic climate change. Unlike the term "geoengineering," which is also used to refer to such technologies, climate engineering emphasizes the intention to exert an influence on the climate system. It does not cover other environmental interventions such as the modification of coastal areas or the diversion of rivers. However, the "engineering" component of the term is not designed to suggest that the climate can or should be controlled by technical means but rather that these interventions are undertaken to influence the climate or restrain climate change in an intentional way. Climate engineering therefore covers more than the mere side-effects deriving from other anthropogenic activities (e.g., greenhouse gas emissions).

Distinction between mitigation, adaptation, and climate engineering

**Climate engineering differs from mitigation and adaptation by virtue of the fact that CE technologies are neither applied to mitigate fossil-fuel emissions into the atmosphere nor to adapt to the impacts of climate change. They occupy a middle ground between these two approaches to dealing with climate change.** Consequently, industrial carbon capture and storage (CCS) does not count as climate engineering because it is applied to reducing the amount of emissions released into the atmosphere (Keith 2000). Climate engineering encompasses technologies devised (i) to address the cause of radiative forcing by reducing the concentration of atmospheric $CO_2$, and (ii) to offset the impacts of radiative forcing by directly influencing the radiation budget. The former are known as carbon dioxide removal (CDR), the latter as radiation management (RM) technologies. Figure 1 shows some of the technologies under discussion.

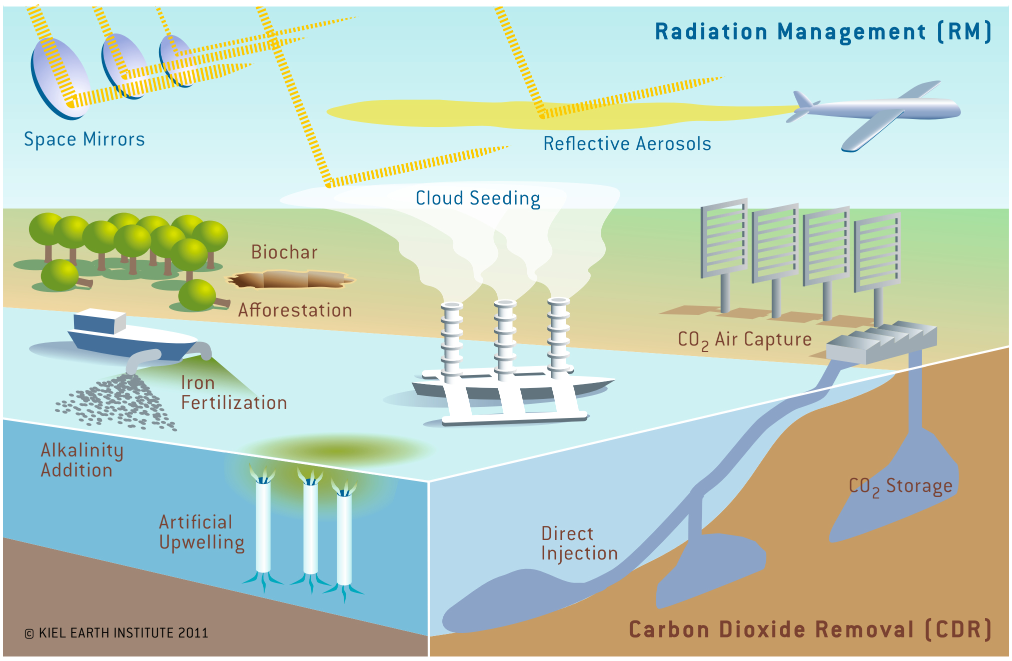



FIGURE 1: Schematic illustration of CE technologies

Source: Own representation.

Carbon dioxide removal and radiation management

CDR technologies utilize biological, chemical, or physical processes to cause the ocean or the terrestrial biosphere to absorb atmospheric $CO_2$ or directly store it geologically. For example, oceanic $CO_2$ uptake can be enhanced via iron fertilization, artificial ocean upwelling, or increasing ocean alkalinity. Terrestrial $CO_2$ uptake can be enhanced via forestation or the production of biochar. However, $CO_2$ can also be chemically filtered directly from the air in order to store it in geological formations on land or beneath the sea. In principle, $CO_2$ filtered from the air could also be fed directly into the ocean, but this was prohibited in 2006 by the London Protocol and will therefore not be discussed here. RM technologies directly influence either short-wave solar radiation or long-wave thermal radiation. Incoming short-wave solar radiation can be reduced by reflectors in space; its reflection (albedo) can be increased by aerosols in the stratosphere, modifications of marine stratus cloud formation, or alterations to the surface of the Earth. Long-wave thermal radiation can be increased by the modification of cirrus clouds.

## 1.2 Anthropogenic climate change

**More and more scientific studies indicate that the rate at which the global climate is changing is getting faster all the time.** In its Fourth Assessment Report, the Intergovernmental Panel on Climate Change (IPCC) established that global warming is an undeniable fact involving appreciable increases in the average global temperatures of the air and the oceans, along with a reduction in snow and ice cover and an increase in mean sea level (IPCC 2007). Climate experts agree that this phenomenon is largely anthropogenic.

Anthropogenic influences on the climate are mainly the result of activities involving the emission of greenhouse gases and aerosols into the atmosphere.[1] Greenhouse gases reduce atmospheric permeability for outgoing long-wave thermal radiation (i.e., they trap it) and consequently have a warming effect. By contrast, aerosol emissions—sulfur and nitrate particles or dusts—primarily increase the reflection of incoming short-wave solar radiation and have a cooling effect. However, the greenhouse effect predominates, so that net radiative forcing is estimated to be +1.6 $W/m^2$ (IPCC 2007). The anthropogenic greenhouse effect is primarily caused by $CO_2$ emissions, which have been on the increase ever since the industrial revolution. While these emissions and the $CO_2$ concentration in the atmosphere are not the sole problem, they are particularly crucial because of the long atmospheric lifetime of $CO_2$. Even though about half of the annual anthropogenic $CO_2$ emissions are absorbed by terrestrial and oceanic sinks (Raupach and Canadell 2010), an entirely natural return to pre-industrial levels of atmospheric $CO_2$ would take far more than 1,000 years, even if emissions were to cease altogether (e.g., Brovkin et al. 2009; Solomon et al. 2009).

Temperature reaction influenced by feedback mechanisms

**Global warming caused by anthropogenic net radiative forcing can be estimated on the basis of models.** However, these estimates require consideration of the various climate system feedbacks. These feedbacks (particularly the increase in water vapor, a natural greenhouse gas, and the depletion of marine ice) are responsible for more than half of the calculated rise in temperature. Yet our understanding of them (and accordingly their modeling) is fraught with uncertainties, meaning that anthropogenic radiative forcing can only be estimated within a certain range of values. This range, which accounts for the mean change in temperature caused by a doubling of pre-industrial atmospheric $CO_2$ concentration, is also called climate sensitivity (IPCC 2007). On the basis of various observations and models, climate sensitivity in the presence of a doubling of pre-industrial $CO_2$ concentration has been estimated to result in a temperature increase between 2 and 4.5°C (Knutti and Hegerl 2008).

1 Further changes in the global radiation budget stem from (anthropogenic) changes to the Earth's surface and from a slight (non-anthropogenic) change in solar radiation (IPCC 2007).

**Uncertainty in predicting climate change is compounded by the possibility of critical thresholds.** If they are exceeded—for example a $CO_2$ concentration threshold or a temperature rise threshold—sudden changes may occur that affect the climate as a result of additional feedbacks and put it on an entirely new track. The pace and extent of these effects are non-linear, and they are intrinsically determined by the climate system. Because of the non-linearity of the reactions, these thresholds are referred to as tipping points (e.g., Lenton et al. 2008; Allison et al. 2009). Potential factors operative in the materialization of these tipping points include for example the melting of Greenland's ice sheet, instability of the West Antarctic ice sheet, breakdown of Atlantic Ocean circulation, or the emission of greenhouse gases from thawing permafrosts. There is still major uncertainty about the nature of these thresholds, the responses of the different tipping factors, and the degree of climate change associated with tipping (Lenton et al. 2008; Kriegler et al. 2009). This uncertainty makes it difficult to determine a temperature limit for global warming that is consistent with the target set by the United Nations Framework Convention on Climate Change (UNFCCC), which is to avert dangerous climate change.

Non-linear climate changes as a result of tipping points

**At a political level, governments have agreed that global temperature increases need to be limited to below 2°C to avert dangerous climate change.** But there are many uncertainties bedeviling our understanding of the Earth system, and it is not just the determination of this temperature limit that is difficult, but also the assignment of emission paths designed to prevent this limit from being exceeded. Meinshausen et al. (2009) estimate that if another 1,000 gigatons (Gt) $CO_2$ is emitted cumulatively between 2000 and 2049, the probability of exceeding the 2°C target is between 10 and 42 percent. However, one third of this amount was already emitted between 2000 and 2010 (Friedlingstein et al. 2010). In the same period, emissions of anthropogenic aerosols, which have a negative influence on the radiation budget and therefore bring about a cooling effect, have significantly decreased. Thus, drastic reductions in the emissions of greenhouse gases, especially $CO_2$, are required if we want to keep to the politically defined 2°C limit.

Limitation of temperature rise to 2°C

## 1.3 The development of the climate policy debate

**At the United Nations Conference on Environment and Development (UNCED) in Rio de Janeiro in 1992, the UNFCCC was signed by the majority of countries.** The aim of the Framework Convention is to prevent dangerous anthropogenic interference with the climate system. To this end, global warming should be slowed down and restricted in a way that would enable eco-systems to adapt to climate change. In addition, measures should be taken to ensure that both food production and economic development are not affected in the long term. In 1997 compulsory (moderate) reductions in greenhouse gas emissions were stipulated for the first time under international law in the Kyoto Protocol to the UNFCCC. The signatory industrialized countries pledged that by 2012 they would reduce their greenhouse gas emissions by 5.2 percent over and against 1990, the base year. As things stand, the Kyoto reduction target has only been implemented successfully in a few countries. In addition, the treaty was not ratified by the USA, and it does not contain any explicit goals for developing and emerging countries. Consequently, emissions of greenhouse gases, and particularly of $CO_2$, continue to increase. The negotiations necessary for a follow-up treaty to Kyoto have proved difficult.

Most countries are falling short of the Kyoto targets

**On the one hand, the most recent UN Conference of the Parties in Cancún at the end of 2010 was able to avert the collapse of an internationally negotiated solution for the reaction to climate change.** The 193 participating countries recognized that climate change should be

No binding post-Kyoto treaty adopted yet limited to a rise in temperature of 2° C, or that, in light of new findings in the IPCC assessment reports, the target can be tightened to 1.5° C (UNFCCC 2010). The Kyoto countries (all industrial countries except the USA) also indirectly conceded that by 2020 greenhouse gas emissions must be reduced by at least 25 to 40 percent over and against 1990. On the other hand, no **precise emission reduction targets** were agreed on, and the voluntary reduction commitments of the UNFCCC Conference of the Parties in Copenhagen in 2009 (Copenhagen Accord) remained well below this objective. If the 2° C target is to be achieved with the reductions promised in the Copenhagen Accord, drastic cuts in emissions will be necessary from 2020 onwards.[2] Admittedly, with a potentially legally binding commitment to the reduction targets at the next UNFCCC Conference of the Parties in 2011 in Durban, the reduction targets could, in theory, be met. But experience of the lengthy ratification processes involved would lead us to expect that once the Kyoto Protocol expires at the end of 2012 there will be a time lapse before the follow-up agreement comes into force.

**A future international agreement and the accelerated implementation of measures like improving energy efficiency or expanding the use of renewable energies[3] could mean that global warming will be halted in time.** However, it is by no means certain that the international coordination required for emission controls will be implemented in time. The decisions made in Cancún reveal that in response to anthropogenic climate change the international community is willing to consider other options in addition to reducing greenhouse gas emissions and to provide appropriate financial resources for this purpose. In Cancún, the potential of the terrestrial biosphere to act as a sink was reaffirmed once again. The protection of tropical forests was adopted as the target of the Framework Convention. In addition, the option of adapting to climate change came to the fore. The industrialized countries declared their willingness to provide developing countries with an annual USD 30 billion for this purpose and for environmentally friendly development. They also undertook to provide a further annual USD 100 billion via a designated climate fund.

## 1.4 Climate engineering as a climate policy option?

Controversial debate on climate engineering

**Against this background, debates on reactions to anthropogenic climate change need to engage with the question whether climate engineering should be envisaged as a potential course of action.** Originally, the debate focused on mitigation via reduction of greenhouse gas emissions, but in recent years it has also started to consider possibilities for adapting to climate change effects (Figure 2).

The arguments for considering climate engineering as a possible response to anthropogenic climate change are mainly that (i) in the event of high climate sensitivity the consequences of climate change may be greater than previously estimated, (ii) the progress of international negotiations on emission control tends to be too slow, (iii) even on a long timescale the warming that has already occurred may be irreversible, and (iv) exceeding critical thresholds in the climate system may trigger disastrous damage. With this in mind, advocates of climate engineering argue that these technologies could represent a necessary (emergency) option in counteracting climate change. Opponents of the idea argue that (i) there is considerable

2 The IEA (2010) estimates that by postponing the necessary cuts in emissions to after 2020 (with respect to an efficient prevention path, which now includes a greater reduction in emissions than provided for in the Copenhagen Accord) necessary investments (to achieve emission targets in the long term) in the period 2010 to 2035 will increase from US$ 17 to 18 trillion.

3 In its latest report on the importance of renewable energies, the IPCC commented very positively on the future expansion of these forms of energy production. In more than half of the scenarios considered in this report, the proportion of renewable energies in global primary energy production by 2050 is over 27 percent (2008: no more than 13 percent). Ideally, it might even reach 77 percent (IPCC 2011a).

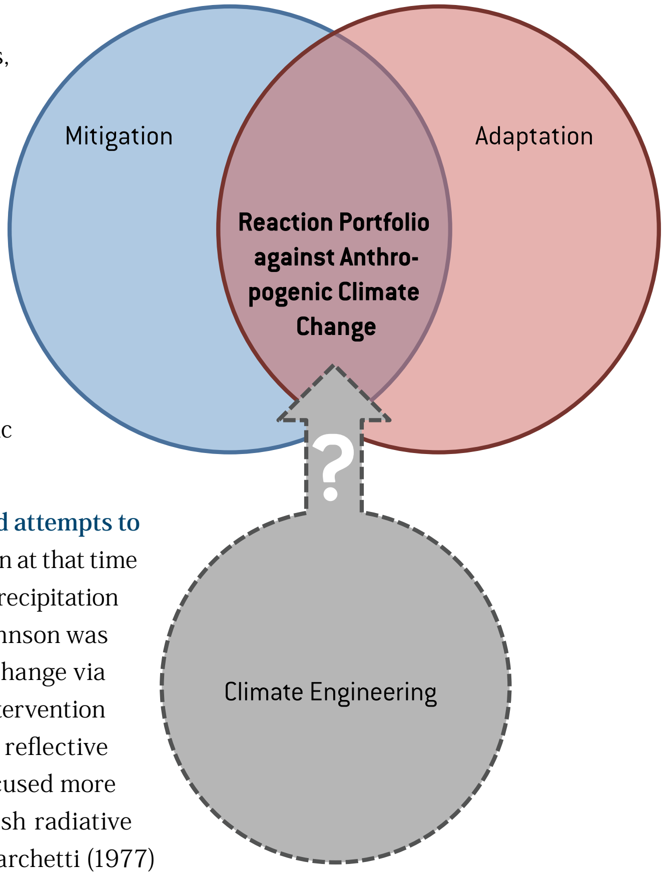



FIGURE 2:
Response strategies for climate change

Source: Own representation.

uncertainty about the side-effects of the different technologies, (ii) terminating CE technologies may result in far worse climate change, (iii) only a partial offsetting of anthropogenic climate change can be achieved, (iv) considerable distributional effects and corresponding social and geopolitical conflict may arise from the various regional effects, and (v) conventional emission control efforts will slacken. In addition, there are fundamental objections based on normative attitudes (e.g., arguments that are religious or based on deep-rooted criticism of civilization, as such). Accordingly, the climate engineering debate tends to be rather adversarial and is no longer limited to the question of scientific feasibility or the efficiency of the technologies involved.

**Debates on technological interventions in the climate system and attempts to institute such measures date back to the 19th century.** The intention at that time was often to change local weather variables such as the amount of precipitation (Fleming 2010). However, already in 1965 US president Lyndon Johnson was advised that it was possible to counteract anthropogenic climate change via technological interventions in the climate system. One possible intervention under consideration was to change global albedo by spreading reflective material on the ocean surface. In subsequent years, the debate focused more on the use of interventions in the global carbon cycle to diminish radiative forcing caused by greenhouse gases. In line with this approach, Marchetti (1977) investigated the possibility of accelerating oceanic carbon uptake by direct carbon injection. He coined the term "geoengineering" to refer to technological interventions of this kind in the context of climate change. However, the intervention he was discussing was geared to a situation in which $CO_2$ had not yet reached the atmosphere. Accordingly, it is now subsumed under the heading of "industrial carbon management measures" (Keith 2000).

**Research in the 1980s focused primarily on potentialities for increasing natural biological activity in terrestrial and oceanic carbon sinks.** Investigations related to achieving higher terrestrial $CO_2$ uptake mainly focused on afforestation and changes in land use. To a limited extent, increasing terrestrial $CO_2$ uptake through land use, land-use change, and forestry (LULUCF) is written into the Kyoto Protocol. There, however, the reference is to small-scale projects from which emission credits can be obtained. For this reason, the term used in the course of the UNFCCC negotiations was not "climate engineering" but "sink enhancement".

Afforestation is part of the Kyoto Protocol

Enhancing the oceanic sink was assumed to allow for large-scale exertion of influence on the carbon cycle and hence on the climate. In this connection the potential associated with iron fertilization was subjected to investigation. In the debate on the iron hypothesis in the early 1990s, John Martin provocatively boasted, "give me a half tanker of iron and I'll give you the next ice age". Field trials to date have confirmed the underlying action mechanism involved in iron fertilization, but they have been too few and far between to properly bolster the claim made by Martin (e.g., Oschlies et al. 2010 a). In the past, these field trials and the debate associated with them have clearly shown that large-scale interventions may trigger a whole variety of side-effects and are therefore perceived critically by the public (e.g., the LOHAFEX project).

Iron fertilization and oceanic $CO_2$ uptake

At first, work on directly influencing the radiation budget (e.g., CSEPP 1992; Teller et al. 1996; Teller et al. 2002) barely got so much as a mention in the scientific debate on the reaction to anthropogenic climate change. **This changed in response to work by Paul Crutzen (2006),**

**who addressed the possibility of technically injecting sulfur particles into the stratosphere (Budyko 1977).** His calculations are based on a natural “experiment” that directly influenced the radiation budget: the eruption of Mount Pinatubo in 1991, which injected sulfur into the atmosphere and reduced global temperature by 0.5° C in the course of the following year (Bluth et al. 1992; Wilson et al. 1993; Lacis and Mishchenko 1995). Crutzen focused on stepping up control of predominantly near-ground sulfur emissions in the event of necessary but overdue reductions in greenhouse gas emissions. Here, he contended, the insertion of markedly smaller quantities of sulfur into the stratosphere could re-establish the cooling effect of these aerosols. Crutzen’s work restored the scientific presentability of the whole subject. As a reaction to subsequent publications and its increasing significance in public debate, the Royal Society published a report in 2009 called “Geoengineering the Climate”, in which it summarized and evaluated the state of knowledge on the different technical options available (Royal Society 2009). The report also addressed political, legal, and ethical issues connected with climate engineering.

Eruption of Mount Pinatubo as a natural CE experiment for injecting sulfur into the atmosphere

**At present, various scientists are addressing the issues involved in climate engineering, and an increasing number of research articles on these different aspects are appearing in renowned peer-reviewed journals.** The prevailing opinion is that large-scale intervention in the climate system would involve numerous side-effects and incalculable risks and that the option of drastically reducing emissions is preferable on all accounts. However, as the political realization of sufficiently effective emission control has proved to be a long time in coming, the number of voices advocating systematic and timely research into climate engineering is increasing.[4]

Need for systematic research on climate engineering

An increasing number of workshops and conferences are discussing the uncertainties of the various technologies, the political problems, and the issues under international law that are associated with implementing these technologies. At a workshop in Lisbon in 2009, international experts from the fields of science, politics, industry, and business discussed these different aspects. In the opinion paper the workshop came up with, reference was made to the necessity for research and international regulation in connection with climate engineering (Morgan and Ricke 2009). Following a report published by the British House of Commons, the Oxford Principles on the regulation of research into climate engineering were formulated (Rayner et al. 2009). The largest conference on climate engineering to date, the Asilomar Conference in 2010, addressed these principles. The conference provided a setting for 175 scientists, scholars, and company representatives to establish voluntary guidelines for studying the topic. Both the Oxford Principles and the Asilomar Conference’s recommendations for voluntary guideline focused on the fact that cooperative research should be carried out, that the various technologies should be iteratively assessed and further developed with the participation of the public, and that a form of international regulation must be found prior to the potential deployment of the technologies. In the meantime, the IPCC has also decided to discuss in its Fifth Assessment Report the significance of climate engineering for the anthropogenic reaction portfolio on climate change and its possible effects on humans and nature.[5] This development points out the fact that current research on climate engineering is no longer restricted to the scientific side of the matter and the technical feasibility of the individual options, but that interdisciplinary issues are increasingly being addressed.

Oxford Principles, Asilomar Conference, IPCC

4 For an overview of this development, see Kintisch (2010).

5 The treatment and approach were scheduled for discussion at a preliminary meeting of experts on 20. – 22.06.2011 (IPCC 2011b). At the time of writing, the results of this meeting were not yet available.

## 1.5 The development of the global CE debate

Initial political examination of climate engineering primarily in English-speaking areas

**The climate engineering debate is presently becoming both more intense and also more political.** In English-speaking countries in particular, various (parliamentary) initiatives have been launched with a view to developing research strategies and exploring the need for regulation. In much the same vein, the US House of Representatives recently published an expert report titled “Engineering the Climate: Research Needs and Strategies for International Coordination” (CST 2010). It was mainly targeted to establish research strategies, but also to reveal the amount of resources already available at various institutions in the USA. Furthermore, the House of Representatives contracted the Congressional Research Service to prepare a study on the applicability of existing US laws and international agreements in the case of tests or the large-scale application of climate engineering measures (Bracmort et al. 2010a). The Government Accountability Office was asked to elaborate an overview of CE research activities undertaken by US federal institutions (GAO 2010). At the same time, the Science and Technology Committee of the British Parliament drafted an expert report entitled “The Regulation of Geoengineering” (STC 2010), which focused on whether and in what form the (international) regulation of climate engineering was required.

Research funding from private enterprise

There also appear to be more initiatives in English-speaking countries than in other countries with regard to the explicit funding of climate engineering research projects. In addition to financing from the US National Science Foundation and the Natural Science and Engineering Research Council, climate engineering research in Canada is primarily supported by private initiatives at present. In the USA, research is largely sponsored by the Climate Response Fund and the Fund for Innovative Climate and Energy Research, which was initiated by Bill Gates. Other initiatives have also been funded privately, for example by Sir Richard Branson (Carbon War Room) or Shell (Cquestrate). However, initiatives have also been funded by groups and think-tanks that have spoken out against drastic reductions in emissions, examples being the American Enterprise Institute or the Copenhagen Consensus Center.

Definite need for regulation and coordination

**Funding remains very heterogeneous and stems largely from private enterprise, which illustrates the need for political regulation and coordination of CE research and deployment.** At present, there are still no treaties or agreements under international law that explicitly refer to or regulate the implementation of climate engineering, and it is similarly unclear to what extent existing treaties or common law standards should be applied to the different CE technologies. As for the adaptation of existing treaties, the only example of note at the moment is the attempt to restrict the use of oceanic iron fertilization to legitimate scientific research within the terms of the London Convention and the London Protocol. However, this modification is still not legally binding. Similarly, the Conference of Parties to the Framework Convention has yet to take up a position on climate engineering.

Interdisciplinary nature of the report

**It was against this background that the German Federal Ministry of Education and Research (BMBF) contracted an interdisciplinary consortium of scientists to produce the present scoping report on climate engineering.** They were asked to take into consideration the findings from as wide a range of sciences as possible and then take up a position on the main issues addressed in the ongoing debate: Is the deployment of CE technologies a viable option in dealing with anthropogenic climate change? With our current level of knowledge, can recommendations be given with regard to certain CE technologies? Should there be even more research on CE technologies? If so, how can it be structured and regulated? On the assumption that the CE debate will become more intense as climate change progresses, the report was to provide initial guidance for the further political decision-making process and for public discourse. In addition, it was expected to supply an overview of the current level of research transcending the predominantly scientific-economic perspective of previous reports.

## 1.6 The structure of the report

Global nature of the technologies makes CE debate extremely complex

**The current debate on climate engineering is far more complex and multilayered than a purely scientific-economic analysis would indicate.** To understand the complexity of the debate, it is necessary to collect, structure, and interrelate the wide range of arguments advanced in favor of or against climate engineering. That is precisely the purpose of the present report. As the analysis reveals, individual arguments can frequently only be assessed for validity and plausibility when different disciplines are taken into account. Accordingly, the following overview of the structure of the debate not only serves as an introduction to the CE controversy but can also be drawn upon for the coordination of the interdisciplinary interaction required for an overall assessment.

**The two issues at the heart of the debate relate to research on, and deployment of, CE technologies.** The deployment issue not only extends to the question of whether a relevant technology should be deployed and if so when, but also to the conditions under which such deployment would be permitted and the way in which the different technologies should be distinguished from one another. The research issue takes precedence over the deployment issue. In addition to the timeframes within which research needs to be carried out, there is also controversy about the appropriate kind of research (technology development versus research on risks and side-effects, etc.) and about prioritization.

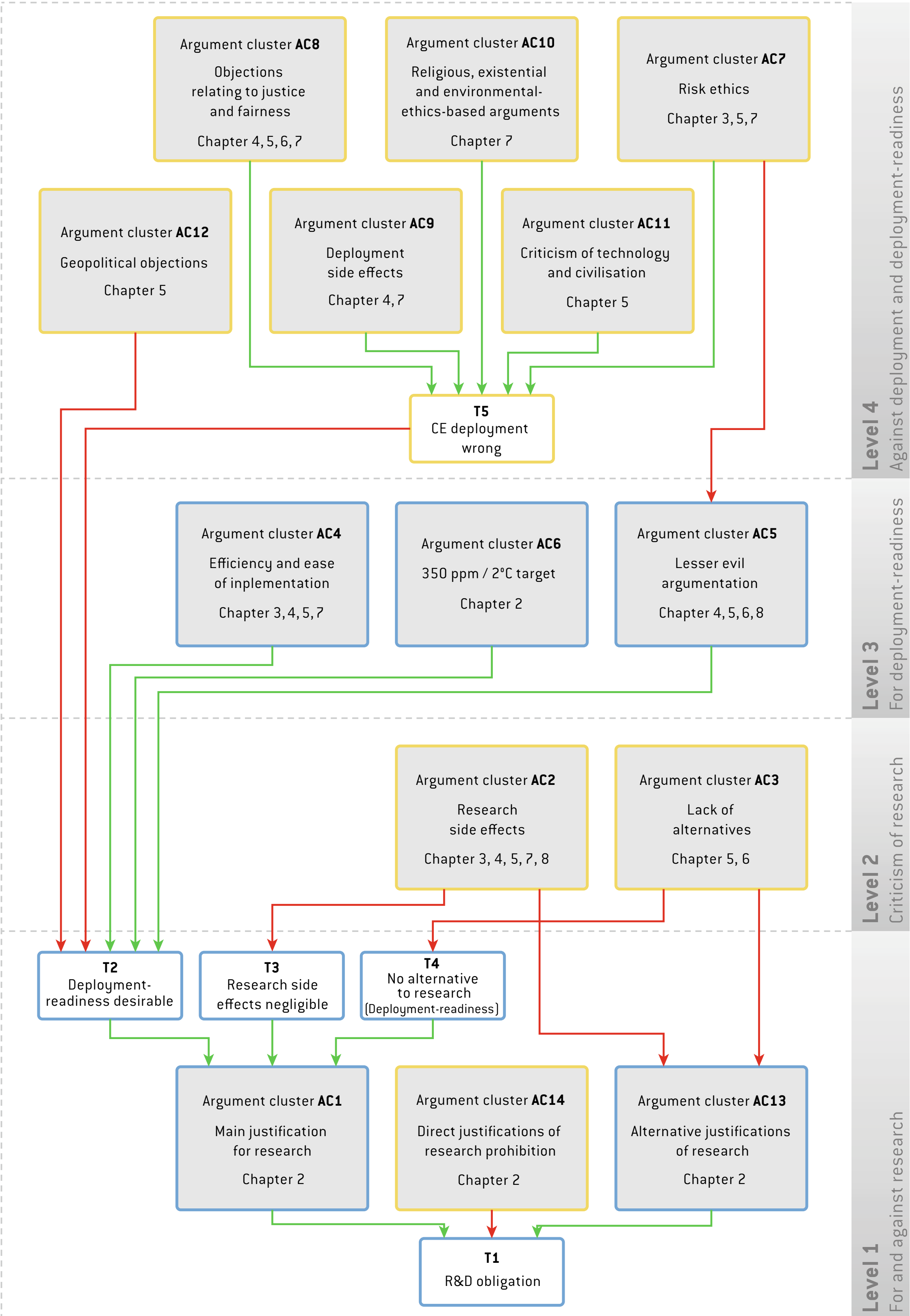
Arguments in the debate can be classified into different argumentative clusters

**The overall debate revolves around various lines of argument pertaining to the two central issues of CE research and deployment.** In the present report, individual arguments are grouped into so-called argument clusters (AC) which support or contradict the various theses put forward in each case. Figure 3 provides an overview of the macrostructure of the debate. It shows the main theses (T1 – T5, T6 not included), the argument clusters (AC1 – AC14), and the different levels (Level 1 to Level 4) of the CE debate.

Level 1 consists of the main justification for research (AC1), which gives a positive answer to the research question (T1), the alternative justifications of research (AC13), and the direct justification of research prohibition (AC14). According to the main research justification (AC1), there should be immediate research on CE technologies so that they are ready for use in good time (AC1). However, this is subject to three prerequisites: First, the technologies should be operational in future (T2); second, the side-effects of research should be negligible (T3); and third, there should be no alternative to immediate research in order to ensure operational readiness in good time (T4). Each of these prerequisites sparks off a more or less wide-ranging sub-controversy of its own.

**The question of the negative side-effects of research on climate engineering (T3) is highly controversial.** In this sub-controversy (shown at Level 2, AC2), research side-effects of very different kinds need to be evaluated, so the main disciplines involved (in addition to the sciences) include economics, political science, sociology, and law. A question that tends to be disregarded in the present debate, although it is in fact highly pertinent, is that of the lack of alternatives to immediate research (AC3), which relates to Thesis T4. Considerations of a scientific and legal nature are of prime relevance for an answer to this question.

**The most wide-ranging and complex sub-controversy is connected with the requirement that CE technologies should be ready for operation in the future.** This sub-controversy, illustrated




Notes: In addition to the main theses of the debate (T1 – T4, T5) the various sub-controversies (argument clusters) and their argumentative interrelations are shown. Green arrows indicate that the arguments within a sub-controversy primarily fulfill a supporting role; red arrows, in contrast, signal that the argument cluster contains predominantly critical considerations. The argument clusters and theses can be roughly organized in favor of or against climate engineering. This is highlighted in the figure by means of a corresponding color scheme (blue or yellow fringe respectively). An argument cluster consists of several arguments, which may constitute quite a complex argument structure, and typically contains objections and counter objections that are not visible in the map.

FIGURE 3:
Macrostructure of the debate on climate engineering

Source: Own representation.

on Level 3 and Level 4, also establishes the link between the research and deployment issue. There are at least three different lines of argument (Level 3) in favor of Thesis T3. The first line of argument claims that CE technologies are economically more efficient and politically easier to implement than mitigation measures (AC4). This argument needs to be primarily reviewed from an economic and political perspective. The second line of argument urges that (admittedly high-risk) CE technologies must be available in case a climate emergency occurs (AC5). This argument can best be investigated from a scientific and sociological vantage. The third line of argument has the contention that CE technologies are vital to achieve ambitious climate targets (AC6). Here, the scientific assumptions behind the argument should also be verified. Typically, the arguments against establishing operational readiness are aimed at preventing any future deployment of climate engineering at all.

The debate also features a variety of arguments against the deployment of CE technologies (Level 4). In addition to objections that rely on firmly asserted normative assumptions (religious, nature-ethical, existentialist arguments (AC10) and criticism of technology and civilization (AC11)), there are various arguments that apparently derive from more moderate normative positions, but at the same time, build on strong empirical claims. Objections based on risk ethics refer to existing uncertainties to oppose the deployment of climate engineering (AC7). These considerations need to be examined from the perspectives of science, sociology, and political science. Arguments related to fairness indicate that the distributional effects resulting from deployment are unfair and make particular use of scientific assumptions (AC8). The economic side-effects of implementation also yield objections to deployment (AC9). Finally, there are geopolitical considerations that are drawn upon to directly object to technologies of this kind being made ready for deployment (AC12).

Argument maps structure the debate—they do not evaluate it

**The argument map is useful enough in roughly structuring the controversies and coordinating inputs from the different disciplines. But this analysis does have its limitations.** First, the argument map represents provisional results that have also been highly simplified. If we want more detailed analyses and reconstructions of the debate, we may have to modify the present structure quite significantly. Second, the analysis (and with it the argument map) is invariably based on an interpretation of the contributions to the debate. Consequently, it is not without alternatives. Other potentially legitimate interpretations might come up with different macro maps. Third—and perhaps most important—an argument map merely reflects a debate; it makes no value judgments. In no way does the argument map say which of these theses or arguments are true or false, plausible or implausible. Besides mapping the debate, this would require an evaluation of the empirical and normative assumptions unearthed by argument analysis. Consequently, an argument map can support the overall evaluation, but it can never replace it.

**With its detailed and extensive consideration of the CE debate, this report is designed to assist politicians in elaborating an overall strategy with regard to climate engineering and adopting a clearly-defined stance, not least in negotiations with other countries.** In addition, the report is intended to contribute to the information and knowledge base required for public and media debate. Thus the findings of the report should help to structure national and international discourse on the principles of climate engineering and specific CE technologies. In addition, the practicability or economic viability of individual CE technologies needs to be examined and important fundamental issues need to be discussed in the process of public and political opinion formation. In many respects, research on climate engineering is still in its early stages, so this scoping report can do no more than formulate initial findings and recommendations. For this reason, the report indicates at many points that knowledge gaps are too large for well-founded, specific decisions on the regulation or deployment of CE technologies to be taken at the moment.

**Chapter 2 outlines the overall structure of the report. It details the macrostructure of the debate about CE research and deployment sketched out above, while at the same time expanding on individual aspects.** The central issues remain, of course, whether the various CE technologies should be deployed and/or investigated. The most important theses advanced in the debate are examined here in relation to one another, and the essential chains of argument are discussed and explained. The following chapters refer back to this more abstract depiction of the structure of the debate when they address specific arguments and sub-controversies from the individual areas of study.

Chapter 2: Argumentative analysis of the overall debate

**Chapter 3 provides a fundamental outline of the factors that influence the Earth's climate via a change in the radiation budget and explains the scientific background of the various CE technologies.** After categorization of the individual technologies, they are then characterized in terms of their effectiveness, their side-effects, and their technical feasibility. This chapter pinpoints the uncertainty that surrounds many scientific statements on the climate system and the possible effects of CE measures.

Chapter 3: The Earth's climate system and climate engineering technology

**Chapter 4 discusses the economic costs and the economic effects of CE technologies.** This extends to both the operating costs and the external costs relating to the side-effects of the individual CE technologies. The expense involved is then compared to the costs for conventional emission control. In addition, the chapter describes how optimum deployment of climate engineering is presented in economic models and how previous mitigation and adaptation strategies have changed accordingly.

Chapter 4: Economic costs and effects

**Chapter 5 discusses public perception of climate engineering from a social-science perspective.** The chapter concentrates on Germany and illustrates the media reporting of the subject. It also assesses the status of the general public's knowledge on the subject. A description of the results of a Delphi panel conducted as part of this report follows, and particular attention is given to the social conflict potential of CE research and the large-scale deployment of CE technologies. On this basis, the chapter addresses the prospects for a potential clarification and communication process in structuring future public debate on climate engineering.

Chapter 5: Risk discourses and public participation

**Chapter 6 discusses questions relating to the validity of existing international legal standards and the necessity for new agreements under international law to regulate CE technologies.** It begins by examining international treaties that might potentially be of significance for climate engineering, moving on from there to assess individual CE technologies in terms of the provisions of international law that are potentially applicable to them. Finally, there is a discussion of the role that the precautionary principle might play in the legal assessment of climate engineering.

Chapter 6: Instruments and institutions of international law

**Building on the results established by Chapters 4, 5, and 6, Chapter 7 outlines the CE technologies that are presently available in terms of unilateral or minilateral deployment and inquires into the potential political consequences of such deployment. Subsequently there is discussion of** the multilateral possibilities for coordinating research on, and deployment of, climate engineering. On this basis, potential criteria are developed for an institutional solution that would need to be monitored in the context of international coordination for research on, and deployment of, climate engineering.

Chapter 7: International coordination and regulation

Chapter 8:
Summary and implications

**The final chapter, Chapter 8, takes up the lines of argument discussed in Chapters 3 to 7 and summarizes them in terms of the argument structure outlined in Chapter 2.** To this end, pertinent questions are derived from the argument clusters on the two main issues (research on and deployment of climate engineering). Answers are provided to these questions by collating the findings from the individual chapters. No assessment or ranking is given to the various questions. Answering the list of questions concludes the epistemic part of the report, and an assessment of the individual CE technologies is undertaken to the extent that this is feasible on the basis of the knowledge currently at our disposal.

# 2 Argumentative Analysis of the Overall Debate

Debate is structured and analyzed on the basis of argument maps

**In this report, argument maps are used to structure the complex, multi-level debate on climate engineering around the two central issues of (i) researching and (ii) deploying CE technologies (Information Box 1).** As described in the introduction, this debate includes many different arguments and theses. Argument maps are used to structure the various arguments and theses with regard to the two main issues. These maps enable one to arrange the diverse arguments according to their mutual dialectic relations without being committed to factual or normative statements as to whether or not a thesis is true / false or plausible / implausible. Against this background, this chapter plays a special role in the overall report by explaining the underlying methodology of the report and demonstrating how assessment and decision-making processes can be structured within the CE debate.

**The term climate engineering covers a number of different technologies which aim to achieve large-scale technical intervention in the climate system, but which, at the same time, differ substantially with regard to the associated risks, effectiveness, side-effects and cost of deployment, for example.** As these different characteristics are decisive for assessing the technologies (with a view to R&D and deployment), the analysis and reconstruction of the CE debate faces the following problem: To treat the different CE technologies in a fair way, each technology would have to be discussed individually. The debate over whether ocean fertilization should be further researched, for example, would have to be reconstructed separately and independently from the debate over whether the modification of marine stratus clouds should be investigated. The same then applies *mutatis mutandis* for the remaining technologies.

Individual analysis for different CE technologies required

This means, however, that—instead of a single CE controversy—several such controversies (each one technology-specific) would have to be distinguished and reconstructed. Since such an analysis would give rise to an extremely large number of outcomes that are, in many respects, redundant, this report takes an alternative route. The reconstructed theses and arguments do not refer to specific CE technologies. Instead, generic placeholders which stand for such technologies are used. Thus, the argument maps effectively comprise so-called argument schemes. It is only when a specific technology, for example air capture, is substituted for the place holder that arguments are fully articulated and can be checked for soundness, which means it can be tested whether their assumptions and conclusions are true or false. Using a place holder ($T_{CE}$), the arguments and theses may hence take the variety of CE technologies into account. Moreover, a second differentiation is made with regard to the various types of CE research and research agendas. Thus, a technology can be researched so as to make it ready for deployment (technology development). A completely different kind of research would consist in spelling out the risks and side-effects more precisely (risk assessment). The specific type of research is indicated by the placeholder $F$ in the theses and arguments. This second place holder, too, has to be replaced first (e.g., with “technology development”, “risk assessment”, “feasibility study”, etc.), before the arguments can be evaluated for soundness and the theses for plausibility and truth.

# A note on how the debate was structured with the help of argument maps

INFORMATION BOX 1

To clarify the various perspectives and assumptions involved in the climate engineering controversy, as well as their complex interrelations, this report employs the method of argument mapping (Betz 2010).

Argument mapping may, first of all, support the analysis of a complex argumentation at different levels of detail. A fairly aggregated analysis consists of identifying the relevant arguments and theses, rephrasing the basic ideas of the arguments in a few sentences and outlining the presumed relationships between the theses and arguments (support or attack). The analysis becomes much more precise as soon as the individual arguments are reconstructed as premises-conclusion structures and the hidden assumptions of the arguments are made explicit. Only at this level of detail does the analysis reveal the exact dialectic relations between the arguments.

Reading argument maps, it is important to keep in mind that reconstructions of arguments are always interpretations. This clearly applies to the aggregate analysis, but even in a more detailed, fine-grained analysis, there is always room for different interpretations, and hermeneutic choices have to be made when reconstructing an argument. For this reason, there is more than one correct way to reconstruct a controversy. This is not to say, however, that argument reconstructions are entirely arbitrary. More specifically, the interpretation and analysis of debates is based on the principle of charity which urges one to render the arguments as strong and convincing as possible. This is supposed to ensure that arguments are not simply discarded because of a biased interpretation. In addition, the underdetermination of interpretation is—in the context of evaluating a complex debate—not as problematic as it may initially appear. Granted, the interpretation fully determines how accurately the argument map represents the reasoning set forth by a participant in the debate. However, given the reconstructed debate, interpretative issues do not decide whether some position is coherent or not. Such questions can be settled objectively on the background of the identified and reconstructed arguments.

Finally, the reconstruction itself seeks to be neutral and can neither be conclusive nor complete, as it does not decide who is right or who has the last word in a debate. The reconstruction merely implies if-then statements: *If* some statements are true, *then* certain other statements in the debate must also be true. The argument map itself does not determine which statements are true; it is therefore neutral and open to different evaluations (depending on which statements one considers to be true, false or uncertain). In other words, the argument map indicates (i) the questions one has to answer so as to adopt a position in the debate and (ii) the consequences of the answers one gives. Moreover, a reconstruction is never conclusive or complete because there are always premises which must remain unsupported and unchallenged (in the finite debate) but which could, in principle, be justified or attacked. As a consequence, a thesis which is supported by many arguments is not necessarily true, and a thesis which is challenged by many arguments does not have to be false. The same applies to arguments. If an argument is challenged, this does not mean that the argument is definitively invalidated. It may be the case, for example, that the attacking arguments rely on highly implausible premises that can be criticized by new arguments that have not been introduced so far.

## 2.1 Macrostructure of the debate

The main theses of the CE debate (Table 1) and their logico-argumentative interrelations with respect to the various arguments (Table 2) are as follows.

| | |
|---|---|
| T1 | R&D OBLIGATION |
| T2 | DEPLOYMENT READINESS DESIRABLE |
| T3 | RESEARCH SIDE-EFFECTS NEGLIGIBLE |
| T4 | NO ALTERNATIVE TO RESEARCH |
| T5 | CE DEPLOYMENT WRONG |
| T6 | PRIORITY OF MITIGATION |

TABLE 1
Theses in the debate on climate engineering
Source: Own representation.

The thesis

[T1 R&D obligation] R&D into the CE technology $T_{CE}$ with research agenda $F$ ought to be carried out

answers the debate's central research-related question in the positive. Three further theses fuel the main justification of this R&D obligation:

[T2 Deployment readiness desirable] CE technology $T_{CE}$ should (*prima facie*) be ready for deployment at a future point in time.

[T3 Research side-effects negligible] The side-effects of researching CE technology $T_{CE}$ with research agenda $F$ are negligible in relation to the CE technology $T_{CE}$ being (probably) ready for deployment in time.

[T4 No alternative to research (deployment readiness)] There are no suitable alternatives to immediate research into CE technology $T_{CE}$ (with research agenda $F$) which lead to $T_{CE}$ being ready for deployment in time.

**The three theses, T2 – T4, together constitute a sufficient reason to research CE technology** $T_{CE}$. Each of these theses is a necessary condition for conducting such research. Should one of these theses be false, it would be wrong to research technology $T_{CE}$, at least with a view to establishing deployment readiness. T2 – T4 form the starting point of more or less comprehensive sub-controversies within the CE controversy. With reference to these theses, the entire debate can be neatly structured into sub-controversies, which, in the introduction to this report, have been assigned to different levels of the macro map (Figure 3).

AC1
MAIN JUSTIFICATION OF RESEARCH

AC13
ALTERNATIVE JUSTIFICATIONS OF RESEARCH

AC14
DIRECT JUSTIFICATIONS OF RESEARCH PROHIBITION

The main justification for research argument cluster (AC1) is located together with the alternative justifications for research (AC13), and direct justification of research prohibition (AC14) on Level 1 (For and against research) of the macrostructure of the CE debate. The alternative justifications in particular do not rely upon the controversial T2, and thus circumvent the most extensive sub-controversy of the entire debate (see below).[6] However, those alternative justifications, too, assume the negligibility of research side-effects or the lack of alternatives to immediate research, as do T3 and T4. Thus, T3 and T4 actually turn out to be key presuppositions of any call for research into CE technologies.

6 Instead of the purpose of creating deployment readiness, other objectives are found in the alternative justifications for carrying out research. These include preventing hasty deployment, stepping up measures for prevention, preparing informed decisions and planning a long-term research strategy (Betz and Cacean 2011: 47ff).

| | |
|---|---|
| **AC1** | **MAIN JUSTIFICATION OF RESEARCH** |
| **AC2** | **RESEARCH SIDE-EFFECTS** |
| A1 | NEGATIVE EFFECT ON MITIGATION |
| A2 | UNDERMINING BETTER OPTIONS |
| A3 | EXTENT OF TRADE-OFF UNCERTAIN |
| A4 | UNSTOPPABLE DEVELOPMENT |
| A5 | COMMERCIAL CONTROL |
| A6 | FIELD TESTS |
| **AC3** | **LACK OF ALTERNATIVES** |
| A7 | POSTPONE RESEARCH |
| A8 | MORATORIUM |
| **AC4** | **EFFICIENCY AND EASE OF IMPLEMENTATION** |
| A9 | EFFICIENCY ARGUMENT |
| A10 | DO-IT-ALONE ARGUMENT |
| A11 | EASINESS ARGUMENT |
| A12 | ONLY PARTIAL OFFSET |
| A13 | INDIRECT COSTS UNDERESTIMATED |
| A14 | HARMING OTHERS |
| **AC5** | **LESSER-EVIL ARGUMENTATION** |
| A15 | LESSER EVIL |
| A16 | SICK-PATIENT ANALOGY |
| **AC6** | **350 PPM/2°C TARGET** |
| A17 | DEPLOYMENT-READY TECHNOLOGIES NEEDED |
| **AC7** | **RISK ETHICS** |
| A18 | TERMINATION PROBLEM |
| A19 | MAKING MATTERS WORSE |
| A20 | NO IRREVERSIBLE INTERVENTIONS |
| A21 | IRREDUCIBLE UNCERTAINTIES |
| A22 | HUMAN ERROR |
| A23 | COMPLEXITY OF THE EARTH SYSTEM |
| A24 | LARGE-SCALE EXPERIMENTS |
| A25 | SOCIO-POLITICAL UNCERTAINTIES |
| **AC8** | **OBJECTIONS RELATING TO JUSTICE AND FAIRNESS** |
| A26 | DISTRIBUTIONAL EFFECTS |
| **AC9** | **DEPLOYMENT SIDE-EFFECTS** |
| A27 | NEGATIVE EFFECTS ON EMISSION ABATEMENT |
| A28 | AMORTIZATION |
| **AC10** | **RELIGIOUS, EXISTENTIAL AND ENVIRONMENTAL ETHICS-BASED ARGUMENTS** |
| **AC11** | **CRITICISM OF TECHNOLOGY AND CIVILIZATION** |
| **AC12** | **GEOPOLITICAL OBJECTIONS** |
| A29 | DUAL USE |
| A30 | CLIMATE CONTROL CONFLICTS |
| **AC13** | **ALTERNATIVE JUSTIFICATIONS OF RESEARCH** |
| **AC14** | **DIRECT JUSTIFICATIONS OF RESEARCH PROHIBITION** |
| A31 | RISK TRANSFER ARGUMENT |
| A32 | NO INFORMED CONSENT |
| **HORIZONTAL ISSUE: PRIORITY OF MITIGATION** | |
| A33 | ARGUMENT FROM REVERSIBILITY |
| A34 | AVOIDING DILEMMAS |
| A35 | POLLUTER-PAYS PRINCIPLE |
| A36 | LACK OF RESPECT |
| A37 | WORST CASE |

TABLE 2:
Argument clusters and arguments in the debate on climate engineering

Source: Own representation.

**AC2**
RESEARCH SIDE-EFFECTS

**AC3**
LACK OF ALTERNATIVES

**The expected research side-effects and their assessment are the subject of the sub-controversy which is triggered by T3 (AC2).** In this sub-controversy, which is located on Level 2 of the macro map, research side-effects are weighed against one another as well as to the objective of creating deployment readiness. Moreover, T4 is quite questionable, as well. According to the current findings of the authors, however, hardly any arguments are cited which counter this main premise of the research justification. The assertion that there are no alternatives to immediate research if the corresponding CE technologies are to be ready for deployment in time is challenged by only a handful of arguments (AC3).

**The most comprehensive sub-controversy of the debate is sparked off by T2, according to which future deployment readiness** is desirable. On the macro map, it spans Level 3 and Level 4 and includes nine argument clusters. There are a large number of pro/con arguments of many different types here. These arguments either relate directly to T2 (i.e., support or negate it) or reinforce the following assertion:

> [T5 CE deployment wrong] Future deployment of CE technology $T_{CE}$ is in any case (morally) wrong.

If T5 were true, T2 would have to be false. For why should some technology be ready for deployment, in the first place if it is morally wrong to deploy it anyway? As a consequence, the arguments which support T5 indirectly undermine T2.

**Another significant thesis says that preventive measures which try to mitigate anthropogenic climate change should be given higher priority than CE technologies. Although this priority claim is conceded by most participants, it mainly fuels the arguments of CE critics.**

> [T6 Priority of mitigation] Mitigation has priority over climate engineering.

T6 is the basis for various arguments of the CE debate and can itself be justified in different ways. It is not specifically listed in the macro map (Figure 3), as it enters into a large number of different considerations.

Based on this macrostructure of the debate, individual arguments of the various clusters and of the various levels are unfolded in the following sections. First, the arguments of Level 2 to Level 4 are unfolded (Section 2.2 to 2.4). These arguments directly address T2 to T5 and T1 indirectly via argument cluster AC1. Second, the arguments directly objecting to T1 in argument cluster AC 14 of Level 1 are unfolded (Section 2.5).[7] Finally, the arguments related to T6 are unfolded as horizontal issue to the vertical structure of the argument map (Section 2.6)

**The arguments to be presented here are chosen with a view to the empirical discussions of the other chapters.** The following discussion focuses on arguments whose factual assumptions are clarified through empirical (scientific, sociological, etc.) analyses in the report. The selection of arguments—to be clear about this—does not imply any normative evaluation. In particular, if an argument is not mentioned in the following, this does in no way indicate that the authors deem it to be inconclusive or negligible. For example, the argument clusters concerning environmental ethics, religion, existentialist thoughts and criticism of civilization were left out completely, as these objections depend less on controversial empirical (and thus scientifically testable) assumptions and much more on strong normative premises. For many people, however, these very arguments may well (and coherently, in fact) be decisive in the debate.

7 For AC13 see Betz and Cacean (2011: 47ff).

## 2.2 Level 2: Criticism of research

### 2.2.1 Argument cluster: Research side-effects (AC2)

**Thesis T3, which states that the side-effects of CE research are negligible, is challenged in the controversy through the identification of possible or probable harmful side-effects.** Such criticism (i) cites various side-effects caused by research of CE technology $T_{CE}$, (ii) claims that these side-effects are harmful, and (iii) weighs them with respect to the intended goal of the research (creating deployment readiness). In the following, some of these side-effects will be discussed.

**One of the most often cited, and in this sense most prominent, objections to climate engineering points out that already researching such technologies could considerably weaken mitigation efforts** (e.g., Jamieson 1996: 333f; Keith 2000: 276; Robock 2008a; Robock 2008b; ETC Group 2009c: 34; Royal Society 2009; Gardiner 2010: 292).

> [A1 Negative effect on mitigation] Even mere research into climate engineering and the vague prospect of a technical solution to the climate problem, it is argued, could deter government and private stakeholders from carrying out more or less painful mitigation measures.

A1
NEGATIVE EFFECTS ON EMISSION ABATEMENT

This argument, which is sometimes also referred to as the moral hazard objection, apparently identifies a potential side-effect of carrying out research into climate engineering and weakens, accordingly T3.

**Why should there be a trade-off between mitigation and CE research at all?** Critics cite a number of different mechanisms which could at least potentially lead to a reduction in mitigation measures should climate engineering be researched:

A2
UNDERMINING BETTER OPTIONS

- If larger sums of money flow into the research and development of CE technologies, lobby groups which have no interest in far-reaching efforts to reduce emissions will arise and grow.
- Researching CE technologies could trigger downright CE hype. The discussion of climate engineering alone could undermine the motivation to implement painful emission abatement and adaptation measures.
- In addition, the financial and cognitive resources used for CE research are not available for the preparation and execution of mitigation measures. [A2 Undermining better options]

**Objections have also been raised against the argument that CE research negatively affects mitigation.** The Royal Society (2009) and Corner and Pidgeon (2010) indicate that the actual extent of the presumed trade-off is uncertain (A3). Keith et al. (2010), on the other hand, reject the argument because it implies false exclusivity, which means both mitigation and CE research can ultimately be carried out. Whether or not these objections actually defuse argument A1, however, cannot be clarified until a detailed reconstruction is made and therefore cannot be determined within the scope of this report.

A3
EXTENT OF TRADE-OFF UNCERTAIN

A1
NEGATIVE EFFECTS ON EMISSION ABATEMENT

Other presumed side-effects of CE research are identified in the following arguments:

> [A4 Unstoppable development] Research into climate engineering might create an internal dynamic which inevitably leads to deployment, without any further central decision being taken. Yet, one must be able to discontinue research into risk technologies at any time (Jamieson 1996: 333f).

A4
UNSTOPPABLE DEVELOPMENT

[A5 Commercial control] CE technologies could ultimately be controlled by companies that act purely on the basis of commercial interests. This would lead to problems similar to those seen in the pharmaceutical industry (Robock 2008a; ETC Group 2009c: 29, 34).

A5
COMMERCIAL CONTROL

[A6 Field tests] Research into CE technology $T_{CE}$ (with research agenda $F$) requires large-scale field studies and thus, for all intents and purposes, the deployment of (not fully researched) technology $T_{CE}$ (Elliott 2010: 11; Robock et al. 2010).

A6
FIELD TESTS

**What empirical issues are raised by the argumentation of this cluster?** Since the arguments laid out here essentially contain an assessment of side-effects, the empirical question arises of whether climate engineering research would actually cause the developments described. Accordingly, it must be studied in more depth whether mere research might really lead to inevitable deployment, whether it is likely that research reduces mitigation efforts, etc. These issues are primarily covered in Chapters 4, 5 and 7. **How does this argument cluster bear on the overall evaluation?** The critique cited in this cluster concerns not only the main—but any justification for researching CE technologies and side-effects. If the negative side-effects of CE research are seen to outweigh the expected benefits, the demand for research cannot be coherently maintained. Conversely, one must consider the side-effects to be negligible overall and weigh the arguments accordingly in order to consistently maintain the research obligation.

### 2.2.2 Argument cluster: Lack of alternatives (AC3)

**A key requirement of all justifications for conducting research is that there are no more suitable means for achieving the presumed objective (e.g., timely deployment readiness) than the immediate research of CE technology $T_{CE}$.** Despite its central position, this requirement is, in comparison to theses T2 and T3, hardly considered at all. Representing a rare exception, Stephen Gardiner makes the following objection:

[A7 Postpone research] Starting research at a later point in time is fully sufficient. What's more, it would be wasteful to prepare for an intervention now which would not be implemented for several decades; the technologies available when the intervention will be carried out are not foreseeable at all today (Gardiner 2010: 288f).

A7
POSTPONE RESEARCH

Research could also be commenced at a later point in time so that the corresponding technology would still be mature by the time it is to be deployed. Obviously, this objection assumes that technology $T_{CE}$ is not to be deployed until the distant future (several decades), if at all.

**By referring to a moratorium, it might be argued against the claim that there is no alternative to research to prevent the hasty deployment of CE technology $T_{CE}$:**

[A8 Moratorium] The hasty deployment of CE technologies can (alternatively) be prevented via an international moratorium.

A8
MORATORIUM

A moratorium of such kind, which is however not legally binding, was recommended in May 2008 by the Convention on Biological Diversity (CBD).[8]

**What empirical issues are raised by the argumentation of this cluster?** Important empirical issues which arise here concern the presumed urgency of research and the anticipated effectiveness of an international moratorium on deployment. **How does this argument cluster bear on the overall evaluation?** The same thing applies here as for AC2. If one considers research at a later point in time a suitable alternative, one cannot rationally hold on to the call for immediate research.

8 For this purpose, see the discussions on ocean fertilization with iron, phosphorous, and/or nitrogen in Section 6.2.2.

## 2.3 Level 3: For deployment readiness

### 2.3.1 Argument cluster: Efficiency and ease of implementation (AC4)

**The efficiency argument (A9), and the closely related do-it-alone (A10) and easiness arguments (A11) all emphasize that the deployment of CE technologies would be** easier **and more cost-effective than the implementation of complex mitigation or adaptation measures.** For this reason, the technologies should be ready for deployment as early as possible, as stipulated in T2. The arguments thus consider climate engineering a replacement for—and not a potential supplement to—mitigation measures.

> [A9 Efficiency argument] The direct and indirect costs of the deployment of climate engineering are considerably less than the cost of emission control and adaptation (Ott 2010 a,b,c; Gardiner 2010; Elliott 2010: 20; Wood in Goodell 2010: 129).

A9
EFFICIENCY ARGUMENT

> [A10 Do-it-alone argument] Climate engineering can also be carried out by a small group of determined countries—without the long-term cooperation of all nations—for the good of all humanity (Ott 2010 a, b, d).

A10
DO-IT-ALONE ARGUMENT

> [A11 Easiness argument] Climate engineering enables dangerous climate change to be avoided without infringing upon lifestyles, habits and vested economic rights (Ott 2010 a,b,c).

A11
EASINESS ARGUMENT

The easiness argument thus cites an aspect of climate engineering—which critics consider a disadvantage—as an advantage.

**The efficiency argument is thoroughly discussed and criticized in the ethical controversy.** The following reasons are brought up to counter the efficiency argument (A9):

> [A12 Only partial offset] Frequently, CE technologies can only remedy some of the consequences of anthropogenic climate change; for example ocean acidification is not undone by RM. Their benefits are thus not as great as those of mitigation (Gardiner 2010; Robock 2008a; Robock 2008b; ETC Group 2009 c: 19).

A12
ONLY PARTIAL OFFSET

> [A13 Indirect costs underestimated] CE technologies are not inexpensive when considering the economic costs which arise as a result of the associated side-effects (Gardiner 2010: 288).

A13
INDIRECT COSTS UNDERESTIMATED

> [A14 Harming others] Simply providing others with technological options for moderating the harm we have caused them does in no way recompense for our wrong-doing. These types of intergenerational asymmetries are not taken into account by the efficiency calculation (Gardiner 2010: 293).

A14
HARMING OTHERS

**What empirical issues are raised by the argumentation of this cluster?** As some of the objections named above suggest, the efficiency, do-it-alone, and easiness arguments raise a number of empirical issues concerning, among other things, the actual effectiveness of the CE technologies, their direct and indirect costs and their political feasibility. **How does this argument cluster bear on the overall evaluation?** Accepting one of the main arguments of the cluster gives one a reason to demand deployment readiness and, possibly, the deployment of climate engineering. However, this implies only together with theses T3 and T4, which means not automatically, the obligation to carry out CE research (T1).

### 2.3.2 Argument cluster: Lesser-evil argumentation (AC5)

**The lesser-evil argumentation is without doubt one of the most important justifications of T2, and, accordingly, of the research obligation in general.** Even in early articles by Schneider (1996) and Jamieson (1996), research into climate engineering was (cautiously) recommended on the basis of this reasoning. The core lesser-evil argument justifies T2 with the following consideration:

A15
LESSER EVIL

> [A15 Lesser evil] We could end up in a future situation (i.e., when climate sensitivity is very high or if our efforts to reduce emissions are insufficient) in which the (admittedly high-risk) deployment of CE technology $T_{CE}$ represents the lesser of two evils. Since otherwise, we would face uncompensated, catastrophic climate change.

Since we could end up in such a climate emergency, CE technologies should—in accordance with precautionary reasoning—at least be ready for deployment, the lesser-evil argument claims.

The lesser-evil argument is based on several assumptions: (i) a (complex) possibility forecast in which a normative evaluation is made, (ii) the precautionary principle and (iii) the general normative assessment that the moral objections to deployment readiness do not outweigh the precautionary considerations. The possibility forecast, which states that the deployment of climate engineering in a climate emergency could be the lesser of two evils, is reinforced in different ways. High climate sensitivity and insufficient emission reductions can lead to climate engineering being the only remaining option to save unique ecosystems (D. Keith in Goodell 2010: 39). An argument recounted by Corner and Pidgeon (2010: 32) goes much further. In a climate emergency, the survival of humanity could be at stake. For this reason, the worst possible consequence of unchecked catastrophic climate change would surpass the worst possible consequence of the deployment of climate engineering.

**The lesser-evil argument is criticized in various ways.** The primary objection is that the deployment of CE technology $T_{CE}$ could potentially worsen the harmful consequences of climate change rather than alleviating them. The lesser-evil argument thus rests on a false assumption, as it is precisely this possibility (that the deployment of climate engineering could make matters worse) which cannot be ruled out due to the irreducible uncertainties involved.

**The sick-patient analogy develops the underlying idea of the lesser-evil argument by means of a metaphor and can therefore be considered a variation of it:**

A16
SICK-PATIENT ANALOGY

> [A16 Sick-patient analogy] The Earth could become a terminally-ill patient for which we would prescribe a high-risk, poorly understood therapy considering that the fate of the patient appears sealed anyway (Lovelock in Goodell 2010: 106).

As with the lesser-evil argument, the sick-patient metaphor, too, represents a justification of the central T2. The argument mentioned above, which sees the survival of humanity at stake as a result of climate change, may be cited here to justify the analogy claim. This analogy claim represents the pivotal assumption of the argument. Any relevant distinction between the currently warming planet and a terminally-ill patient could bring down the entire sick-patient analogy (A16).

**What empirical issues are raised by the argumentation of this cluster?** The lesser-evil argument depends on, among other things, the empirical assumption that the corresponding CE technology can be deployed in short order as an emergency measure. Here, the issue arises as to whether the CE technology is actually effective on a short time scale and comparatively safe (i.e., it does not make matters worse). **How does this argument cluster bear on the overall evaluation?** The lesser-evil argument supports the demand for deployment readiness. Accepting this argument does not, however, automatically result in the demand for immediate research. Theses T3 and T4 are, once again, required to draw this conclusion.

### 2.3.3 Argument cluster: 350 ppm / 2° C target (AC6)

**A third argument in favor of T2 arises from the demand to stabilize the atmospheric $CO_2$ concentration at max. 350 ppm (Hansen 2009; Greene et al. 2010).**[9] Since the current concentration is considerably higher than this stabilization target, the 350 ppm -target therefore requires large-scale removal of carbon from the atmosphere. The argumentation is straightforward. First of all, the requirement to have CE technologies ready for deployment (T2) is warranted as follows:

[A17 Deployment-ready technologies needed] The atmospheric $CO_2$ concentration can only be reduced to 350 ppm by deploying CE technology $T_{CE}$ (Hansen 2009; Greene et al. 2010).

A17
DEPLOYMENT-READY TECHNOLOGIES NEEDED

The subsequent argumentation seeks to show that the $CO_2$ concentration must be reduced to 350 ppm in order to avoid dangerous climate change (Hansen 2009). The following independent items of evidence are cited for this purpose:

- Above 350 ppm, paleoclimatic data suggest, a catastrophic increase in sea levels could occur as a result of the melting of ice sheets.
- Above 350 ppm, a majority of species would be threatened with extinction.
- Above 350 ppm, the radiation budget of the Earth is not in equilibrium, and extreme global warming could occur if climate sensitivity were very high.

**What empirical issues are raised by the argumentation of this cluster?** One of the decisive empirical issues which arises when evaluating these arguments is the degree to which ambitious climate targets can actually no longer be achieved solely through mitigation and adaptation measures. In addition, it has to be clarified which CE technologies would in fact allow one to reach those ambitious goals. **How does this argument cluster bear on the overall evaluation?** As in the case of AC4 and AC5, the following applies: The argumentation of this cluster results in the demand for deployment readiness, but not directly in the demand for immediate research.

## 2.4 Level 4: Against deployment and deployment readiness

### 2.4.1 Argument cluster: Risk ethics (AC7)

**Unforeseeable side-effects and uncertainties constitute a main objection against the deployment of CE technologies.** Arguments based on risk ethics, which explicitly refer to the uncertainties of deployment, primarily substantiate T5 and form an argument cluster with a comparatively complex dialectic structure—whereas only a few of the main arguments can be discussed here. Three justifications of T5 which focus on risks and uncertainties can be outlined as follows:

[A18 Termination problem] CE technology $T_{CE}$ has no viable exit option. An unforeseen, abrupt cancellation of deployment would lead to sudden, catastrophic climate change (Ott 2010 a,b,c; Robock 2008 a; Robock 2008 b).

A18
TERMINATION PROBLEM

[A19 Making matters worse] In the worst case scenario (which is decisive), climate engineering aggravates catastrophic climate impacts.

A19
MAKING MATTERS WORSE

As the lesser-evil argument (A15), the worst case scenario (A19) adopts a precautionary stance.

[A20 No irreversible interventions] Climate engineering represents a large-scale intervention which cannot be reversed.

A20
NO IRREVERSIBLE INTERVENTIONS

9 The argument cluster can also be reconstructed in a similar way assuming a global 2° C or 1.5° C target.

Some authors justify the proscription of irreversible large-scale intervention, assumed in A20, with reference to the fact that such interventions limit the options of future generations in an unacceptable way (e.g., Jamieson 1996: 330f). Against A20, however, it is argued that even mitigation measures might be conceived as irreversible interventions with unforeseeable side-effects (Corner and Pidgeon 2010: 28).

**A decisive issue in the whole argumentation based on risk ethics is whether the prevailing uncertainties can be reduced and eliminated through further research.** In particular, both the assessment of argument A19 as well as the critique of the lesser-evil argument (A15) critically hinge on this question. The claim that some climate engineering-related uncertainties are irreducible is justified by argument A21.

> [A21 Irreducible uncertainties] There are considerable irreducible uncertainties regarding the effectiveness and consequences of CE deployment (Keith 2000: 277; Robock 2008a; Bunzl 2009).

A21 IRREDUCIBLE UNCERTAINTIES

The following items are cited as more detailed reasons that back up A21:

> [A22 Human error] Complex, long-term technical interventions cannot be prognosticated due to the possibility of human error (Robock 2008 a; ETC Group 2009 c: 34).

A22 HUMAN ERROR

> [A23 Complexity of the Earth system] The complexity of the Earth system implies that we will never be in a position to grasp (let alone quantify) all the side-effects of a large-scale intervention (Grunwald 2010; ETC Group 2009 c: 34).

A23 COMPLEXITY OF THE EARTH SYSTEM

> [A24 Large-scale experiments] Only large-scale field studies which effectively amount to the full deployment of climate engineering could prove the effectiveness and safety of these technologies. This means that we cannot know whether climate engineering works until it is deployed (Robock et al. 2010).

A24 LARGE-SCALE EXPERIMENTS

> [A25 Socio-political uncertainties] The effectiveness and safety of climate engineering depend on a stable institutional framework over a period of many decades. Such social boundary conditions are unpredictable.

A25 SOCIO-POLITICAL UNCERTAINTIES

**What empirical issues are raised by the argumentation of this cluster?** It must be clarified empirically whether the arguments stated above rely on accurate characterizations of CE-related uncertainty and irreversibility. **How does this argument cluster bear on the overall evaluation?** Those who demand deployment readiness must reject objections A18, A19 and A20. If one shares the concerns based on risk ethics, however, one cannot coherently hold on to T2 (and consequently, not to the main justification for researching CE methods, either). T1 could, however, very well be retained for other reasons.

### 2.4.2 Argument cluster: Objections relating to justice and fairness (AC8)

**The consequences of deploying CE technologies might vary widely on a regional level. This concerns both the offset of climate impacts as well as unintended side-effects. Such regional variations form the starting point of another important set of objections to the deployment of climate engineering.** They drive, in particular, arguments based on justice and fairness which support T5. As far as the CE controversy is concerned, arguments from justice and fairness have not been developed in great detail, yet. The common line of reasoning of various such arguments, which is also referred to in the literature, is as follows:

[A26 Distributional effects] The uneven distribution of climate impact offsets (benefits), costs and harmful side-effects associated with CE deployment is unjust (Keith 2000: 276; Robock 2008 a; ETC Group 2009 c: 34).

**A26**
DISTRIBUTIONAL EFFECTS

To flesh out arguments of this type, the regional consequences of CE deployment have to be specified. In addition, the depicted regional differences must then be evaluated according to one standard of justice and fairness or another. The following four theories, each providing independent arguments in favor of A26, might serve as such a normative basis:

- >> The deployment of climate engineering leads to fewer people having the basic capacities required for leading a flourishing human life (Nussbaum and Sen 1993).
- >> The deployment of climate engineering leads to further worsening of the situation of the world's most disadvantaged people and nations (Rawls 1975).
- >> The deployment of climate engineering increases existing socioeconomic inequalities rather than decreasing them (Gosepath 2004).
- >> The deployment of climate engineering changes the global institutional and economic framework in such a way that human rights are recognized and realized to a lesser degree (Pogge 2002).

**What empirical issues are raised by the argumentation of this cluster?** To check arguments from justice and fairness, the spatially and temporally heterogeneous distribution of benefits (offsets of regional climate impacts) and costs (economic costs of the deployment, unintended side-effects of deployment, etc.), among other things, must be specified as precisely as possible. **How does this argument cluster bear on the overall evaluation?** If one accepts an objection from justice and fairness (including the normative assessment), one can no longer coherently demand deployment readiness.

### 2.4.3 Argument cluster: Deployment side-effects (AC9)

Another side-effect argumentation, which resembles the moral hazard problem (A1) and suggests (uncertain) consequences and side-effects of CE deployment, has been set forth by Klepper and Rickels (2011); it bears similarities with the arguments reported in Section 2.4.1 on risk ethics. Besides carrying out CE research, it is argued, the deployment of climate engineering technologies, too, could undermine mitigation measures:

[A27 Negative effects on emission abatement] The deployment of CE technology $T_{CE}$ would make it considerably less probable that far-reaching mitigation measures would be taken or continued.

**A27**
NEGATIVE EFFECTS ON EMISSION ABATEMENT

The reason for this is the high capital intensity of CE technologies:

[A28 Amortization] In order for the investments in capital-intensive CE technology $T_{CE}$ to amortize, the technology must be deployed for as long as possible. This would require that $CO_2$ emissions not be reduced too drastically.

**A28**
AMORTIZATION

**What empirical issues are raised by the argumentation of this cluster?** Among other things, the extent to which mitigation measures would be substituted by climate engineering methods must be specified. Whether or not such substitution is actually unavoidable must also be determined. **How does this argument cluster bear on the overall evaluation?** If one accepts the objection raised in this cluster (including the normative assessment), one can no longer coherently call for deployment readiness.

#### 2.4.4 Argument cluster: Geopolitical objections (AC12)

**Geopolitical and military-strategic consequences of the mere fact that CE technologies are ready for deployment form the starting point of further consequentialist objections to T2 (objections which deny that CE technologies should be ready for deployment).** The dual use problem, which is also relevant in other technology debates, for example in the nuclear energy controversy, applies to the case of climate engineering as well:

> [A29 Dual use] CE technologies may, potentially, serve as weapons of mass destruction (Keith 2000: 275; Corner and Pidgeon 2010: 30; Goodell 2010: 210ff; Robock 2008a; ETC Group 2009c: 34).

A29
DUAL USE

Another prominent argument of the CE debate reads:

> [A30 Climate control conflicts] Available CE technologies puts future generations in a position to control the climate. This ability itself will generate new conflicts and could ultimately even trigger wars (Hulme 2009: 351; Robock 2008a).

A30
CLIMATE CONTROL CONFLICTS

According to this argument, the creation of a global thermostat would create more new problems and dangers than it would solve.

**What empirical issues are raised by the argumentation of this cluster?** Among other things, the potential for conflict arising from CE technologies being available needs to be understood more precisely. **How does this argument cluster bear on the overall evaluation?** If one shares an objection of this cluster (including the normative assessment), one can no longer coherently demand deployment readiness.

## 2.5 Argument cluster: Direct justifications of research prohibition (AC14)

**The CE debate includes arguments against climate engineering research which directly support a prohibition of such research.** The critical considerations listed above, in contrast, mainly concern T2 and T3 (which are required to justify CE research) and therefore only represent indirect objections to T1. Two of the direct arguments against research into climate engineering which are established on Level 1 of the macro map are outlined in the following.

Various authors assert that even planning climate engineering would represent part of an objectionable risk transfer from current to future generations:

> [A31 Risk transfer argument] By carrying out research into and planning for climate engineering, one passes on risks that arise today to future generations (Ott 2010 a; Ott 2010 b; Ott 2010 c; Gardiner 2010: 293; Jamieson 1996: 331).

A31
RISK TRANSFER ARGUMENT

This argument (presumably) assumes that CE technologies are being conceived as an alternative to emission reductions or, at least, that mitigation measures are not simultaneously implemented.

Whereas A31 is based on a principle of intergenerational ethics, the following argument builds upon a basic democratic principle:

> [A32 No informed consent] Climate engineering should only be researched and carried out with the broad and well-informed consent of everyone involved (Jamieson 1996: 329f; Ott 2010 a; Ott 2010 b; Ott 2010 c; Gardiner 2010: 293f; Elliott 2010:19).

A32
NO INFORMED CONSENT

**What empirical issues are raised by the argumentation of this cluster?** The plausibility of the arguments outlined here depends on, among other things, the extent of potential harm and risk accompanying the CE deployment in comparison to measures for reducing emissions and the probability of a broad consensus on climate engineering. **How does this argument cluster bear on the overall evaluation?** Since the objections are aimed directly at research requirement T1, each of these objections must be refuted if one is to maintain the demand for immediate research.

## 2.6 Horizontal issue: The priority of mitigation measures

**Many of the objections to CE research, and many of the arguments in its favor, assume that emission reduction represents *prima facie* the more appropriate means for avoiding dangerous climate change.** This comparative evaluation (T6) is supported in the CE controversy in different ways. The independent justifications of the priority of mitigation are as follows:

[A33 Argument from reversibility] Changes in behavior which prevent dangerous climate change are reversible to a much greater degree than technical interventions (Jamieson 1996: 331).

A33
ARGUMENT FROM REVERSIBILITY

[A34 Avoiding dilemmas] We should avoid upfront ending up in a situation where we, or future generations, are forced to choose between two evils (Gardiner 2010: 300f; Elliott 2010: 13).

A34
AVOIDING DILEMMAS

[A35 Polluter-pays principle] The principle that problems should be solved by those who cause them (polluter-pays principle) speaks clearly in favor of emission abatement (Jamieson 1996: 331).

A35
POLLUTER-PAYS PRINCIPLE

[A36 Lack of respect] Pollution is morally wrong even if the damage caused can be fully compensated for and remedied afterward, as it still expresses a lack of respect (Hale and Grundy 2009).

A36
LACK OF RESPECT

[A37 Worst case] Regardless of whether or not CE technologies are deployed, the worst case without emission abatement is clearly worse than the worst case with emission abatement.

A37
WORST CASE

The priority of mitigation measures is, for example, presumed in the arguments which see the reduction of mitigation measures as a negative side-effect of climate engineering (A1, A27). The risk transfer argument (A31) also appears to start from this assumption, whereas the efficiency argument (A9) contradicts the thesis that emission reductions take priority.

## 2.7 Summary of argumentative analysis

Argumentative complexity of the CE controversy

The argumentative analysis reveals the complexity of the CE controversy. On multiple levels, arguments are set forth which support or attack—in a variety of ways—(i) the obligation to research and (ii) the admissibility to deploy CE technologies. On the one hand, the arguments make use of empirical assumptions which can be assessed scientifically. On the other hand, they always rely on more or less far-reaching normative premises, as well. Such normative assumptions may involve the weighting of side-effects or the moral assessment of inequalities; in any case, they evade an empirical, scientific evaluation. But the overall positions held by the debate's participants comprise both empirical as well as normative claims. When using the argumentative analysis for evaluating CE technologies, it is also pivotal to substitute specific CE technologies for the place holder $T_{CE}$. Only then can the individual arguments be checked for plausibility. Arguments which may be very strong and convincing with a view to one technology could turn out to be inconclusive for other technologies.

# 3
# The Earth's Climate System and Climate Engineering Technology

**The debate on the implementation and the effectiveness of CE technology is limited by our scientific and technical knowledge.** In this chapter, after a brief introduction to the Earth's radiation budget, we present potential methods that could be used to completely or partially compensate for anthropogenic effects on the Earth's climate system. In Sections 3.2 and 3.3, which discuss technology that is currently being under consideration for development, the proposed methods are evaluated in terms of their effectiveness, side-effects, and levels of technical development. Methods that aim to prevent anthropogenic emissions from reaching the atmosphere are not discussed here.

## 3.1 Principles of atmospheric physics and types of climate engineering

### 3.1.1 Earth's radiation budget

At the top of the atmosphere the incoming flux of solar radiation, called incidental solar radiation, is about 1,368 W/m² (solar constant, $S_0$). However, when the temporal and spatial factors that are related to the shape of the Earth are accounted for, only 1/4 of this amount (i.e., $S_0/4$ = 342 W/m²) actually reaches the upper atmosphere. Clouds and the Earth's surface then further reflect about 30 percent of this back into space (a planetary albedo (*A*) of 30 percent), which means that only about 240 W/m² of the incidental radiation warms the Earth. If a thermal equilibrium is assumed, then there must be an equal flux of thermal radiation in the opposite direction (i.e., the incoming radiation flux equals the outgoing radiation flux). As illustrated in Figure 4, the spectral distributions of these radiation fluxes are significantly different.

At thermal equilibrium the outgoing flux of thermal radiation is equal to the incoming incidental solar radiation

The wavelengths of most of the incidental solar radiation are in the visual light range (vis) and at the shorter end (a few µm) of the infrared (IR) spectrum, while the wavelengths of the Earth's outgoing thermal radiation peak at around 15 µm in the IR spectrum. Since there is little overlap in their distribution it is established practice to differentiate between them as incidental short-wave (SW) and outgoing long-wave (LW) radiation.

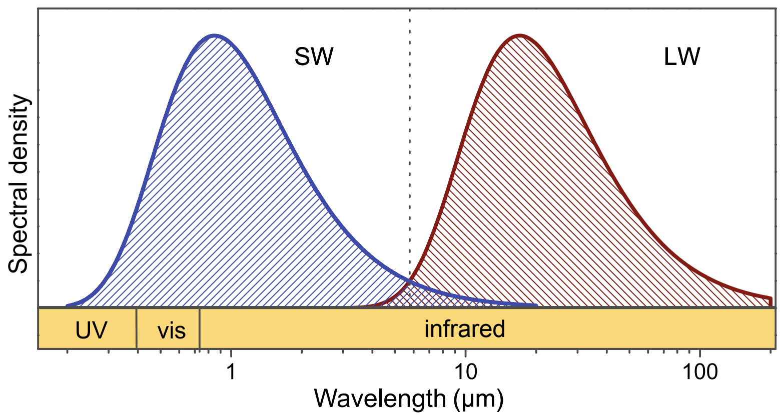



FIGURE 4:
Schematic diagram of the spectral distribution of the Earth's solar radiation (SW) and thermal radiation (LW)
Source: Own representation.

The temperature of the Earth's surface is determined by the balance between the fluxes of SW and LW radiation ($F_{SW}$ and $F_{LW}$). The atmosphere plays an important role in controlling these fluxes because while it allows SW radiation to mostly pass through unhindered, some atmospheric tracer gases, called greenhouse gases, can absorb and reemit a broad spectrum of LW radiation.

**These concepts can be demonstrated with a simple two-layered model that uses spatially and temporally averaged values.** In this model (Figure 5) the atmosphere, which is represented as a single layer with a temperature $T_a$, has an albedo (*A*) in the SW spectral range (left section), but is otherwise transparent to SW radiation. For LW radiation there is a probability ($\alpha$<1) that the radiation will be absorbed by the atmosphere (Kirchhoff's Law).

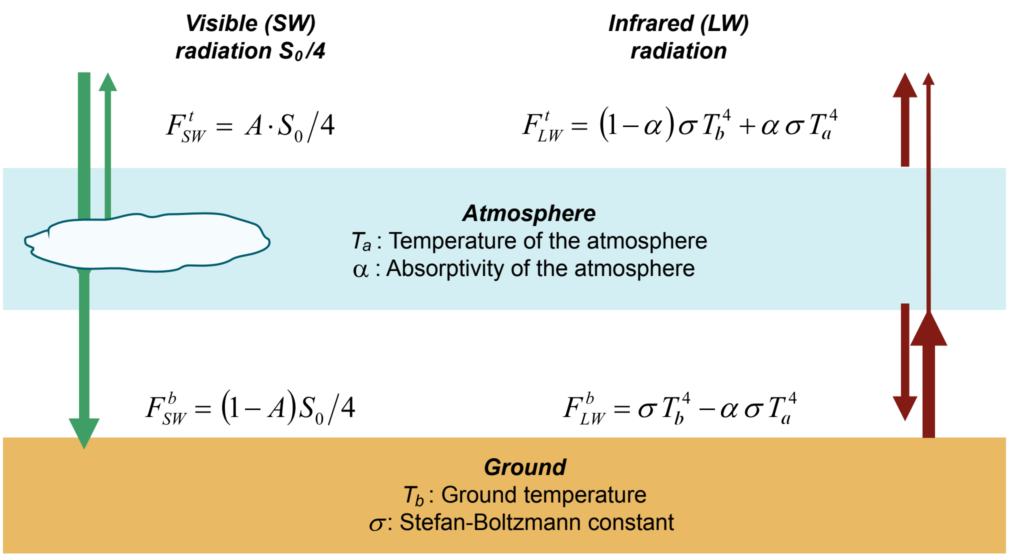



FIGURE 5:
Conceptional model of the short-wave and long-wave radiative flux ($F_{SW}$ and $F_{LW}$) in the atmosphere

Source: Feichter and Leisner (2009).

If the SW and LW energy fluxes are in equilibrium, then the ground temperature ($T_b$) can be calculated using the Stefan-Boltzmann Law of thermal radiation:[10]

$$T_b = \sqrt[4]{\frac{S_0(1-A)}{2\sigma(2-\alpha)}} \qquad (1)$$

Although this simple model disregards many important climatic processes, for a realistic $\alpha$ of 0.8 the Earth's calculated temperature ($T_b$) is 15° C which is amazingly close to the actual average temperature of the Earth. Equation (1) also shows that the ground temperature increases if either the absorption of LW radiation in the atmosphere ($\alpha$) increases, which could occur if the concentrations of greenhouse gases increase, or if the albedo ($A$) falls. If this calculation is done without taking atmospheric absorption into account ($\alpha$=0), then the resulting ground temperature is around -18° C. This 33° C difference, which is due solely to atmospheric absorption, highlights how important atmospheric trace gases (in particular water vapor and $CO_2$) are in determining the Earth's temperature.

The climatic importance of natural trace gases

**Climate sensitivity, which is defined here as the change in temperature that is caused by a change in radiative forcing, can be estimated by deriving Equation (1) for $S_0/4$.** For the values used above this results in a climate sensitivity of about 0.2° C per W/m² (i.e., a change in radiative forcing of 1 W/m² changes the ground temperature by about 0.2° C).[11] However, more sophisticated model calculations and recent palaeoclimatological observations indicate that the actual climate sensitivity is higher and more in the range of 0.4° C to 1.1° C per W/m² (Forster and Gregory 2007). The differences between these climate sensitivity calculations are the result of taking into account important feedback effects that also influence the climate system and are not included in Equation (1).

10 σ is the Stefan-Boltzmann constant ($\sigma = 5.67 \cdot 10^{-8}$ W/(m²K⁴)).

11 The definition of climate sensitivity used in this paper is based on Forster and Gregory (2006). In the literature climate sensitivity is also frequently referred to as the temperature response corresponding to a doubling of the $CO_2$ concentration.

A considerably more detailed, quantitative overview of the Earth's radiation budget that includes these feedbacks is illustrated in Figure 6. In this figure the SW (left) and LW (right) radiative fluxes and the effects of various atmospheric and terrestrial processes on them are quantified. The indicated inequality between the incidental and outgoing radiation fluxes can be traced back to the human activities, as explained below.

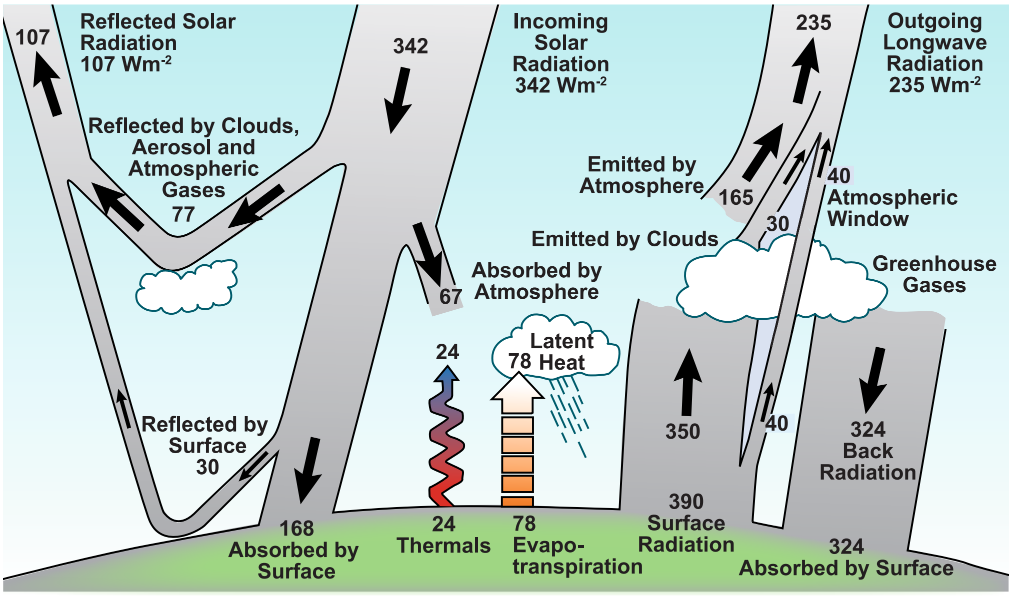



FIGURE 6:
Schematic diagram of the Earth's radiation balance

Source: Le Treut et al. (2007), FAQ 1.1,Figure 1.

### 3.1.2 Human influence on the radiation budget

Anthropogenic radiative forcing

Since the start of industrial revolution (ca. 1750) human activities have significantly altered the atmosphere and the Earth's surface. As a result the global radiation budget has changed. The term "radiative forcing", which describes the net change in the difference between incoming SW radiation energy and outgoing LW radiation energy at the tropopause in W/m$^2$ relative to "unperturbed" values (i.e., the budget before humans altered it), is used to quantify these changes (Forster et al. 2007). Since the start of industrial revolution radiative forcing is estimated to have changed by +2.6 W/m$^2$, primarily due to an increase in the concentrations of atmospheric $CO_2$ and other greenhouse gases that reduce the amount of LW radiation that is radiated into space (FLW). As a result warming has occurred because more energy is trapped near the Earth's surface. This warming has been further intensified by positive feedbacks. A particularly important feedback, which is due to warming, is an increase in the concentration of water vapor, the most potent greenhouse gas, as a result of increased evaporation from the ocean. Note that since the concentration of water vapor can only be significantly effected by this feedback effect, humans have only indirectly changed the concentration of this important greenhouse gas. Concentrations of the greenhouse gas ozone have also increased in the troposphere as a result of human activities because the precursors compounds that form it are emitted by a number of human activities. The change in radiative forcing due to an increase in ozone is about +0.3 W/m$^2$ (Forster et al. 2007).

Albedo and aerosols

In many regions the albedo (reflection of short-wave radiation) of the Earth's surface has increased as a result of changes in land use, thereby reducing SW radiation absorption (a change in radiative forcing of about -0.2 W/m$^2$). However in other regions, the albedo has decreased due to an increase in soot particle deposition on snow and ice, thereby increasing SW radiation absorption (a change in radiative forcing of about +0.1 W/m$^2$). Aerosols, which have also been impacted by human activities, play a role in the radiation budget by scattering short-wave radiation in the atmosphere and by altering the properties of clouds. Changes in these effects are estimated in the fourth IPCC assessment report to have reduced radiative forcing by -1.2 W/$m^2$. However, this estimate is associated with a great deal of uncertainty (Forster et al. 2007). Of all the anthropogenic airborne dust particles, soot aerosols are unique because like greenhouse gases they can absorb radiation and thus have a climatic warming effect (Jacobson 2001; Hansen 2002). However, this warming effect can sometimes be weakened or reversed due to feedbacks cause by interactions between soot and clouds or the effects of soot on the thermal stratification of the atmosphere (Koch and DelGenio 2010; Koch et al. 2011). Fortunately, in contrast to the major anthropogenic greenhouse gases, the typical atmospheric lifetime of soot is very short of about 2 to 7 days (Ogren and Charlson 1983). Thus, if soot-emitting sources can be eliminated, soot aerosols will quickly cease to have an effect on the climate. Accordingly, technologies that aim to reduce soot aerosols are not categorized as climate engineering but as conventional emission control.

**Models have estimated that the change in radiative forcing due to anthropogenic activities is +1.6 W/$m^2$ with a margin of uncertainty of +0.6 to +2.4 W/$m^2$ (Forster et al. 2007).** Satellite observations, which include feedback effects, from 2000 – 2004 indicate that for this period alone, radiative forcing increased by about +0.9 W/$m^2$ (Trenberth et al. 2009). However, there is a significant degree of uncertainty associated with these measurements.

Various timescales

**The Earth's climate system reacts to changes in radiative forcing on a variety of time scales.** The Earth's surface can reach a new temperature equilibrium within few years (Schwartz 2007, 2008), while most of the water in the oceans and the rock and soil that lie below the surface take centuries to warm (Knutti and Hegerl 2008). The lifetime of many greenhouse gases is also quite long. Carbon dioxide, the most important anthropogenic greenhouse gas, takes hundreds of years to be removed from the atmosphere. More than 20 percent of anthropogenic $CO_2$ will remain in the atmosphere for longer than 1,000 years (Archer and Brovkin 2008) and only be removed by geological weathering processes that occur over hundreds of thousands of years.

### 3.1.3 Temperature increases due to changes in radiative forcing

**Warming caused by changes in radiative forcing can be estimated using models that take into account important feedbacks (such as how an increase in water vapor, the most potent greenhouse gas, will reduce sea ice coverage and thus change the Earth's albedo).** These feedbacks are responsible for more than half of the calculated temperature changes, although there is much uncertainty associated with them. If CE technologies are successful, then the additional warming caused by these feedback will largely not occur.

Climate sensitivity

The change in the mean global surface temperature for a given radiative forcing is referred to as the climate sensitivity of the system. Various observations and model estimates suggest that doubling the pre-industrial $CO_2$ concentration will cause the temperature to increase by about 3° C (with a margin of uncertainty of 2 to 4.5° C) (Knutti and Hegerl 2008). However, it is not possible to exclude even larger increases from occurring. The Fourth IPCC Assessment Report attributes warming from greenhouse gases emissions to have been about 0.2° C per decade up until 2005 (Forster et al. 2007). Projections of warming through the end of the 21$^{st}$ century depend greatly on predicted changes in anthropogenic emissions and range from 1.1 to 6.4° C, depending on the emissions scenario. Furthermore, warming does not occur equally everywhere. More warming occurs in the Arctic and over land than elsewhere (Forster et al. 2007).

### 3.1.4 Tipping points in the climate system

Crossing critical thresholds

**Possible or likely tipping points in the climate system are frequently listed as a reason for the future deployment of climate engineering (Caldeira and Wood 2008; Irvine et al. 2009).** A tipping point is a critical threshold at which a tiny perturbation (i.e., a small change in radiative forcing) can qualitatively alter the state or development of the system. A tipping element describes subsystems of the Earth system that are at least subcontinental in scale and can be switched—under certain circumstances—into qualitatively different states by small perturbations (Lenton et al. 2008; Allison et al. 2009). Frequently discussed tipping elements are the melting of the Greenlandic ice sheet, instability of the West Antarctic ice sheet, breakdown of Atlantic Ocean circulation, or the emission of greenhouse gases from thawing permafrost. While most current climate models do not provide any clear indication of where these critical thresholds lie or if they will be approached in the future due to human activities, the few that make such predictions have been criticized because of the large uncertainty associated with these thresholds (Hoffmann 2009).

### 3.1.5 Types of CE technology

CE technologies either treat the symptoms or eliminate the causes

**CE technologies can generally be differentiated according to whether they aim to treat the "symptoms" of climate change by altering the Earth's radiation budget without reducing greenhouse gas concentrations, or whether they aim to treat the "cause" of climate change by reducing the greenhouse gas concentrations that have changed the Earth's radiation budget.** The first group of methods can be further sub-divided into which component of the radiation budget (SW or LW radiation) they aim to change in order to compensate for temperature increases due to anthropogenic radiative forcing.

**Methods which directly influence SW solar radiation (Solar Radiation Management, SRM) and/or LW thermal radiation (Thermal Radiation Management, TRM), are discussed here as Radiation Management (RM).** Accordingly the other methods could be termed Concentration Management, but since they are generally focused on $CO_2$, **we stay with the term CDR (Carbon Dioxide Removal)**. Most of the proposed CDR technologies work by manipulating the Earth's natural $CO_2$ sequestration mechanisms, which act through a variety of physical, chemical and biological pathways, to regulate atmospheric $CO_2$ concentrations. In contrast to RM, CDR addresses the major cause of anthropogenic climate change and would therefore potentially be more sustainable than a solitary deployment of RM technology, which would need to be maintained for a period of many centuries to several millennia owing to the long lifetime of $CO_2$ in the atmosphere. RM can, therefore, also be described being a symptomatic cure and CDR as being a causative cure. However, since CDR would also cause feedbacks to occur, they would also affect the radiation budget. Table 3 provides an overview of the different methods.

In the column "Leverage effect" an attempt has been made to give a qualitative measurement of the efforts associated with the relevant method versus the results that are achieved (i.e., a high leverage effect means that a little bit of effort gives you a big effect). Time must also be taken into account when evaluating the effectiveness of these methods because while some RM methods have the potential to rapidly cool the planet (some of them in as little as a few months), CDR methods take considerably longer to work because of the extremely large quantities of $CO_2$ that have to be removed from the atmosphere (currently the atmosphere contains a little under 3,000 Gt $CO_2$).

In the "Method lifetime" column a period of time is specified within which the effect of a CE method wears off after its termination (in terms of a half-life period). For CDR methods a lifetime

| Category | Type | Method | Leverage effect | Anticipated potential | Method lifetime |
|---|---|---|---|---|---|
| Symptomatic cure: Modification of incidental or outgoing radiation (RM) | Reduction of short-wave radiation (SRM) | Reflectors in space | Low-medium | Unlimited | Decades – centuries |
| | | Aerosols in the stratosphere | Large | Unlimited | About 1 year |
| | Increase in long-wave radiation (TRM) | Modification of cirrus clouds | Large | -1 to -4 $W/m^2$ | Days – weeks |
| | Reduction of short-wave radiation (SRM) | Modification of marine stratus clouds | Large | -4 $W/m^2$ | Days |
| | | Modification of the Earth's surface albedo | Low | -0.2 to -3 $W/m^2$ | Years |
| Causative cure: Reduction in the concentration of LW-absorbing atmospheric components (CDR) | Physical/ocean | Artificial upwelling/downwelling | Low | Not effective | – |
| | Chemical/ocean | Reactions with olivine | Low | 4 Gt $CO_2$/year | – |
| | | Reactions with calcium oxide/hydroxide | Low | 1.5 Gt $CO_2$/Gt $CaCO_3$ | – |
| | | Reactions with powered limestone | Low | 0.3 Gt $CO_2$/Gt $CaCO_3$ | – |
| | Biological/ocean | Fertilization using macronutrients | Low | Not effective | – |
| | | Fertilization using micronutrients | Large | 5 Gt $CO_2$/year | – |
| | Chemical/land | Air capture | Low | Unlimited | – |
| | Biological/land | Biochar | Low | 5 Gt $CO_2$/year | – |
| | | Afforestation | Medium | 4 Gt $CO_2$/year | – |

TABLE 3:
Overview of the different CE methods

Source: Own representation.

is not specified because it is assumed that $CO_2$ leakages are already taken into account and that $CO_2$ storage is permanent for the timescales underlying the evaluation.

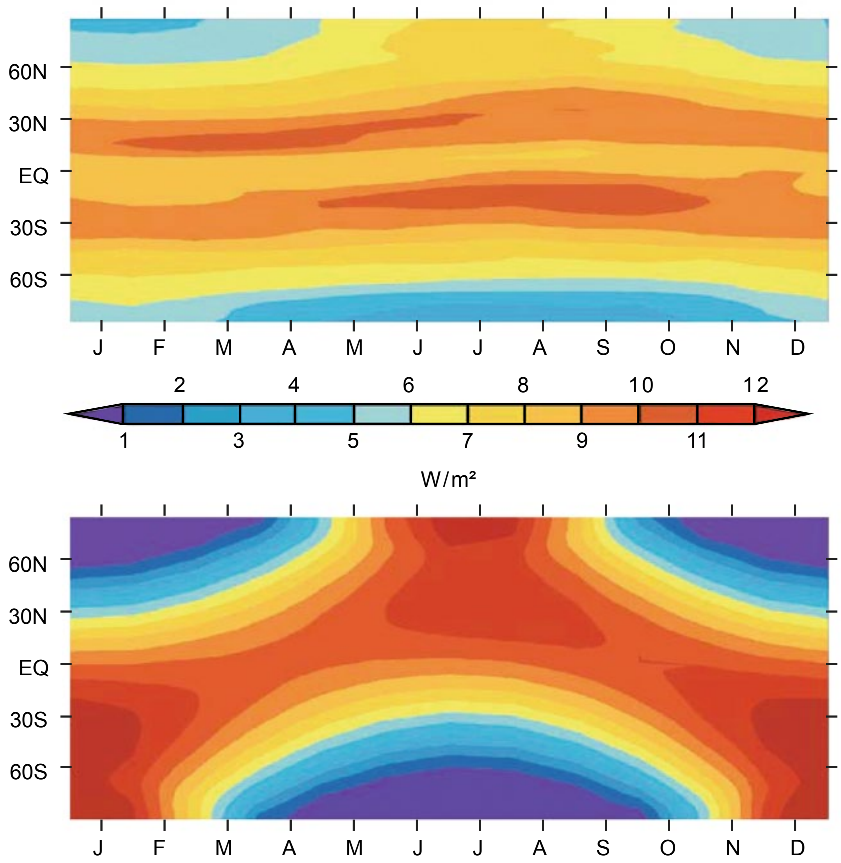
### 3.1.6 Side-effects of radiation management

**Even if RM methods work as desired, they all have unavoidable side-effects that occur because of the different spatial and temporal factors that regulate LW and SW radiative fluxes.** In Figure 7 zonally averaged changes in LW (upper panel) and SW (lower panel) radiative fluxes are compared for an assumed quadrupling of the $CO_2$ concentration and the deployment of SRM methods (Govindasamy and Caldeira 2000). While LW radiative forcing is largely constant throughout the year and highest in the subtropics, SW radiative forcing varies substantially in terms of both latitude and seasonality.

Surprisingly, despite these geographical and temporal radiative forcing imbalances, models indicate that these RM methods could homogenously reduce the Earth's temperature. This is possible because energy would rapidly and effectively be transported throughout the atmosphere as it adapts to RM induced changes. However, as a result atmospheric circulation patterns and the atmospheric component of the hydrologic cycle would change (Feichter and Leisner 2009). Since other RM methods operate on the same principle, similar atmospheric changes could be expected for them as well.

A26
DISTRIBUTIONAL EFFECTS

**Operating principles and individual components of these RM methods can be tested in model simulations or laboratory experiments.** However, according to prevailing opinion, evidence of their effectiveness would need to be provided by means of large-scale field trials prior to full deployment. Robock et al. (2010) argue that field tests of RM technologies would only be meaningful if carried out on a global scale. Even then, identification and interpretation of a climate signal would be difficult and time-consuming. Furthermore, a multitude of side-effects (see Section 3.2) could be expected. Thus, an extensive field test would be difficult to differentiate from a gradual initiation of RM technology, combined with a monitoring program, and a discontinuation option.




Notes: Changes in the LW radiative flux (upper panel) and SW radiative flux (lower panel) according to an assumed multiplication of the $CO_2$ concentration and a SRM method that leaves the Earth's mean temperature unchanged as a result of homogeneous shading. The values (in W/m²) are averaged for each zone and given as a function of the geographic latitude and season.

FIGURE 7:
Different distribution of the LW and SW radiative flux in terms of latitude and time

Source: Govindasamy and Caldeira (2000).

**RM only indirectly influences the atmospheric $CO_2$ concentration by causing temperature feedbacks and even then the effect is small (e.g., Mercado et al. 2009; Oschlies et al. 2010b).** Thus, radiative forcing due to greenhouse gases is largely unchanged. As a result, even if emissions cease RM must remain in place until greenhouse gas concentrations have decreased (see Section 3.1.2). Using a climate model, which makes certain assumptions about emission scenarios, Brovkin et al. (2009) show that for all methods, RM would have to be deployed for several thousands of years if it is assumed that $CO_2$ is only removed from the atmosphere by natural means. If these methods were interrupted during this period, very rapid and likely catastrophic temperature increases could occur (Brovkin et al. 2009; Ross and Matthews 2009). Furthermore, the deployment of RM methods will always lead to the creation of an "artificial" climate that, in the event of an interruption to- or discontinuation of the method, would not necessarily return to the initial state that existed prior to implementation.

A18
TERMINATION PROBLEM
A21
IRREDUCIBLE UNCERTAINTIES

## 3.2 RM technologies

As shown in Table 3, the radiation budget can be controlled by a variety of technologies. These can be categorized according to

- >> the height of the reflector(s) above the Earth's surface, with the fundamental effectiveness increasing with height,
- >> the type of reflector, with the material expense, its lifespan (decay period of the measure), and the "leverage effect" representing significant criteria.

Below some popular technologies are presented and briefly discussed.

### 3.2.1 Reflectors in space

Substantial material and energy costs are required

**The basic idea is to place reflective material between the Sun and the Earth to prevent some SW radiation from reaching the Earth.** Although the theoretical potential of this method is unlimited, it could be expensive because the reflective material needs to cover a significant percentage of the Earth's cross-sectional area, $A_q = \pi \cdot R^2$ (R = Earth's radius), to be effective (e.g., 1 percent for a reduction of 3.4 $W/m^2$). Since the material also has to be fired into space using missiles or rockets whose launching mass is about 2 – 3 times that of the load, the expense could be much more. However, using material already found in space, such as asteroids, may be a way to avoid the costs of a space launch (Mautner 1991; Pearson et al. 2006).

Calculations based on celestial mechanics indicate that the reflective material could be deployed in orbit near the Earth (Mautner 1991; Pearson et al. 2006) or at the inner Lagrange point L1 (Early 1989; Angel 2006).

Deploying the material in a near-Earth orbit has a disadvantage because when any section of the material is on the dark side of the Earth it would not reflect any radiation (i.e., as the reflector orbits the Earth it would pass from the lit side to the dark side). Furthermore, with such a method even shading would be difficult to achieve. The reflectors would also add material to the near-Earth environment (Pearson et al. 2006), which is already crowded with "space junk" and satellites. In principle near-Earth reflectors could also obstruct thermal (LW) radiation. This would have to be prevented or cooling could not be achieved. The advantage of this method lies in the relatively easy accessibility of a near-Earth orbit. Model investigations of the effectiveness of this method using coupled General Circulation Models (GCM) have found that it results in significant cooling in the tropics, but warming with a drop in sea ice coverage at high latitudes. Additional research has also predicted that the hydrologic cycle, the ENSO[12] climate pattern, and Atlantic deep-water formation (Lunt et al. 2008) will be impaired. Despite the disadvantages and possible side-effects of this method the American company Star Technologies and Research Inc. is actively pursuing the ideas proposed by Pearson et al. (2006).

If reflective material is deployed at the inner Lagrange point (L1), a distance of 1.6 million kilometers from the Earth, the attractive forces of the Earth and the Sun would cancel each other out. Based on the ideas of Early (1989), Angel (2006) proposed that mirrors positioned at this point could reduce short-wave radiation and in 2008 a European patent was filed for this purpose (Wakefield 2008).

Placing the Earth in a shadow is also a possibility from L1. Unfortunately, a major disadvantage of using the L1 point is that it is difficult to reach from Earth (about twice as much energy is required when compared to reaching near-Earth orbit). In addition, to create a shadow the surface area of the radiation blocking material must be twice as large as the Earth's cross-sectional area because when viewed from L1, the Earth rotates around the Earth-Moon system's center of gravity, which lies roughly on the Earth's surface. Furthermore, a reflector placed at the L1 point would not stay there and thus the position of the reflector would have to be continuously corrected. However, these adjustments have been estimated by Angel (2006) to only be necessary once every 50 years. Nonetheless, despite these disadvantages, this CE technology could be quite effective since simulations with a simple climate model indicate that it could compensate for much of the warming caused by anthropogenic $CO_2$ emissions (Govindasamy and Caldeira 2000; Govindasamy et al. 2002).

12 ENSO = quasi-periodic variations in the ocean and atmospheric circulation patterns in the tropics and South Pacific.

### 3.2.2 Aerosols in the stratosphere

**In principle, adding reflective sub-micrometer aerosols to the stratosphere is a good method for reducing SW solar radiation because these aerosols are inexpensive and can have a significant effect on SW radiation (Budyko 1982).** In addition, stratospheric aerosols have a relatively long lifespan of 1–2 years (primarily due to the lack of rainfall) when compared to those in the troposphere which have a lifespan of lesser than 1 week. The effectiveness of these aerosols has already been confirmed from observing "natural experiments" in which major volcanic eruptions caused 1° C of global cooling by adding 1 million tons of sulfur (as $SO_2$) to the stratosphere, where it was converted into an aerosol (Lacis and Mishchenko 1995).

The effectiveness has been demonstrated with "natural experiments"

This CE technology, which has been the subject of a relatively long-standing debate (Budyko 1982; Dickinson 1996; Teller et al. 1997; Keith 2000), became especially popular owing to the work of Paul Crutzen (2006) (Wigley 2006; Rasch et al. 2008b). The method has considerable potential (a reduction of many $W/m^2$) and is in principle effective enough to offset a multiplication of the pre-industrial $CO_2$ concentration. Modeling studies have supported the effectiveness of the basic method and discussed it's possible side-effects (Govindasamy et al. 2003; Rasch et al. 2008a; Murphy 2009; Lenton and Vaughan 2009; Heckendorn et al. 2009; Jones et al. 2010). However, as Heckendorn et al. (2009) and Pierce et al. (2010) show the method's effectiveness does not increase in proportion to the amount of sulfur that is added to the stratosphere. The initial estimates of amount of sulfur that is required have already been revised upwards (Katz 2010) and the expected stratospheric lifetime of the aerosols revised downwards (Tuck et al. 2008). Although, Pierce et al. (2010) suggest avoiding these difficulties and the undesirable warming of the lower stratosphere by directly deploying a sulfuric acid aerosol over a large area. Unfortunately, the technical challenges of getting large amounts of either sulfur or sulfuric acid to a height of 20–25 km are considerable.

Estimates of the necessary quantity of sulfur have been corrected upwards

There have been many proposals regarding the technological implementation of a stratospheric aerosol shield. One patent filed in 1991 addresses the insertion of aerosols into the stratosphere (Chang 1991). A more recent patent is for a method that uses commercial aircraft to deploy reflective aerosols by adding a special additive to their fuel (Hucko 2009). The Microsoft-funded company Intellectual Ventures has promoted the development of a method called a "stratoshield", which uses a balloon to carry a tube from the ground to the stratosphere to deliver the aerosols, or aerosol generating chemicals, by pumping them through the tube. Keith (2010) has also proposed to use photophoretic forces to increase the concentration and lifespan of certain reflective particles in the stratosphere and to reduce their effect on ozone chemistry.

**A26**
DISTRIBUTIONAL EFFECTS

Various side-effects

**The side-effects of stratospheric aerosol injection have been debated in a number of publications.** Many possible negative effects on the global hydrologic cycle have been deduced by comparing the proposed stratospheric manipulation with the largest volcanic eruption of the 20$^{th}$ century, Mt. Pinatubo (Hegerl and Solomon 2009). Simulations by Ricke et al. (2010) suggest that it is not possible to achieve cooling without changing precipitation patterns. However, using GCM simulations Irvine et al. (2010) more optimistically suggest that it is possible to reduce solar radiation with only minimal regional effects on precipitation. Other side-effects also include those caused by the potentially catalytic acceleration of ozone depletion by stratospheric particles (Heckendorn et al. 2009). Adding sulfur to the stratosphere would also increase the acidity of rainfall in the vicinity of the addition. However, according to modeling studies by Kravitz et al. (2009; 2010) the global effects of acidification would be negligible. To minimize the negative side-effects of adding these aerosols Ban-Weiss and Caldeira (2010) and Eliseev et al. (2010) propose that this method can be optimized by evenly distributing the aerosols across different latitudes. However, not all side-effects are negative; one positive side-effect is that these methods would increase diffuse solar radiation, which could have a positive effect on plant productivity (Roderick et al. 2011; Mercado et al. 2009).

### 3.2.3 Modification of cirrus clouds

**High altitude ice clouds (cirrus clouds) can obstruct either LW or SW radiation.** As reviewed by Zhang et al. (1999), the type of radiation that is blocked depends on the latitude of the clouds, their altitude, particle size, and the crystal structure of the ice. Although all of the factors are important, the latitude of the clouds is generally the dominant factor that determines which type of radiation they block. Currently, the composition and location of cirrus clouds causes them to have a warming effect (Lee et al. 2009). However, if they can be artificially dispersed or modified then they can be forced to have a cooling effect. According to a proposal by Mitchell et al. (2009) this could happen if the sky is sown with certain types of ice nuclei that promote cirrus cloud formation. The presence of these nuclei would result in fewer, but larger ice particles being produced during cirrus cloud formation, thus causing them to sink more rapidly. As a result the lifespan of the clouds and the overall cloud coverage would be reduced. In addition, these nuclei would also change the optical properties of the clouds.

One merit of this proposal is the extremely low material cost that would be involved in the deployment of this method. Ice nuclei are only needed in very low quantities and could even be deployed at suitable locations by commercial aircraft with only a few kg of material needed per flight.

Little material is needed to modify cirrus clouds

**The ultimate climatic effect of generating cirrus clouds by injecting ice nuclei into the atmosphere cannot easily be quantified.** In particular, research is needed to determine how different injection methods influence the crystal structure of the resulting ice particles. Regardless, these methods could be expected to strongly modify both the SW and LW components of the radiation budget. Furthermore, because of the different geographical and spatial factors that effect SW and LW radiation[13], this method has the potential to cause large changes in regional climates and hydrological cycles. Thus, this method may conceal particularly dangerous and unknown meteorological side-effects.

A26
DISTRIBUTIONAL EFFECTS

Influences of $F_{LW}$ and $F_{SW}$

### 3.2.4 Modification of marine stratus clouds

**Generally, if aerosol concentrations are increased it has an effect on cloud formation because aerosols act as condensation nuclei and having more nuclei allows more water droplets of a smaller size to form (i.e., the density of clouds is increased).** This then leads to an increase in the backscattering of SW radiation, which means the albedo (Twomey 1974). This effect can be particularly intense if the existing natural concentration of condensation nuclei is low, as is the case in some oceanic regions. In these regions higher cloud albedo due to the emission of smoke by ships can clearly be seen in satellite pictures (Coakley Jr. et al. 1987).

Early studies also hypothesized that higher aerosol concentrations suppress the formation of rain in clouds, thus extending their lifespan and thereby also increasing the planetary albedo (Albrecht 1989). However, this hypothesis has been challenged in more recent studies (Small et al. 2009; Stevens and Feingold 2009).

**Latham (1990; 2008) proposed a CE method that uses sea salt particles to increase aerosol concentrations as a means of changing the albedo in marine boundary layer clouds (stratocumulus clouds).** According to estimates by Latham et al. (2008), radiative forcing

13 See Section 3.1.4.

in regions where this method is used could be reduced by up to -4 $W/m^2$, which is enough to cancel out the positive radiative forcing arising from a doubling of the atmospheric $CO_2$ concentration. However, Jones et al. (2009) estimate that if this CE method was used in all stratocumulus regions, which cover 3.3 percent of the Earth's surface, radiative forcing would only decrease by -1 $W/m^2$ and thereby compensate for only 35 percent of the current positive radiative forcing that is due increases in greenhouse gases. Rasch et al. (2009) estimate that if very high water droplet concentrations can be achieved with this methodology, radiative forcing could be reduced by -2.5 $W/m^2$ to -3.9 $W/m^2$.

The primary side-effects of this method are expected to be related to changes in the hydrologic cycle. Although these side-effects will initially be local, effects on remote regions as a result of atmospheric circulation cannot be excluded (Rasch et al. 2009).

A26
DISTRIBUTIONAL EFFECTS

Effects on the hydrological cycle

**Large fleets of ships have been proposed to distribute the sea salt aerosols in as uniform a manner as possible (Salter et al. 2008).** Estimates by Latham et al. (2008) suggest that a global total of 23 $m^3$ of seawater per second would have to be atomized to achieve the desired effect. Currently, the technology to efficiently atomize this much seawater does not exist and would have to be developed. The best-suited oceanic regions in which to deploy this method would be the persistent stratocumulus layers in the southern hemisphere off the coasts of Peru and Namibia.

Technology does not yet exist for efficient implementation

**The majority of model investigations on the effectiveness of this CE proposal assume that there is a constant increase in droplet concentration in the target areas.** However, due to dynamic aerosol and cloud interactions this assumption is not realistic, as Korhonen et al. (2010) were able to demonstrate with a global aerosol model. Even with particle concentrations that were five times higher than previously assumed, the albedo effect was lower in these simulations than previous estimates. The authors also point out possible air-chemical interactions with the surface of the sea salt aerosols, the effects of which still need to be studied. In the practical implementation of this method it must also be ensured that an appreciable proportion of the sea salt nuclei are transported into the target cloud layer. Since evaporative cooling may occur during aerosol generation, achieving this may be difficult.

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COMPLEXITY OF THE EARTH SYSTEM

The water droplet concentrations that have been used in some models are not realistic

### 3.2.5 Modification of the Earth's surface albedo

**In principle the Earth's surface albedo could be increased through a targeted modification of land surfaces.** In fact humans have already been influencing the land surface and the Earth's albedo for around 10,000 years through agriculture and animal husbandry. Technical options include covering desert areas with brighter more reflective material, increasing the reflectivity of residential areas (i.e., white roofs), or altering vegetation (i.e., planting vegetation that is more reflective or genetically modifying crops to increase leaf reflectivity).

However, if vegetation is manipulated, potential influences on the carbon cycle must also be considered. For example, replacing forests with more highly reflective grasslands would change the terrestrial $CO_2$ sink. In addition to altering the flow of energy, manipulating vegetation may also affect water vapor and the flow of rivers (Marland et al. 2003), with the result being that any reduction in atmospheric $CO_2$ quantities achieved through afforestation (planting of forests) could be partially offset by opposing climate effects. However, generally afforestation in tropical areas has a cooling effect and afforestation in boreal areas has warming effect (Bathiany et al. 2010).

Feedbacks between the carbon reduction methods and albedo must be considered

Bio-geoengineering

Singarayer et al. (2009) and Ridgwell et al. (2009) proposed a "bio-geoengineering" method that is based on planting crops with specific leaf shine and/or with specific shape to increase albedo. Using a coupled climate model they have demonstrated a relevant effect. However, the potential alteration of the global carbon cycle as a result of their method was not discussed in their studies. Akbari et al. (2009) have also proposed to increase the albedo of urban areas in order to offset regional or even global greenhouse gas warming.

**The potential to change the albedo of the Earth's surface is low (< 1 $W/m^2$) because there would be land-use conflicts or limited areas that could be modified, even if in models higher values are theoretically possible through large-scale modification of desert areas.** In addition, changes in albedo could have side-effects depending on how the radiation budget is affected.[14] Other negative effects could also potentially occur if the methods altered critical habitats or reduced biodiversity. Nevertheless, more reflective surfaces in urban environments would help to reduce regional heat islands and thereby reduce the $CO_2$ emissions generated by the energy used for air conditioning.

## 3.3 CDR technologies

The atmosphere currently contains about 800 Gt carbon

As explained in Section 3.1.5, CDR generally works by enhancing natural $CO_2$ sequestration through a modification of the physical, chemical, and biological processes that control the carbon cycle and previously determined the amount of $CO_2$ in the atmosphere (i.e., before humans started adding it). However, before discussing the various CDR methods, we will first give a brief overview of these processes and their role in the carbon cycle, along with a description of the relevant carbon reservoirs. The atmosphere currently contains about 800 Gt carbon.[15] This is roughly the same amount of carbon as is contained in terrestrial vegetation and that is dissolved in the top 100 m of the ocean. With the seasonal changes that alter vegetation (i.e., summer vs. winter productivity) and increase or decrease water temperatures, the atmosphere exchanges approximately 100 Gt of carbon every year with these reservoirs, in which gains and losses essentially cancel each other out (the difference is only a few percent). Other carbon reservoirs include the soil, which stores about 1,500 Gt carbon, and the deep sea, which holds about 37,000 Gt of dissolved carbon. Since soils contain about twice as much carbon as the atmosphere does, and the ocean about 50 times as much, even relatively small changes in the size of these reservoirs can cause large changes in the atmospheric $CO_2$ content. However, the exchange between the atmosphere and these major carbon reservoirs is much slower than with terrestrial vegetation or the upper ocean. So far terrestrial carbon reservoirs have absorbed most of the anthropogenic $CO_2$ emissions that can be traced back to changes in land use and the ocean has absorbed, via air-sea gas exchange, about 40 percent of the other anthropogenic $CO_2$ emissions (Raupach and Canadell 2010). On a timescale of thousands of years almost all of the anthropogenic $CO_2$ will be removed from the atmosphere in this manner, with the oceanic uptake rate limited by ocean circulation, which only slowly brings the deep ocean into contact with the atmosphere.

The ocean contains about 50 times as much carbon as the atmosphere

On long time scales the oceans will absorb nearly all of the anthropogenic $CO_2$

A number of CDR methods aim to accelerate the rate of oceanic $CO_2$ uptake (see Table 3). Unfortunately, a significant side-effect of increasing oceanic carbon uptake is the associated dissolution of $CO_2$ in water and the corresponding acidification of the oceans. Recently, as atmospheric $CO_2$ concentrations have increased, surface waters have already become more acidic. However, if these methods are deployed, this effect could be reversed since the acidity

Ocean acidification is caused by the uptake of $CO_2$

14 See Section 3.1.6.

15 This equates to nearly 3,000 Gt $CO_2$ (1 ton C = 3.66 tons $CO_2$).

of the surface ocean would decrease as $CO_2$ is removed from the atmosphere. Instead, the main problem associated with these methods is that acidification will occur where the $CO_2$ is stored (generally at great depths) (Oschlies et al. 2010a). Figure 8 provides an overview of the various CDR methods.

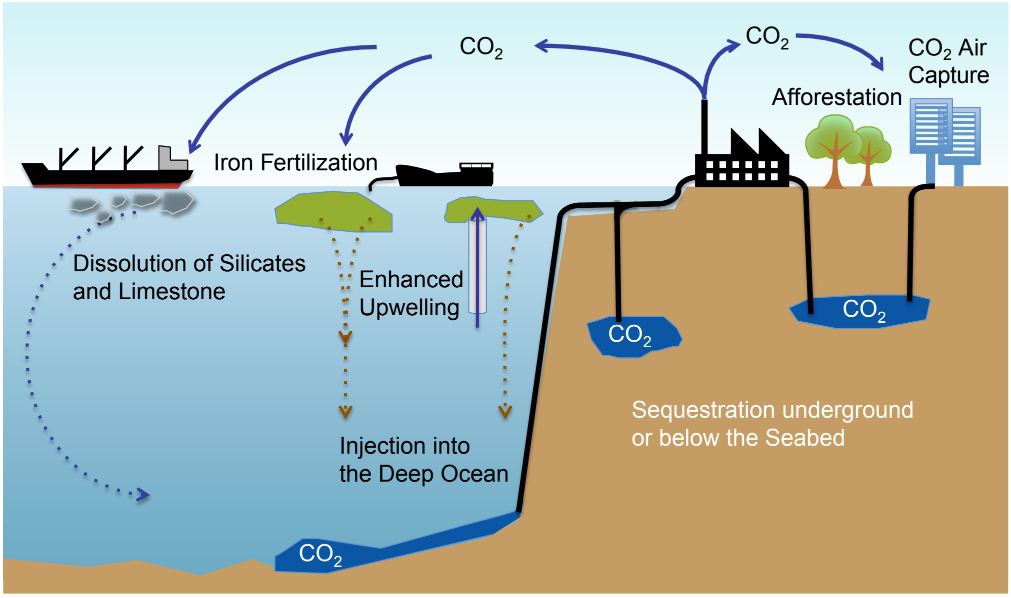


FIGURE 8:
Overview of the different CDR methods

Source: Own representation.

### 3.3.1 Physical methods for increasing oceanic carbon uptake

**Theoretically, possible physical methods that could increase oceanic $CO_2$ uptake involve either accelerating the ventilation of the ocean (the process by which water is transferred downward from the ocean's surface and circulated around the globe) by increasing circulation or by directly transporting $CO_2$ to the deep sea.** The latter method was first investigated in the 1970s as a carbon capture and storage (CCS) approach (see Marchetti, 1977, who also used the term "geoengineering" for the first time in this context). For methods that transport $CO_2$ to great depths, the $CO_2$ will ultimately dissolve in the surrounding seawater, return to the surface due to ocean circulation, and eventually reach the atmosphere again via air-sea gas exchange. Thus, these methods do not result in permanent storage. Model simulations suggest that for an example discharge depth of 3,000m, within 500 years slightly less than half of the discharged $CO_2$ will have again reached the atmosphere (Orr 2004). However, since 2006 the direct discharge of $CO_2$ into the ocean has been implicitly prohibited by the London Protocol and consequently will not be pursued further in this report.[16] In addition, these methods require a relatively high concentration of $CO_2$ such as the concentrations that arise from carbon capture and storage at power stations. Since only the capture of atmospheric $CO_2$ is classified as climate engineering, this method would instead be classified as industrial carbon management (Keith 2000).

Direct injection of $CO_2$ is implicitly prohibited by the London Protocol

Proposals to accelerate oceanic $CO_2$ uptake by intensifying downwelling ocean currents have been analyzed by Zhou and Flynn (2005). However, the cooling of surface water at high latitudes, so that it sinks and transports $CO_2$ with it, does not appear to be energetically feasible. Furthermore, the potential side-effects of doing this have not been thoroughly assessed. Other

Intensification of downwelling ocean currents and artificial upwelling

16 Paragraph 1.8 of Annex 1 of the London Protocol permits the use of "carbon dioxide streams from carbon dioxide capture processes for sequestration". This permission is, however, restricted by paragraph 4: "Carbon dioxide streams referred to in paragraph 1.8 may only be considered for dumping, if: (1) disposal is into a sub-seabed geological formation; and (2) they consist overwhelmingly of carbon dioxide. They may contain incidental associated substances derived from the source material and the capture and sequestration processes used; and (3) no wastes or other matter are added for the purpose of disposing of those wastes or other matter."

possible physical methods are based on artificially forcing colder water from deeper layers up to the ocean surface. This can be achieved, for example, by using wave-driven pumps (such as those developed by Atmocean, Inc. Santa Fe, NM, USA) and a patent for oceanic $CO_2$ capture and storage through artificial upwelling has already been filed (Bailey and Bailey 2010). The water that is forced to the surface with this method is typically colder and "older". As a result it has a higher solubility and was exposed to a lower atmospheric $CO_2$ partial pressure during its last contact with the atmosphere, making it easier for $CO_2$ to be taken up. However, despite this, the potential for carbon capture and storage is low (much less than 1 GtC/year, Oschlies et al., 2010b). Modeling studies also suggest that the resulting redistribution of warm and cold water would lead to a disturbance of the global energy budget. As a result if the pumps were turned off, as was tested in one simulation, it would lead to rapid warming with resulting average global temperatures that are even higher than those in simulations in which artificial upwelling was not used (Oschlies et al. 2010b).

A18
TERMINATION PROBLEM

Interruption of artificial upwelling results in rapid warming

### 3.3.2 Chemical methods for increasing oceanic carbon uptake

**Before humans altered the carbon cycle $CO_2$ emissions from volcanic sources were removed from the atmosphere primarily by chemical weathering reactions with rock (i.e., the $CO_2$ becomes bound to minerals in the rock).** Once bound, erosive processes eventually transport these weathering products into rivers and then the ocean. Unfortunately, the natural rate of weathering is only about one hundredth of the current rate of anthropogenic $CO_2$ emissions so it is not effectively removing this additional $CO_2$. Chemical methods for increasing the storage of carbon in the ocean are based on artificially accelerating the weathering process, primarily by manipulating limestone or silicate bedrock (olivine). This can be achieved by enlarging the surface area of the rock, for example by crushing and grinding it. Rock dust can then either be spread on land, preferably in warm, humid tropical areas (Schuiling and Krijgsman 2006; Köhler et al. 2010), or discharged directly into surface waters (Kheshgi 1995; Rau and Caldeira 1999, Caldeira and Rau 2000; Harvey 2008; Rau 2008). A patent has already been filed for one technology that can be used to capture and store $CO_2$ in minerals (Cooper 2008). Note that if limestone is used to create calcium hydroxide (a mineral that reacts with $CO_2$ to form calcium carbonate and water), consideration must be given to the fact that $CO_2$ is released when the limestone is burned to form it, and thus this $CO_2$ would have to be captured and stored separately.

Artificial acceleration of the natural weathering processes

Thermal methods require additional $CO_2$ capture and storage

House et al. (2007) suggest using an electrochemical method to artificially increase $CO_2$ removal by weathering. Their method works by electrochemically removing hydrochloric acid (HCl) from the sea on a major industrial scale for use in accelerating the slow natural weathering process on land (i.e., HCl can be used to facilitate some weathering reactions). A positive side-effect of this method is that removing HCl from the ocean increases its alkalinity, which in turn facilitates oceanic $CO_2$ uptake without intensifying ocean acidification. The techniques to remove the constituents of HCl from the seawater and combine them into hydrochloric acid are well-known in chemical engineering. However, the large-scale use of strong acids might not be without problems.

**The potential to reduce atmospheric $CO_2$ through chemical weathering methods is very high but these methods all require the mining and crushing of large quantities of rock.** The chemical reaction that removes one ton of $CO_2$ from the atmosphere requires about one ton of olivine (Köhler et al. 2010) and thus, involves mining activities that are on the same scale as those involved in the extraction of fossil fuels. Köhler et al. (2010) estimate that the upper limit of $CO_2$ removal with these methods is a few gigatons of carbon a year. Weathering reactions

Resource acquisition on the same scale as global coal mining create basic (alkaline) compounds that would initially react against ocean acidification but could ultimately, in the event of rapid, large-scale artificial weathering, also lead to an alkalization of the ocean with largely unknown side-effects. Other, currently uninvestigated, side-effects could also be expected because of the optical, chemical, and potentially toxic effects of the quantities of rock dust involved, and the mineral impurities that it may contain.

### 3.3.3 Biological methods for increasing oceanic carbon uptake

In large areas algal growth is limited by a lack of macro- or micronutrients

**Although the world's oceans only contain a small portion of the planet's biomass (1 – 2 percent), marine phytoplankton in the surface layers are responsible for about half of the planet's photosynthesis which biologically converts $CO_2$ into organic carbon (Groombridge and Jenkins 2002).** A small portion of this biomass sinks to great depths or to the bottom of the ocean before remineralization processes transform the organic material into $CO_2$, nutrients, and other chemical forms. The transport of carbon containing biomass from the surface to the deep ocean is known as the "biological carbon pump" (Volk and Hoffert 1985). Photosynthesis can only occur when there are sufficient nutrients, trace elements, and sunlight. The distribution of the nutrients and trace elements in the surface ocean depends on input from rivers, the air, and deeper waters and is consequently imbalanced. Thus, there are large areas of the ocean where algal growth is limited by the lack of one or several nutrients or trace elements such as nitrate or iron. In these regions biological processes can be enhanced to increase oceanic carbon storage by fertilizing the water to stimulate algal growth and intensify the biological carbon pump (i.e., increase net $CO_2$ transport from the surface to the deep ocean). When this occurs the lower concentrations of $CO_2$ in the surface water will then increase the amount of $CO_2$ that flows into the ocean from the atmosphere during air-sea gas exchanges.

Fertilization with macronutrients

**When discussing fertilization, a distinction needs to be made between macronutrients (e.g., nitrate, phosphate) and micronutrients (e.g., iron).** To export any amount of carbon, roughly the same amount of macronutrients is required. Thus, fertilization with macronutrients obtained on land would necessitate an enormous effort in terms of logistics and energy. In addition, this could cause there to be a lack of these nutrients for terrestrial food production. However, there is a method that circumvents these problems by using macronutrients that are already dissolved in the deep ocean. This method works by artificial upwelling nutrient-rich water from a depth of several hundred meters using, for example, wave-driven pump systems (Lovelock and Rapley 2007). However, since nutrient-rich water is also generally rich in $CO_2$ because both nutrients and $CO_2$ arise from the remineralization of organic material, this method must additionally remove this $CO_2$ to be effective. Oschlies et al. (2010b) used a climate model to show that pumping up deep water will cause algae to bloom and can lead to a net oceanic drawdown of $CO_2$. However, even if an optimum distribution of perfectly functioning pump systems could be deployed, the potential drawdown of $CO_2$ with this method is low (about 0.2 Gt C/year). Furthermore, the Earth system model simulations suggested that the upwelling of colder water only leads to a temporary cooling of the atmosphere and also has the effect of slowing terrestrial ecosystem respiration (especially in soils), with an overall barely detectable globally distributed sequestration of atmospheric $CO_2$ by about 0.7 Gt carbon per year (Oschlies et al. 2010b).

Iron fertilization in the Southern Ocean

**In many oceanic regions the growth of algae is limited by a lack of iron and not macronutrients, which are sufficiently available.** These regions comprise large sections of the North Pacific, the Equatorial Pacific, and the Southern Ocean. In all three regions the experimental addition of iron has resulted in an increase in biological production. Numerical models indicate that the best location to achieve the sustained capture and storage of $CO_2$ by means of iron fertilization would be in the Southern Ocean because fertilization in the other regions would eventually lead to the depletion of macronutrients and thus, cause biological production to fall again (Sarmiento et al. 2010). In the Southern Ocean natural fertilization by iron-containing sediments from islands significantly increases carbon fixation and export to deeper waters, when compared to surrounding waters that contain little iron. In modeling studies, extrapolation of these natural fertilization effects to the entire Southern Ocean leads to carbon capture and storage of about 1 Gt of carbon per year (Oschlies et al. 2010 a). Patents have been filed for various methods of iron fertilization (Howard Jr. et al. 1999; Maruzama et al. 2000; Lee 2008). A patent has also been filed for a method that enables iron fertilization to be monitored (Suzuki 2005).

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COMPLEXITY OF THE EARTH SYSTEM

The long-term effects of large-scale iron fertilization are unknown

**Fertilization with macro- or micronutrients is an intended manipulation of marine ecosystems to boost carbon export.** Experiments and natural fertilization processes suggest that the desired increase in carbon export to the deep ocean could be achieved in terms of quality. However, the capture and storage potential appears to be restricted to about 10 percent of the current anthropogenic $CO_2$ emissions. Moreover, the effects of manipulating these ecosystems are not restricted to carbon export. For example, increases in particle export lead to additional oxygen consumption in deeper water (which would likely only result in relatively small changes in the oxygen-rich Southern Ocean). In addition, nitrous oxide ($N_2O$) is formed as a by-product of remineralization. Estimates from modeling studies indicate that the additional release of this potent greenhouse gas would compensate (i.e., replace one greenhouse gas with another) for about 10 percent of the reduction in radiative forcing that was achieved with fertilization-induced $CO_2$ uptake (Jin and Gruber 2003; Oschlies et al. 2010 a). Furthermore, side-effects that alter the productivity (Gnanadesikan et al. 2003) and the entire food chain of the ocean (Denman 2008) could be potentially expected. Other possible side-effects include changes in marine trace gas emissions (Jin and Gruber 2003) and potential changes in the ozone layer (Lawrence 2002). The risk of increases in harmful algae blooms has also been mentioned (Trick et al. 2010). Unfortunately, with our current level of scientific understanding it is impossible to confidently predict the long-term effects of large-scale ocean fertilization (e.g., Wallace et al. 2010).

### 3.3.4 Chemical $CO_2$ scrubbing (air capture)

Air capture technologies are being pursued by scientific and corporate researchers

**$CO_2$ scrubbing works by directing air over a sorption agent that selectively adsorbs $CO_2$.** The sorption agent is then regenerated in order to release the $CO_2$ for storage and to be available again for the ad- or absorption of $CO_2$ from the air. There are a few different methods that have already been investigated to some extent in the private sector or in joint ventures with universities or research institutes.[17] The different methods can be fundamentally distinguished by whether liquid (e.g., sodium hydroxide[18]) or solid (e.g., carbonate polymer) sorption agents are used (Lackner 2010).

To capture one megaton of $CO_2$ per year using a sodium hydroxide based process, Socolow et al. (2011) estimate that for current $CO_2$ scrubbing system designs, an area of land of about 1.5 $km^2$ would be required. Accordingly, to annually capture 10 Gt $CO_2$, an area of about 122 x 122 km would be needed. However, these rough calculations do not take into account the additional surface area and infrastructure that would be needed to provide the electricity, heat, and water that is required to remove the captured $CO_2$ from the system.

17 See Lackner (2010) for an overview of the various research institutes and companies involved.

18 With this method sodium hydroxide and calcium carbonate are produced during the second processing step from a reaction involving calcium hydroxide. The sodium hydroxide is then used again as an adsorber in the first step, while the calcium carbonate is broken down by calcination into calcium oxide and $CO_2$. Water is then used to convert the calcium oxide to calcium hydroxide for use again in the second processing step and the $CO_2$ can be stored or converted.

**Energy is required to move air through the scrubber and to regenerate the sorption agent.** Energy requirement estimates vary greatly depending on the extent to which natural air circulation can be utilized to move the air and how elaborate the sorption agent regeneration process is. Lackner (2010) estimates that to take up one ton of $CO_2$ about 1.1 GJ of electricity is needed, whereas Socolow et al. (2011) estimate that about 1.8 GJ of electricity is required. The net effectiveness of the method is determined by quantifying how much $CO_2$ is absorbed versus the amount of energy that is required. When making these calculations with renewable energy provision, it must be taken into account that this energy could replace some of the $CO_2$-intensive forms of energy production. However, $CO_2$ scrubbing could opportunistically utilize otherwise stranded energy resulting from short term fluctuations in the actual generation of renewable energy.

Estimates of how much energy is required vary

**Once captured $CO_2$ has to be stored permanently and securely.** Overviews of suitable reservoirs around the world are discussed in an IPCC report (2005) and Michael et al. (2010). Alternatively, $CO_2$ can be discharged into the ocean as carbonate after further processing (i.e., in a carbonate reactor) (Rau and Caldeira 1999) or converted into synthetic fuels through reactions with hydrogen (Keith 2009; Socolow et al. 2011).

Storage or further chemical processing of the captured $CO_2$ is possible

**The different methods for scrubbing $CO_2$ from the air must all contend with the fact that $CO_2$ is a trace gas and comprises only about 0.01 percent of air.** Thus, these methods can never be as effective as power station CCS (Keith 2009). Nonetheless, they have an advantage because this technology can more easily be deployed near suitable storage facilities or near renewable energy sources that cannot be incorporated into the power grid (or only incorporated into the grid with great difficulty).

### 3.3.5 Biological methods for enhancing terrestrial carbon uptake and storage

**All methods for increasing carbon storage in terrestrial plants or their remains are based on photosynthesis.** They differ only in how they handle the carbon-containing material that is obtained through this biosynthesis. According to optimistic estimates by Lenton and Vaughan (2009) such methods have the potential to decrease atmospheric $CO_2$ concentrations by 100 ppm by the year 2100. However, these methods may conflict with food production.

**A26**
DISTRIBUTIONAL EFFECTS

Potential is primarily limited by land availability

**To increase carbon storage in terrestrial plants Ornstein et al. (2009) propose planting suitable forest vegetation in the Sahara and Australian desert regions.** Charney hypothesized (Charney 1975; Charney et al. 1975) that artificially irrigated vegetation in the Sahara could change the regional atmospheric circulation so that more rainfall would occur, which would then reduce the need for irrigation. Despite cloud formation over the newly designed forests, Ornstein et al.'s climate model showed no significant changes in albedo, which would reduce the desired effect on the global radiation budget. However, the authors do discuss other side-effects that include a reduction in the upwelling of cold water off the coast of West Africa, which would have a negative impact on regional fishery, because of changes in the wind field due to the new forest cover. In addition, they discuss a possible reduction in the dust-borne export of iron from the Sahara region that could lead to a decrease in the fertilization of Northern Atlantic phytoplankton and South American forests. The technology and expertise to artificially irrigate the Sahara exists. However, the possible ecological and climatologically side-effects have barely been investigated and are poorly understood. Despite this, several patents have been issued that are based on these $CO_2$ storage methods (Kodo et al. 2000; Bayless et al. 2003; Baird 2010). Note that while these methods may work in some regions, at boreal latitudes increasing forest cover could potentially have a global warming effect because of the Tundra-Taiga feedback effect (Bala et al. 2007; Bathiany et al. 2010).

**Manufacturing biochar (Lehmann et al. 2006) produces, through pyrolysis, a chemically inert solid that could potentially be used to securely store carbon for thousands of years.**[19] By-products of this process include biogas and bio-oil, which could also potentially replace fossil energy sources if biochar is manufactured on a large enough scale. Additionally, biochar could potentially be useful as an additive to loosen soil. Pyrolysis technology for producing biochar is mature. Patents have already been issued to Meier et al. (2005) for a pyrolysis technology that uses biomass and to Ueno et al. (2004) for a method to store biochar. The use of biochar as a soil additive still requires further research (Sohi et al. 2009).

Production of biochar would ensure long-term storage of $CO_2$

## 3.4 Summary of the scientific and technical aspects of CE technology

**Despite the recent increase in publications about various CE technologies, there are several reasons for why it is not possible to make a reliable assessment of the scientific effectiveness and technical feasibility of any of the technologies currently under discussion.** First, our current understanding of Earth system processes limits our ability to simulate different CE technologies. In particular, regional simulations of climate change, which attempt to look at more than just changes in temperature, are still a long way from being able to account for the possible side-effects of climate engineering. Furthermore, it is not possible to make credible claims on the ecological consequences of deploying or abandoning the deployment of individual CE methods. Second, consideration must be given to the fact that the desired climate effects and side-effects are currently often just based on estimates from the proponents of the CE technologies, without having undergone independent peer review. However, the geoengineering model intercomparison project (GeoMIP) (Kravitz et al. 2011) does aim to standardize some of the methods used to study RM and thereby represents a first step towards a more objective and critical assessment of them.

Reliable assessment of the scientific effectiveness is not yet possible

**Since anthropogenic climate changes occur on top of natural climate variability, a further crucial uncertainty relates to the measurement and monitoring of CE implementations.** For example, annual satellite measurements reveal a natural global variability in the short-wave radiative flux of 0.3 $W/m^2$ ($1\sigma$). To differentiate between a CE effect of this magnitude and natural variability, measurements would have to be taken for at least 10–15 years using current satellite systems (Loeb et al. 2007). However, the stability of current satellite systems is by no means assured for such periods of time.

The number of patents granted for climate engineering related technology has risen rapidly in recent years. However, patent protection should not be regarded as a clear sign that the described technology will soon be implemented. Patents are often filed for distant future technical possibilities as a means to protect against potential competitors or to prevent specific technologies from being pursued by other parties. As far as we are aware, the CE methods discussed here have not been commercially implemented.

**Earth system models play a key role in CE research and can be used to gain a necessary understanding of the system, and its potential responses to climate engineering, long before any actual CE deployment (if it becomes necessary to do so).** These models can also help to determine the limits of our predictive ability. At present, Earth system modeling is still in the early stages of development. However, with a large-scale and coordinated effort it is certainly

An improved understanding of the Earth system is needed

19 The term biochar is a more comprehensive term than charcoal since, in addition to wood, the starting material can also include harvest remnants, green waste, cattle dung, slurry, sewage sludge and biological waste.

possible to make significant progress within a time span of about 10 years. Investigations to improve our understanding of all the involved physical, chemical, and biological processes in and between the related Earth system components would be included in such a research program. The result of this fundamental research would be Earth system models that could simulate the potential and side-effects of CE deployments. These models could also be used to assess the consequences of discontinuing CE deployment after it has been implemented. Such improved models would be a fundamental tool that could provide a robust assessment of CE technologies and supply important information for planning or abandoning any experimental CE research.

# 4
# Economic Costs and Effects

**In addition to the issues connected with technical feasibility and effectiveness, the costs of CE technologies are a crucial factor in assessing the efficiency and economic feasibility of climate engineering.** If climate engineering is regarded as a supplement to, or replacement for, emission control, then the costs incurred by implementing CE technologies need to be compared with the cost of emission control. A whole range of different cost components and factors have to be taken into account in this comparison. The variable costs of operation and the capital costs associated with the investment determine the operational costs for the different CE technologies. Available estimates are, however, based on existing prices, so they potentially underestimate the actual operational costs. The operational costs arising from deploying CE technologies are expected to be significantly affected not only by price effects, but also by economies of scale. If, say, a CE technology requires a large quantity of a specific fuel, then prices for that fuel can be expected to rise considerably. This will also affect other markets and market players. If a realistic estimate of the costs of deploying any CE technology is to be obtained, effects like these must be taken into consideration. On the other hand, the large-scale use of certain CE technologies might create substantial economies of scale that would counteract these price effects.

AC4
EFFICIENCY AND EASE OF IMPLEMENTATION

Price effects and economies of scale not taken into account so far

Beside the impact of price effects on other markets, the costs associated with external effects must also be considered. These arise where potential side-effects of CE technologies are not included in the cost calculation. Such side-effects may be either positive (i.e., generate social benefits) or negative, resulting in social benefits or social costs for the global community or for individual countries or regions, respectively. Assigning these external benefits and costs to the various CE technologies can change their welfare implications significantly. Consequently, the economic costs of a CE technology are determined by the sum of the operational costs and the external costs/benefits, taking into account price effects and economies of scale.

A13
INDIRECT COSTS UNDERESTIMATED

**At present it is impossible to determine the economic costs because quantitative research findings on external effects and potential price and scale effects do not exist.** In the literature, the assessment of economic efficiency is limited to a discussion of operational costs, which presumably make up only a small proportion of the overall economic costs. Furthermore, the estimates available only consider the effectiveness of the various technologies in isolation. Interactions between different technologies are scarcely taken into account at all. For example, deploying CDR technologies with terrestrial biological carbon sequestration will also have an impact on albedo. Conversely, deploying RM technologies will have a positive effect on the natural carbon uptake of sinks. Taking these interactions into account could result in a significantly higher or lower assessment of the effectiveness, and hence the efficiency, of the various technologies.

Not yet possible to determine economic costs

Comparing RM technologies with conventional emission control methods or CDR technologies is complicated because of the way their approaches to influencing the radiation budget differ. **While emission control and CDR directly influence the concentration of atmospheric $CO_2$ and hence the root cause of greenhouse gas-induced radiative forcing, RM only compensates for temperature impacts from greenhouse gas-induced radiative forcing.** Accordingly, the costs of CDR technologies occur only once with regard to the carbon stored, whereas the costs for RM technologies continue to occur until the carbon concentration has naturally declined or

Comparing the costs of RM and CDR technologies is difficult has been reduced by CDR technologies. Accordingly, it is impossible to assess RM technologies economically without explicitly taking the time factor into consideration. There is no straight forward calculation enabling us to compare the effectiveness of RM technologies directly with that of CDR technologies.

A26
DISTRIBUTIONAL EFFECTS

**The efficiency of CE technologies is not only determined by the absolute cost level, but also by the long-term distribution of costs between countries and across generations.** Efficient deployment of CE technologies therefore looks different from a global vantage than from a decentralized vantage, and the impacts on emission control are similarly variable. In the following, the discussion addresses these issues, devoting much of the space at its disposal to the operational costs because these have been examined most thoroughly in the literature to date.

## 4.1 Economic costs of CE technologies

### 4.1.1 Cost comparison with emission control

**The estimated future costs of conventional emission control set out in the latest World Energy Outlook 2010 (IEA 2010) can be drawn on for comparison with the costs for CDR technologies.** This estimate assumes that an atmospheric stabilization level of 450 ppm $CO_{2equiv}$ is sufficient to limit the temperature increase to 2°C. To evaluate the associated costs, the IEA (2010) assumes a scenario in which (i) by 2020 the voluntary emission reductions in the Copenhagen Accord will have been fully realized, and (ii) as of 2020 an emission path will be embarked on to achieve stabilization at 450 ppm $CO_{2equiv}$ in the atmosphere. At the current prices in this scenario, the marginal costs in 2035 for one ton of $CO_2$ will be between USD 90 and 120. This estimate is more or less consistent with that of the latest McKinsey Report, which reckons that given a somewhat more moderate emissions reduction path, the marginal costs for one ton of $CO_2$ will be approximately USD 80 in 2030 (Enkvist et al. 2010).

**In addition to the estimated marginal abatement costs for one ton of $CO_2$, the investment required to limit the temperature rise to 2°C also calls for consideration.** The IEA (2010) estimates that in the period from 2010 to 2035 a total USD 18 trillion investment will be required to bring about the necessary emission reductions. It should be noted that the costs of conventional emission control methods also involve numerous uncertainties. The range of these costs is determined by uncertainties regarding technological development, varying assumptions about the underlying emission path without intervention (BAU), changes in energy prices, the intended reduction target, and the timeline to which emission control is subject.

A9
EFFICIENCY ARGUMENT

Assessing the costs of RM technologies requires definition of references for atmospheric $CO_2$ concentration and the relevant time scale

**To compare RM technologies with conventional emission control, we need to convert the radiative impact of radiation management into an equivalent quantity of $CO_2$ removed from the atmosphere.** The calculation behind this conversion is primarily defined by the concentration of atmospheric $CO_2$ and the reference period selected. RM technologies have a direct influence on the radiation balance but only an indirect impact on the concentration of atmospheric $CO_2$ via feedback mechanisms. Doubling the atmospheric concentration of $CO_2$ corresponds approximately to a radiative forcing of 3.71 $W/m^2$ (Lenton and Vaughan 2009). However, the relationship between atmospheric $CO_2$ concentration and radiative forcing is non-linear: the higher the existing atmospheric $CO_2$ concentrations, the larger the quantities of $CO_2$ that need to be removed from the atmosphere to achieve a corresponding change in the radiation budget. Accordingly, the comparative costs for changing the radiation budget by means of conventional emission control rise in accordance with the prevailing concentration of atmospheric $CO_2$. Put simply, the higher the existing concentration of $CO_2$ is, the less costly RM technologies become relative to conventional emission control.

No existing dynamic cost comparisons consider feedback effects

**Determining the comparative costs is not simply a matter of multiplying the amount of carbon to be saved by the estimated $CO_2$ price.**[20] There are two reasons why this type of calculation is erroneous. First, the estimated $CO_2$ price for the year 2035 represents the marginal abatement costs for one unit of $CO_2$ based on an economic estimate. But a comparative calculation would require the use of the average $CO_2$ abatement costs for the 1 W/m$^2$ change in radiation budget, provided that estimates of the economic costs for RM technologies are available. Second, it is difficult to define a reference period. With conventional emission control and CDR technologies, the concentration of $CO_2$ in the atmosphere is influenced directly. In the case of RM technologies, the influence is only indirect. Accordingly, the implementation of RM technologies has to be maintained until GHG-induced radiative forcing has declined naturally. So the reference period must cover this timeframe. However, even on an operational costs basis, we have no such dynamic cost comparisons explicitly taking into account the various feedback effects of RM technologies on natural $CO_2$ uptake.

The report by the Royal Society determines the comparative costs by drawing upon the economic costs of conventional emission control for stabilization at 2°C in the year 2100 (Royal Society 2009). This results in a cost estimate of approximately USD 200 billion per W/m$^2$ per year. In an emission scenario without emission control, the RM technology in question would need to be in place for several millennia, depending on how fully GHG-induced radiative forcing is to be compensated for (Brovkin et al. 2009). Accordingly, the Royal Society estimate obviously *over*estimates the comparative costs by a factor of approximately 10, because the comparative horizon is restricted to 100 years. Conversely, if the efficiency of measures is judged in terms of the way they affect the radiation budget within a short timeframe (e.g., five years), this calculation may also grossly *under*estimate the comparative costs. What we see from this is that it is impossible to define general comparative costs for RM technologies because they vary so widely depending on the atmospheric concentration of $CO_2$ already attained and the reference period selected.

### 4.1.2 Operational costs

**Operational costs encompass the variable costs of operation and the capital cost of the investment required to set up systems and put logistics in place.** Capital expenditure for the development of the CE technologies should also be taken into account. Nevertheless, there is no standardized information in the literature on the various components of operational costs for the different technologies. For CDR technologies, operational costs are estimated per ton of $CO_2$, for RM technologies per W/m$^2$. It is often unclear to what extent capital costs for investment in equipment, infrastructure, logistics, and research have been taken into account.

**Table 4 provides an overview of estimates of the anticipated potential, operational costs, capital expenditure, major uncertainties, and stage of development of the various CDR technologies currently under debate.**[21] The mean of the range of operational costs and the range itself are specified for the various technologies. These are ranked by the mean of the range within the different categories (biological, chemical, physical). There are hardly any quantitative data on investment and logistics expenditure. To offset this deficit, a qualitative assessment has been undertaken (Klepper and Rickels 2011). The assessment categories are low, medium, and high. Throughout, the estimate is based on the assumption of achieving the full annual potential that is theoretically possible.

20 Given an atmospheric $CO_2$ concentration of 450 ppm and a $CO_2$ certificate price of USD 100 per ton of $CO_2$, the comparative costs for a change in the radiation budget of 1 W/m$^2$ would exceed USD 60 trillion.

21 Here we do not consider technologies such as the use of carbonate reactors or the injection of concentrated $CO_2$ from power plants into the deep ocean, as these come into play before $CO_2$ is emitted into the atmosphere and therefore constitute industrial carbon management (Keith 2000).

| Technology | Anticipated potential in W/m$^2$ | Operational costs in USD/t $CO_2$ | Investment in R&D, equipment, infrastructure, and logistics | Major uncertainties |
|---|---|---|---|---|
| Conventional emission control | | 90 – 120 (in 2035) | USD 220 billion /year (2010 – 2020)<br>USD 940 billion/year (2020 – 2030)<br>USD 1280 billion/year (2030 – 2035) | World Energy Outlook simulation results for medium-term stabilization at 450 ppm $CO_{2equiv}$ (IEA 2010) |
| **BIOLOGICALLY-BASED CDR TECHNOLOGIES** | | | | |
| Biochar production | 5 Gt $CO_2$/year | 45 (15 – 76) | No quantitative studies available (investment: medium) | Net carbon storage potential due to use as energy source; use as fertilizer may reduce operational costs to USD 26 (10 – 42)/t $CO_2$ (stage of development: implementation phase) |
| Southern Ocean iron fertilization | 5 Gt $CO_2$/year | 45 (8 – 82) | No quantitative studies available; estimates for fleet of ships required vary between 20 and 500 ships (investment: medium) | Amount of iron sulfate required and arrangements; processing to prevent coagulation from occurring too quickly; extent of export production that sinks into deep sea (stage of development: field trials and modeling) |
| Afforestation | 4 Gt $CO_2$/year | 60 (19 – 101) | No quantitative studies available (investment: low); large-scale afforestation requires high investment in irrigation systems | Measurement of carbon uptake, costs, and leakage varies between studies (stage of development: implementation phase) |
| Nutrient supply from land to ocean | Not an effective CDR technology based on current knowledge (Lampitt et al. 2008; Oschlies et al. 2010) | | | |
| Enhancement of natural upwelling | This technology is not actually a CDR technology because $CO_2$ uptake primarily occurs via temperature feedback in the terrestrial biosphere (Oschlies et al. 2010). Accordingly, this technology needs to be compared with RM technologies for its carbon sequestration potential (no specific studies on this as yet). | | | |
| **CHEMICALLY-BASED CDR TECHNOLOGIES** | | | | |
| Spreading pulverized olivine in catchment areas of large rivers (mainly tropical) | 4 Gt $CO_2$/year | 42 (27 – 57) | No quantitative studies available, high costs for exploitation, transport, processing, and spreading infrastructure (investment: high) | Necessary capital costs and spreading limited in practice by areas being hard to access (stage of development: modeling) |
| Spreading of pulverized calcium oxide/ hydroxide in the ocean combined with geological storage of $CO_2$ released as a result of calcination | 1.5 Gt $CO_2$/ Gt $CaCO_3$ | 50 (45 – 54) | No quantitative studies available; high costs for exploitation, processing, calcination, geological $CO_2$ storage, and fleet of ships (investment: high) | Necessary capital costs; infrastructure and logistics for exploitation, processing, and spreading (stage of development: modeling) |
| Spreading pulverized lime in the ocean | 0.3 Gt $CO_2$/ Gt $CaCO_3$ | 65 (57 – 72) | No quantitative studies available; high costs for exploitation, processing, and fleet of ships; estimated size of fleet required: approx. 6000 ships (investment: high) | Necessary capital costs; infrastructure and logistics for exploitation, processing, and spreading (stage of development: modeling) |
| Air capture (sodium hydroxide) | 1.0 – 1.2 Mt $CO_2$/unit/ year | 250 (69 – 430) | USD 247 – 480 million /unit | No experience as yet with scale effects, and uncertainty about geological and submarine $CO_2$ storage (stage of development: field trials) |
| **PHYSICALLY-BASED CDR TECHNOLOGIES** | | | | |
| Enhancement of deep water formation in the North Atlantic | In terms of the emissions associated with implementation, this technology does not constitute an effective CDR technology (Zhou and Flynn 2005). | | | |

TABLE 4: Overview of current operational cost estimates for various CDR technologies

Source: Klepper and Rickels (2011).

**The overview in Table 4 shows that, with the exception of air capture, there are no explicit estimates of the investments and logistics expenditures required for CDR technologies.** For chemically-based CDR technologies like spreading of olivine, calcium oxide/hydroxide, or lime, the deployment scale is probably restricted by the investment expenditures involved, which are expected to be high. Among other factors, the broad range of operational costs for air capture stems from the different ways in which capital costs are treated. In the study by Socolow et al. (2011), the pure acquisition costs of USD 480 million are multiplied by a factor of 4.5 to obtain the capital expenditure involved in full deployment. Keith (2009) estimates, however, that the costs per ton of $CO_2$ are nearer to USD 100 than USD 500. However, depending on the $CO_2$ intensity of the energy source used, costs may rise to as much as USD 610 per net ton of $CO_2$ taken from the atmosphere.

**Table 5 provides an overview of the anticipated potential, operational costs, investment expenditures, major uncertainties, and stage of development of the various RM technologies currently under debate.** There are hardly any quantitative data on investment and logistics expenditures. To offset this deficit, a qualitative assessment has been undertaken (Klepper and Rickels 2011). The assessment categories are low, medium, and high. Throughout, the estimate is based on the assumption of achieving the full annual potential that is theoretically possible.

As we saw in Section 4.1.1, no standardized comparative costs can be determined for RM technologies. If we take the comparative costs from the 2009 Royal Society report (USD 200 billion per $W/m^2$) as an upper limit, technologies designed to increase the albedo in urban areas or deserts and reflectors in space can immediately be excluded from the set of economically reasonable RM technologies on the grounds of their operational costs alone. Although there are no cost estimates for technologies increasing forest or green-space albedo, their potential is almost certainly too restricted to make them efficient RM technologies that would have an effective impact on the radiation budget at the climate level.[22] If we limit our purview to operational costs, the information we have at the moment suggests that technologies for modifying cirrus and marine stratus clouds and for injecting aerosols into the stratosphere for limited periods can be viewed as cost-effective RM technologies. However, the anticipated potential effect of modifying cirrus clouds is considerably more uncertain than in the case of the other two technologies.[23]

**Operational cost estimates for technologies modifying cirrus clouds and marine stratus clouds are likely to be subject to the same kind of corrections as technologies for distributing sulfur in the stratosphere.** While these costs appear to be extremely low, no studies have in fact been published on the operational costs for modifying cirrus clouds. The estimate reported on here is based on a personal communication (Mitchell 2011), but in terms of material inputs, it does tally with the estimate in Section 3.2.3. Estimates for modifying marine stratus clouds are still based on the study by Salter et al. (2008), which was also the reference underlying the Royal Society report (2009). By contrast, publications appearing later than the Royal Society report indicate a clear rising trend for the estimated operational costs of technologies for distributing sulfur in the stratosphere.[24] Cost estimates for modifying cirrus clouds and marine stratus clouds are expected to change accordingly.

22 See Section 3.2.5.

23 See Section 3.2.3.

24 The Royal Society report (2009) estimates the annual amount of sulfur needing to be spread to bring about a compensation of -4 $W/m^2$ at 1.5 to 5 Mt of sulfur, corresponding to costs of USD 0.2 billion per $W/m^2$. More recent work has shown that a quantity of up to 75 Mt of sulfur might be necessary (Heckendorn et al. 2009; Pierce et al. 2010), but this can be reduced to 9 – 10 Mt of sulfur by extending the spreading area and delivering the chemical in the form of hydrogen sulfide.

| Technology | Anticipated potential | Operational costs in B USD per W/m$^2$ | Investment in R&D, equipment, infrastructure, and logistics | Major uncertainties |
|---|---|---|---|---|
| **SRM TECHNOLOGIES FOR REFLECTORS IN SPACE** | | | | |
| Insertion of dust or reflectors in low Earth orbit or at Lagrange point L1 | Unlimited | 1700 | No quantitative studies available; implementation costs estimated at USD 200 trillion | Insertion and capital costs (stage of development: modeling) |
| **SRM TECHNOLOGIES FOR INJECTING AEROSOLS INTO THE STRATOSPHERE** | | | | |
| Sulfur injection with existing aircraft (> 18 km) | Unlimited | 16 – 67 | Investment for fleet between USD 18 and 56 billion; additional investment per base station approx. USD 1 billion | Coagulation between new and existing particles (stage of development: modeling) |
| Sulfur injection with newly designed aircraft (> 18 km) | Unlimited | 2 – 12 | Investment for fleet between USD 6 and 36 billion; additional investment per base station approx USD 1 billion | Coagulation between new and existing particles (stage of development: modeling) |
| Sulfur injection with newly designed airships (> 18 km) | Unlimited | 5 – 18 | Investment for fleet between USD 19 and 66 billion; additional investment per base station approx. USD 1 billion | Coagulation between new and existing particles; reaching required spreading height (stage of development: modeling) |
| Release of engineering nanoparticles | Unlimited | These types of nanoparticle do not exist yet. The study by Keith (2010) assumes that the particles would hover in the stratosphere after spreading by leveraging photophoretic forces. The amount that would need to be spread would therefore drop considerably and theoretical cost savings of around a factor of 200 might be possible in terms of spreading. | | |
| **TRM TECHNOLOGIES FOR MODIFYING CIRRUS CLOUDS** | | | | |
| Seeding cirrus clouds with bismuth(III) iodide (BiI3) | -1 to -4 | 0.007 | No quantitative studies available (investment: low) | Necessary aerosol concentration and spreading frequency (stage of development: modeling) |
| **SRM TECHNOLOGIES FOR MODIFYING MARINE STRATUS CLOUDS** | | | | |
| Injection of sea salt particles from Flettner ships | -4 | 0.135 | R&D investment: USD 27 million, setting-up investment: USD 30 million; investment on fleet USD 1.7 billion; additional logistic and maintenance costs (e.g., ports) | Automatic operation of ships; deployment of Flettner rotors (stage of development: modeling with field trials planned) |
| **SRM TECHNOLOGIES FOR MODIFYING PLANETARY SURFACE ALBEDO** | | | | |
| Increase of urban albedo | -0.2 | 2000 | No quantitative studies available (Investment: high) | Renewal of coatings or material (stage of development: implementation phase to reduce energy costs) |
| Increase of forest or green space albedo | -1 | n /a | No quantitative studies available (Investment: low to medium) | Replacement of existing forests and green space (stage of development: modeling) |
| Increase of desert albedo | -3 | 1000 | No quantitative studies available (investment: high) | Maintenance and upkeep of material (stage of development: modeling) |
| Increase of ocean albedo | No studies available | | | |

TABLE 5: Overview of current operational cost estimates for RM technologies

Source: Klepper and Rickels (2011).

### 4.1.3 Price effects and economies of scale

**The estimates on the operational costs for CDR and RM technologies given in Section 4.1.2 are based on the assumption that the materials and capital goods needed to implement CE technologies can be purchased at today's prices.** They ignore the potential price effects on upstream and downstream markets that might materialize if these technologies were implemented on a global scale. If they were, demand would increase dramatically in the markets for some raw materials and goods, making price rises inevitable. Price effects would also arise on the financing side, particularly as a number of measures would involve considerable capital expenditure. Taking all this into account, capital costs could increase significantly, even if credit risks were backed by state guarantees. These market mechanisms are the main reason why the operational costs of CE technologies have been underestimated so far. Such effects also influence economic costs, which are discussed in more detail below. An assessment of welfare effects needs to consider both the negative and the positive impacts on the suppliers and buyers of the raw materials and products required in large quantities for the deployment of CE technologies.

Price effects need to be taken into account when estimating operational costs and impact on welfare

The significance of ignoring price effects can be illustrated by looking at chemically-based CDR technologies for increasing oceanic carbon uptake. To remove a gigaton of $CO_2$ from the atmosphere by spreading pulverized lime in the ocean, the quantity of lime to be moved corresponds to around 2/3 of annual global coal production. Applying calcium oxide or calcium hydroxide instead requires only 0.74 Gt of lime to remove 1 Gt $CO_2$, but the quantity of lime to be moved still corresponds to approximately 1/8 of global coal production. Additional high investment expenditure is required for calcination and processing. In addition, spreading the material would call for a fleet of ships corresponding to approximately 1/8 of current marine transport capacity. Implementing these technologies would therefore require a huge expansion of production capacity to provide capital equipment for mining and shipyards. Such expansion is more than likely to be accompanied by considerable price increases in the relevant markets.

**A28**
AMORTIZATION

Price effects expected to increase operational costs

Rising prices in the shipping market are also anticipated in connection with the modification of marine stratus clouds and iron fertilization in the Southern Ocean. However, for the latter measure, the number of ships required is considerably lower than for chemically-based technologies for oceanic carbon uptake. When it comes to distributing particles in the stratosphere, similar price effects should be envisaged in the aviation and fuel markets. As we have seen, these price effects would not only call for a revision of operational costs but also imply analogous distributional effects in other industries. Higher prices for ships would raise the operational costs for ship owners, for example, while at the same time generating higher revenues for shipyards.

Price effects imply distributional effects

**Afforestation and biochar production generate similar distributional effects as a result of land use conflicts.** Sooner or later, cost-effective afforestation measures would compete with the use of fertile arable land in food production. In many regions, the subsequent rise in food prices would also put food security at risk. Obviously, there would also be price effects in markets for $CO_2$ certificates if CDR technologies were implemented using decentralized incentive mechanisms such as assigning these certificates.

**A13**
INDIRECT COSTS UNDERESTIMATED

**The deployment of the various technologies could also generate economies of scale.** Whereas price effects would be expected to dominate in the case of proven technical components like ships and aircraft, economies of scale might be the prevailing feature of newer technology components. Therefore, over time, the costs of production for newer technology components may fall. For example, Lackner (2010) estimates that large-scale use of air capture could cause

For individual technologies, price effects may be dominated by economies of scale operational costs to fall from USD 200 to as low as USD 30 per ton of $CO_2$. It should be noted, however, that this estimate for air capture is limited to adsorption technology and does not take into account the possibility that storage costs could rise as a result of large-scale use.

#### 4.1.4 External costs

Neglecting external effects distorts basis for decision-making

**The costs of external effects are the costs incurred by those side-effects of CE technology that still have economic or ecological consequences although they are unintentional.** Side-effects can be positive or negative. If external effects are not taken into account in the cost calculation for a CE technology, the economic costs will be over- or underestimated, depending on whether the external effects are positive or negative. We can distinguish between direct and indirect external effects from CE deployment. Direct external effects relate to damage to the environment, such as that caused by spreading a material. Indirect external effects may vary on a regional basis and may be caused by feedback effects from the climate system. RM technologies entail such indirect external effects of a climatic nature. However, there are still major uncertainties about the extent of direct and indirect climatic external effects, and there are currently no quantitative studies estimating the potential economic costs of these effects.

**The extent of the external effects and the economic costs associated with them will increase in accordance with the scale of CE deployment.** If limited use is made of CDR technologies, for example in the form of small-scale afforestation, the likelihood of feedback effects tends toward the negligible. If, however, the aim is to store many gigatons of $CO_2$ on land by means of afforestation, the external effects this will have on ecosystems and biodiversity must be considered. Similarly, iron fertilization in the Southern Ocean would be expected to have a significant impact on the marine ecosystem if this option were adopted on a large-scale. However, it is not yet clear to what extent economic benefits may arise from this impact on the marine ecosystem as a result of a potential rise in fish stocks. The widespread use of air capture could lead to problems arising from $CO_2$ storage.

Much the same applies to technologies for modifying marine stratus or cirrus clouds and spreading stratospheric aerosols. If these options are implemented on a scale that would have an impact on the global climate, then side-effects must be anticipated. In the modification of cirrus clouds, the potential direct external effects are primarily limited to the properties of the particles introduced to promote ice nucleation. The spreading material proposed by Mitchell and Finnegan (2009)—bismuth (III) iodide (BiI3)—is non-toxic. Furthermore, the concentration of spreading material in precipitation is too low to represent a risk to human health (Warburton et al. 1995; Mitchell and Finnegan 2009). If the modification were discontinued, the aerosols would rain down after one to two weeks (Mitchell and Finnegan 2009). The direct external effects of introducing sea salt particles to modify marine stratus clouds also appear to be low. No extraneous material is introduced into the marine cycle, and if the measure is discontinued, the salt aerosols will rain down within a few days.[25] Spreading sulfur can have direct effects due to the impact on the ozone layer, the additional discharge of sulfur, and changes in the ratio between direct and diffuse radiation. Current knowledge leads us to expect that the direct external effects related to the substance inputs associated with spreading sulfur in the stratosphere are economically negligible, or at least that the positive external effects will probably offset the negative external effects (Klepper and Rickels 2011). Nevertheless, the high degree of uncertainty about these potential external effects necessitates further research for the economic costs to be estimated more precisely.

25 See Section 3.1.5 for details on the residence times.

**For RM technologies, the economic costs are primarily determined by external effects in the climate system.** In the case of SRM technologies, the long-wave radiative forcing induced by GHGs is compensated for by a change in short-wave radiation. In terms of the total radiation balance, a net effect of zero is induced, but other climate variables such as precipitation are compensated for in different ways.[26] The modification of cirrus clouds (TRM) is aimed at influencing long-wave radiation, but it also has an impact on the short-wave radiation. Although no studies have been published on this subject yet, changes to the regional climate and the hydrological cycle are to be expected, along with corresponding impacts on the amount of precipitation and its variability.[27] Although little is known about the varying impacts of RM technologies on regional climate, it must be assumed that economic effects can vary widely on a regional basis, too. Quantifying these effects would require the use of climate models with regional resolution, so that appropriate impact assessment studies can quantify the findings in terms of their economic consequences. However, integrated studies of this kind do not yet exist. The studies undertaken so far on different regional climate impacts show the high degree of uncertainty involved in modeling the regional effects of RM technologies.

**A12**
ONLY PARTIAL OFFSET

Economic costs of RM result mainly from varying compensation of different climate variables

## 4.2 Economic effects

The possibility of counteracting climate change by means of climate engineering raises the question of how the existing mitigation and adaptation options are influenced by the various CE technologies and what distributional effects are implied by their application (Barrett 2008; Kousky et al. 2009; MacCracken 2009). The existing literature focuses on RM technologies because, on the face of it, they represent a distinctive new option with respect to their effectiveness in influencing the radiation budget, their ostensibly low operational costs, and not least their novelty value in the climate change reaction portfolio.

### 4.2.1 Substitutionality of emission control and climate engineering

Economic implications only examined theoretically

We have seen that the available information about operational costs only allows at present for a very limited comparison with existing emission control measures. This is due to the imprecision of the relevant scientific predictions and to the fact that a number of dynamic and economic aspects have not been properly taken into consideration. **Hence, we have no empirically substantiated answer to the question whether CE technologies have a cost advantage over emission control.** Accordingly, economic analyses on climate engineering have so far been restricted to analytical approaches deriving general CE implications from theoretical models. The deployment of climate engineering is typically discussed on the basis of microeconomic partial models that minimize the total costs of abatement and damages. In these models, the abatement costs are the sum of the costs related to the application of conventional emission control and CE technologies, while the damage costs are determined as arising from climate change and CE-related side-effects. Depending on the level of detail achieved by the models, the damage costs of climate change are defined in terms of temperature change or the rise in atmospheric $CO_2$ concentration or a combination of both. Positive effects such as $CO_2$ fertilization and negative effects such as ocean acidification may be factored in.

**A9**
EFFICIENCY ARGUMENT

**A key finding produced by theoretical analyses is the substitutability of CE technologies and emission control. If CE technologies are cheap enough, they will be deployed and to some extent replace conventional emission control.** Moreno-Cruz and Smulders (2010) demonstrate

26 See Section 3.1.6.

27 See Section 3.2.3.

this for RM in a static framework. In such a static framework, CDR is hardly distinguishable from conventional emission control in terms of effectiveness. In a dynamic framework, Rickels and Lontzek (2011) demonstrate the substitution effect for CDR, an effect that makes it possible to extend the period of time in which fossil fuels can be extracted in reasonable amounts beyond what would be the case without CDR being implemented. Although both models substitute CE technologies for conventional emission control, the atmospheric $CO_2$ concentration may be lower than it would be without this substitution.

A27
NEGATIVE EFFECTS ON EMISSION ABATEMENT

Climate engineering replacing emission control to a certain extent

**The atmospheric concentration of $CO_2$ is lower when CDR substitutes emission control to some extent.** Rickels and Lontzek (2011) demonstrate that with the use of CDR, the peak atmospheric concentration of $CO_2$ is lower than it would be without CDR, given that the use of fossil fuels is defined by the scarcity of fossil reserves.[28] In a deployment scenario involving RM instead of CDR, we do not necessarily have the same result because RM mainly affects temperature. In theory, however, it is also possible to observe lower atmospheric $CO_2$ concentration while deploying RM, if the additional uptake of the natural sinks via the greater $CO_2$ fertilization effect joins with simultaneously lower temperature to overcompensate for lower emission control (Moreno-Cruz and Smulders 2010).

Influence of CDR technologies on atmospheric $CO_2$ concentration

The technical substitution effect is also confirmed in the studies by Gramstad and Tjötta (2010) and Goes et al. (2011). Both investigations consider the use of RM in an intertemporal cost-benefit analysis[29] and show the optimum to be a scenario with emission control combined with the deployment of RM, implying that a partial substitution effect takes place between emission control and RM.

A27
NEGATIVE EFFECTS ON EMISSION ABATEMENT

### 4.2.2 Climate engineering as risk management

**Replacing emission control with RM can also make sense if influence on the climate system needs to be instituted quickly.** As discussed in Chapter 3, RM enables the temperature to be lowered relatively quickly and can therefore be deployed to compensate for an unexpectedly strong temperature reaction or to prevent thresholds from being exceeded in a way that could not be achieved by intensifying emission control. In this respect, there is practically no alternative to RM because emission control and CDR are too limited in their potential for allowing quick and substantial changes in temperature. Moreno-Cruz and Keith (2009) explore this issue with the help of a dynamic model where uncertainty about climate sensitivity is revealed at a later juncture and RM can be deployed accordingly. Without RM, significantly higher emission control is required than when these technologies are available. The authors show that the availability of RM technologies can be regarded as a form of insurance against uncertain or abrupt (i.e., unanticipated) climate change.

A27
NEGATIVE EFFECTS ON EMISSION ABATEMENT

A9
EFFICIENCY ARGUMENT

Readiness for deployment of climate engineering lowers precautionary emission control

The optimal range of RM deployment is therefore higher (and the extent of emission control lower), the lower the side-effect-related damages associated with RM are and the higher the effectiveness of RM in controlling temperature is. However, if the effectiveness of the chosen RM technology is low and the side-effect-related damages are high, it is still optimal to deploy RM to some extent when climate sensitivity is high and there is a convex increase in the damages caused by climate change (Moreno-Cruz and Keith 2009). The insurance character of RM diminishes in importance as uncertainty about effectiveness and damages becomes more acute. In line with this, emissions control is then intensified again. There is thus a trade-off between

A15
LESSER EVIL

A27
NEGATIVE EFFECTS ON EMISSION ABATEMENT

28 This result assumes that the social costs resulting from the concentration of atmospheric $CO_2$ are convex. If the maximum atmospheric $CO_2$ concentration is exogenously limited by a ceiling, this ceiling should optimally also be attained when deploying CDR.

29 In both cases the model used is the Dynamic Integrated Model of Climate and the Economy (DICE) by Nordhaus (2008).

the risk of potentially catastrophic climate change and the risk of potentially far-reaching side-effects from RM deployment. On the question of combining emission-control policies with RM, Moreno-Cruz and Keith (2009) argue that the two measures are risk complements.

**The risk of deploying RM is bound up not only with its effectiveness or its potential side-effects, but also with the eventuality of the deployment being discontinued.** Although discontinuing CDR would cause economic losses due to the potentially high investment expenditures, it would have no immediate impact on the climate. By contrast, discontinuing RM would cause drastic climate change relatively quickly.[30] Goes et al. (2011) demonstrate that for a scenario where only RM is deployed, discontinuing the deployment may lead to welfare losses in excess of those arising from a scenario involving no climate change intervention at all. This finding does, however, depend on the weighting given to the speed of temperature changes in relation to general temperature change. It is nevertheless true that the insurance character of RM declines as the probability of discontinuation increases.

A28
AMORTIZATION

A13
INDIRECT COSTS UNDERESTIMATED

A18
TERMINATION PROBLEM

Possibility of discontinuous RM deployment reduces its insurance character

**Insurance against climate risks creates new dependencies because once RM technologies have commenced, they must be maintained over a long period (lock-in effect).** The work of Brovkin et al. (2009) supports these new dependencies. In their scientific study, they basically confirm that RM can provide insurance against climate risks and that lowering of temperature plus the $CO_2$ fertilization effect will reduce the atmospheric concentration of $CO_2$ from what it would be in a BAU scenario excluding RM. However, the authors also indicate that the deployment of RM will need to be maintained for several millennia if no other emission path is realized at the same time, or no other ways are found to reduce the concentration of $CO_2$ in the atmosphere.[31]

A13
INDIRECT COSTS UNDERESTIMATED

RM can result in a lock-in effect

### 4.2.3 Evaluating the long-term impact

**The lock-in effect connected with the deployment of RM and the evaluation of potential damages arising from discontinuing such technologies raise the issue of how to assess events that might arise in the distant future.** These include such things as discounting the future damages that might be incurred by discontinuing RM deployment. However, without such an assessment of events taking place at different times, we would have no way of knowing whether with CDR, carbon would be stored for a sufficiently long time. The Kyoto Protocol defines the period of 100 years as the basis for the assessment of permanence (UNFCCC 1997). In other words, if $CO_2$ is stored for longer than 100 years, this is regarded as permanent storage.[32] This definition also means that subsequent release into the atmosphere is no longer assessed as damage. In the economic analysis, the assessment of future events and with it the assessment of irreversibility and future damages are strongly influenced by the choice of discount rate.

Determining an appropriate discount rate is a central issue in the debate about mitigating climate change, and this takes it beyond the scope of the CE debate. It should, however, be kept in mind that a consumption path that grows over time is sufficient to obtain a positive social discount rate, even if, for ethical considerations, the pure time-preference rate is set at zero.[33] By contrast, a falling consumption path leads to a negative social discount rate, which means that future damages need to be assessed as higher than at present.[34]

30 See Section 3.1.6.

31 The reason for this is the relatively long residence time of $CO_2$ in the atmosphere, which over long timescales is determined mainly by the natural oceanic carbon uptake (Sarmiento and Gruber 2006). For comparative purposes, see also Section 3.3.

32 The choice of 100 years was not based on any scientific rationale but was rather a political decision (Leinen 2008).

33 The social time-preference rate depends on the pure time-preference rate, the rate of growth in consumption, and the elasticity of marginal utility.

34 For an overview of the current debate on discount rates, see Dasgupta (2008) and Heal (2009).

### 4.2.4 International conflicts of interest

**Irrespective of the time factor, global welfare does not necessarily have to increase as a consequence of CE deployment.** This was the key assumption underlying the statements we have just been making: When climate engineering is deployed, the global reduction in economic damage costs as a result of reducing the temperature or the atmospheric concentration of $CO_2$ is greater than the global damages caused by climate engineering itself. However, this condition only has to be fulfilled for a global decision on CE deployment. For a unilateral or minilateral decision on CE deployment, it is sufficient for this condition to be met at a national or regional level only. Global welfare will not necessarily increase.

A14
HARMING OTHERS
Decentralized decision-making on deployment requires local welfare gains only

**Offsetting the long-wave radiative forcing induced by GHGs by, say, increasing the reflection of short-wave solar radiation may lower the average temperature on Earth but will not uniformly compensate for all climate variables.**[35] If all climate variables are considered, the deployment of RM may lead to a situation in which welfare losses in individual regions are greater than in a climate change situation without the deployment of RM. The evaluation and optimization of global CE deployment should therefore be not only assessed with reference to the global average temperature but should also take into account other climate variables (precipitation, ice cover, etc.) and their local characteristics.

A26
DISTRIBUTIONAL EFFECTS
RM deployment may result in welfare losses for some regions

**We still do not know whether a level of RM deployment exists that generates a welfare gain for all countries.** Moreno-Cruz et al. (2010) examine whether RM can be deployed in such a way that the regional variations in temperature and precipitation changes will improve welfare in all regions worldwide. The authors come to the conclusion that it is possible to increase welfare for all regions via RM deployment. This means that all countries would have an incentive to agree to such RM deployment. According to the model underlying the study, West Africa emerges as the area most sensitive to RM deployment and hence as the limiting region over and against global optimization. With global optimization, the resulting aggregate global welfare gain would be larger, but it would also involve welfare losses in individual regions.

A26
DISTRIBUTIONAL EFFECTS

**Their model result is, however, based on relatively restrictive assumptions.** The assessment criteria and the weighting given to temperature change compared to changes in precipitation definitely require more detailed debate. For some regions, for example, the deviation in temperature weighs more heavily than the deviation in precipitation, whereas in other regions the opposite is true. For some regions, the situation will not potentially worsen if they deviate from their original state due to an increased concentration of GHGs. It remains uncertain whether RM deployment can achieve a positive effect on welfare for all regions if different climate variables are taken into account with their relative changes and with a weighting adjusted to the specific region. Considering that individual regions may actually benefit from climate change, it seems unlikely that an level of RM deployment could be found that all countries would accept.

A26
DISTRIBUTIONAL EFFECTS
Existence of a globally accepted level of RM deployment unlikely

**The question of global or regional welfare changes basically raises the question of the optimal level of compensations in the radiation budget.** There is no study that discusses minimum or maximum limits for modifying the radiation budget, particularly through RM, with regard to set-up costs, risk assessment, or other aspects. Moreno-Cruz et al. (2010) do, however, demonstrate that different levels of CE deployment are optimal for different regions. Ascertaining "optimal" CE deployment when decisions are taken on a decentralized basis poses numerous issues of a political and economic nature. For example, it is vital to explore whether countries have any incentives to embrace unilateral CE initiatives or whether they

"Optimal" CE level varies by region

35 See Section 3.1.6.

should proceed with a multilateral solution. There are also strategic interactions between countries that affect decisions on possible CE deployment and emission control. These aspects are analyzed in Chapter 7.

#### 4.2.5 Strategic benefits of CDR

**CDR deployment has strategic efficiency advantages over emission control.** Emission control reduces demand for fossil fuels, causing their global market price to fall. If emission control is introduced unilaterally or minilaterally, the lower global market price will mean that non-participating regions will use more fossil fuels and that their emissions will increase accordingly (e.g., Markusen 1975; Sinn 2008; Frankel 2009; Eichner and Pethig 2011). This international carbon leakage is defined as the relationship between the rise in emissions by non-participating countries and the reduction in emissions by participating countries (Barker et al. 2007). Another problem associated with emission control lies in the fact that instruments such as emissions trading or taxes on carbon or energy only influence the demand side for fossil fuels and take no account of the supply side. For this reason, the consumption of fossil fuels will not necessarily decline over the long term. Instead, consumption is simply brought forward (Sinn 2008; Edenhofer and Kalkuhl 2009).

CDR deployment allows these effects to be circumvented, because they involve no change in the demand for fossil fuels. So unlike emission control, they are also effective on a unilateral or minilateral basis. This finding has not yet been explicitly explored with reference to CDR, but it can be extrapolated from research on CCS. Quirion et al. (2011) show that in a scenario restricting emission control to OECD countries, international carbon leakage can be more than halved when CCS is combined with emission control.

CDR deployment helps to circumvent international carbon leakage problem

#### 4.2.6 Divergent generational interests

**Attitudes toward climate engineering and the deployment thereof are likely to vary more than just by country.** Different generations may also have different views on climate engineering, which may have special implications for decision-making in connection with research on climate engineering. Goeschl et al. (2010) demonstrate that a different assessment may well mean that as well as refraining from research on CE technologies, the present generation is opting for more stringent emission control to reduce the probability of subsequent CE deployment. The current generation has an incentive to refrain from research if it is conceivable that the subsequent generation will not only deploy climate engineering as an insurance against catastrophic climate damage but may also wish to deploy climate engineering as a substitute for emission control in the event of lower climate sensitivity. Conversely, however, the situation may also arise that—from the perspective of the second generation—emission control is found to have been set too low and because research has been conducted on climate engineering, this generation may then to some extent feel duty bound to deploy those technologies.

A1
NEGATIVE EFFECTS ON EMISSION ABATEMENT

A34
AVOIDING DILEMMAS

#### 4.2.7 Research on climate engineering

**Overall, the issue of research on climate engineering is not yet being appropriately addressed from an economic perspective.** Above all, no thought has been given to the optimal time for research on climate engineering. Gramstad and Tjötta (2010) demonstrate, however, that the welfare losses incurred by delayed deployment over and against optimal use of RM are still relatively low. Depending on the development times estimated for the various technologies, it could be argued that at present there are viable alternatives to embarking on RM research without delay.

A7
POSTPONE RESEARCH

Postponing research on RM

The analysis by Brovkin et al. (2009) has shown that without additional measures to lower the concentration of atmospheric $CO_2$, RM will potentially need to be deployed for several millennia. This may generate substantial feedback effects in the climate system. Research will never be able to entirely remove the uncertainties involved before this process begins. Accordingly, the deployment of RM might trigger a situation involving substantial medium-term economic costs, if the climate system responds differently from the way it was expected to and the unwanted side-effects are larger than anticipated. The economic costs resulting in this way might even exceed the economic costs incurred if the RM deployment was discontinued despite persistent GHG-induced radiative forcing (Goes et al. 2011).

Readiness of CDR deployment a condition for RM deployment

It follows from this that RM should only be used as insurance against the risks of climate change if, at the same time, CDR technologies exist that enable RM to be deployed for a limited time. This scenario has not yet been examined, however. By contrast, Barrett (2009) argues that in terms of the increasing risks associated with advancing climate change, deferring or limiting research on RM technologies is unjustifiable. More generally, we need to bear in mind the fact that decisions pertaining to research on climate engineering cannot be made in isolation from decisions on emission control (e.g., Goeschl et al. 2010).

## 4.3 Implementing CE technologies

### 4.3.1 The role of scales

Small-scale opportunities for implementation not adequately considered so far

**The various studies on climate engineering so far have almost entirely neglected the role of scales as an important factor influencing effectiveness and side-effects.** For example, it may be possible to implement small-scale CE projects without any appreciable side-effects, whereas large-scale implementation could involve high operational or external costs.[36] In the case of afforestation, local projects may efficiently supplement conventional emission control. However, large-scale afforestation would prevent efficient deployment due to the operational costs of irrigation alone.[37]

The extent to which specific CE technologies can be implemented on a decentralized and small-scale basis is determined by technical and scientific factors. Making effective use of RM technologies to modify marine stratus clouds or cirrus clouds, or to inject aerosols into the stratosphere, calls for international coordination and agreement. Implementing oceanic iron fertilization on a decentralized basis does not seem realistic either, because effective deployment requires the fertilization area and frequency to be centrally coordinated.

Biochar production, air capture, and a change in albedo of urban areas and green spaces can be realized in a decentralized way by means of incentive schemes

By contrast, the use of air capture or the production of biochar both appear suitable for decentralized implementation in an appropriate regulatory framework. In terms of project scope, these measures can be realized by individual stakeholders. The same applies to modifications to the albedo of houses and green spaces, which can also contribute to mitigating local heat islands.[38] Chemically-based CDR measures for increasing oceanic carbon uptake, such as spreading lime or calcium oxide/hydroxide, appear to require less central coordination than oceanic iron fertilization because storage does not require a biological reaction. Spreading pulverized lime could potentially be realized on a small scale in response to a system of incentives, particularly as shipping is relatively unevenly distributed across the different routes worldwide.

36 See Section 4.1.4.

37 Based on the study by Ornstein et al. (2009), Klepper and Rickels (2011) estimate that with large-scale afforestation in the Sahara or large parts of Australia, the operational costs associated with complex irrigation could amount to more than USD 1000/t $CO_2$ even without considering capital costs.

38 See Section 3.2.5.

### 4.3.2 Instruments for CE deployment

Almost no research whatsoever has been done on the issue of the political instruments that could be used to implement CE technologies. Lack of clarity as to the role of economic policy instruments or regulatory provisions still holds with regard to many CE technologies. Another deficit makes itself felt when it comes to examining the issue of whether CE measures should be carried out by companies or government institutions.

Quantification and verification essential for issue of $CO_2$ certificates

**CE technologies that can be realized by individual stakeholders can be encouraged by means of monetary incentives such as $CO_2$ certificates.** A prerequisite for the introduction of such incentives for CDR technologies is that carbon uptake be quantifiable and verifiable. Technologies for land-based carbon uptake like air capture or biochar production make it relatively easy to quantify the carbon uptake. By contrast, even applying a technology like spreading olivine would cause problems, because the amount of carbon stored cannot be verified by measurements or sampling. Instead, it has to be estimated on the basis of the quantity of olivine that has been spread. Nor is it feasible to directly measure the amount of carbon stored as a result of spreading calcium oxide/hydroxide in the ocean. Again it would have to be estimated based on the quantity spread. For these technologies, however, the underlying chemical reactions are relatively well understood, which makes it easier to estimate average oceanic carbon uptake. However, due to regional variations in ocean circulation or actual concentrations, uptake as a result of a specific instance of spreading may vary widely. While it does seem possible that average figures could be agreed on, they would have to be related to the respective region and the spreading frequency.

The situation is even more complex for technologies requiring a biological reaction, such as oceanic iron fertilization. For oceanic iron fertilization, various companies have tried to put $CO_2$ credits on offer in voluntary $CO_2$ offset markets[39], but none of these credits are officially recognized by an emissions trading scheme. Although Rickels et al. (2010) show on the basis of a model how $CO_2$ certificates can be issued for oceanic iron fertilization, they also point out that effective realization and verification is only possible as part of a centrally coordinated project. Nor should we forget that the certification schemes currently in existence does not consider how other carbon sinks will react. If, for example, oceanic carbon uptake is increased by spreading calcium oxide or iron sulfate, the natural uptake of terrestrial sinks would decline due to the lower $pCO_2$ gradient. This effect is negligible in connection with individual small-scale projects, but as part of a decentralized incentive strategy it needs to be borne in mind with respect to the total amount of certificates.

No climate policy instruments for RM technologies so far

**In connection with RM technologies, we cannot draw upon existing climate policy instruments because of the different characteristics they display.** In principle, this poses two problems: (i) a scale would need to be found that would enable us to gage the effectiveness of global RM, and (ii) this measurability must be valid for individual technologies. The difficulty lies in evaluating RM relative to CDR and conventional emission control. As set out in Section 4.1.1, comparing RM with CDR or emission control requires a reference period and reference concentration for atmospheric $CO_2$. We cannot define these referential factors unequivocally on the basis of scientific findings alone. A political decision is imperative.[40] Similar political decisions have been taken on comparing different GHG emissions. Here, the effect of the different GHGs on the retention of long-wave thermal radiation in relation to $CO_2$ is weighted over a period of 100 years (UNFCCC 1997).

Political definition of comparative metrics

39 In such voluntary markets, people are able to compensate for their own GHG emissions by acquiring credits for their share of emissions from a flight, for example.

40 See also Requirement 4 in Section 7.4.

## 4.4 Summary of economic aspects

Cost of CE technologies systematically underestimated

**CDR and RM technologies do not just differ in terms of how they work, they also have different economic characteristics. Cost estimates for deploying the various CE technologies involve not only a high degree of uncertainty, they are also too low across the board.** The estimates in the existing literature are limited to operational costs, with capital costs only partially taken into account. Additionally, a variety of factors that influence costs have simply been ignored. Price effects on markets for raw materials and supplies for CE technologies, or feedback effects from one market onto others due to competition for natural resources have yet to be considered. There has also been little quantification of the economic costs arising from external effects.

One feature of the costs generated by many CDR technologies is that they require high investment in infrastructure and in some cases large amounts of material. The resulting price effects have not been adequately taken into account in the literature and are likely to produce higher operational costs than previously assumed. However, external costs resulting from conflicts over land use and the impact on ecosystems are expected to be low if CDR technologies are only deployed on a small-scale. The role of scales for the various CDR technologies has not been explored adequately.

Economic models suggest that the deployment of CDR would lead to less emission control. Nevertheless, the concentration of atmospheric $CO_2$ would be lower than without CDR deployment. This is the fundamental difference between CDR and RM deployment, which also occasion a reduction in emission control but do not result in a decrease in the concentration of $CO_2$ in the atmosphere.

A13
INDIRECT COSTS UNDERESTIMATED

High risk associated with RM in terms of economic costs

In many studies, RM technologies are regarded as relatively cheap in comparison with emission control. This comparison fails to appreciate the fact that external costs and intertemporal effects have not been taken into account. The external costs, the potential costs of the long-term use that would need to be made of RM, and the costs that would arise from discontinuing RM are largely unknown. In particular, the external costs arising from regional side-effects might become a key factor in the overall economic costs. At present, our knowledge of the economic costs associated with RM deployment is inadequate because of the unpredictability of potential side-effects. Under these circumstances, the deployment of such technologies seems very risky.

A15
LESSER EVIL

Insurance by RM

**On the one hand, there are uncertainties about the economic costs of RM. But there are also uncertainties connected with unabated climate change.** The latter uncertainties are most likely to come to a head if international climate policy is unable to reduce emissions sufficiently to a level that would obviate the risk of exceeding those thresholds referred to as “tipping points” for the climate system.[41] Potentially, the economic costs associated with exceeding these thresholds could exceed the economic costs of RM deployment. Accordingly, economic models indicate that even with the potentially high economic cause involved, RM deployment could be beneficial because it can deliver results quickly.

Definition of an upper limit for influencing the radiation budget by RM in analogy to the 2° C limit

To a certain extent, RM technologies represent a form of insurance against the risk of abrupt climate change and the serious damage associated with it. At the same time, though, the existence of such an insurance lessens the incentive to undertake appropriate emission control at an early stage in order to avert potentially abrupt climate change in the first place. This of course increases the risk of abrupt climate change. We have no risk analyses dealing with how

41 See Section 3.1.4.

these effects interact. These uncertainties could however be offset to some extent by setting an upper limit on the direct manipulation of the radiation budget via RM, similarly to the way in which the 2°C target has been defined as the upper limit for temperature change.

So far there have been no proposals as to how climate policy instruments could be designed to effect the implementation RM technologies. The metrics needed to compare the impact of RM technologies with that of CDR technologies or emission control cannot be defined on the basis of science alone. What is needed is a normative decision of a kind that can only be taken by political bodies.

On the whole, virtually all economic analyses show that climate engineering and emission control must not be viewed in isolation. Their effects interact with one another. Both in terms of the economic consequences of deploying individual CE technologies and the interaction between various climate policy measures, there are substantial knowledge gaps that need to be bridged by research before any conclusions can be reached as to whether a specific CE technology may prove economically advantageous in a specific future situation.

# 5 Risk Discourses and Public Participation

Uncertainty is a key factor influencing social acceptance of CE technology

**Uncertainty about the potential risks of climate engineering is one of the most significant factors determining its acceptance by society.** As outlined in Chapter 3, quantifying these risks is difficult, as climate engineering involves major interactions between human interventions and natural phenomena. Gaps in our current state of knowledge make it difficult, if not impossible, to estimate the likelihood of individual CE technologies causing particular effects, the intensity of those particular effects, or the severity of the damage these effects would cause. The very possibility that application of CE technologies could cause extremely severe damage—on the scale, say, of a major nuclear disaster—might be reason enough to forgo using them, even if the probability of such a disaster actually occurring is estimated to be extremely low. Analyses of the risks posed by CE technologies have been founded on plausible (but still unverified) assumptions, with most analyses using Bayesian or portfolio approaches and expert best estimates to gauge the risks.

**AC11**
CRITICISM OF TECHNOLOGY AND CIVILIZATION

**The perception of these risks by the public and the media is, however, not only influenced by scientific opinion.** It is also the product of personal values/opinions and general attitudes towards risk. Arguments based on natural ethics or theories of justice must also be taken into account. They are quite likely to materialize, and in some cultures they may go hand in hand with a general distrust of technology or even of civilization in general.

## 5.1 Societal perception of risks

Objective probabilities are of subsidiary importance for public perceptions

**Only to a minor extent are public perceptions of risk determined by the objective probability of particular outcomes.** Perceiving risks in terms of impending disasters influences their assessment of technological risks. Cases in point are large-scale installations such as nuclear power stations, chemical manufacturing sites, or other man-made sources of risk that can have potentially grave effects on humans and the natural environment. The prospect of being exposed to such effects makes many people feel threatened and powerless. Most of us feel more severely threatened by potential sources of danger that might catch us unawares than we do by constant sources of danger or hazards that give us sufficient time to avert damage once the event has occurred (Renn et al. 2007).

Before we can discuss the analytic, normative, and psychological aspects of risk management, we need to clarify the **social definition of desirable and undesirable effects and a number of other issues** (Renn et al. 2007: 21f). One important question is who actually determines what is or is not desirable. It is often the case with certain CE technologies that some groups or states will perceive particular effects as beneficial, while others will perceive them as detrimental (e.g., fewer days of sunshine in a particular tourist area). This issue plays a major role in appraising the effectiveness and efficiency of various CE technologies.[42] Another important issue is how to determine the quality of effects and the significance of different hazardous factors in the overall definition of risk.

**A25**
SOCIO-POLITICAL UNCERTAINTIES

**The discussion of research on, and possible deployment of, CE technologies may provoke powerful responses from the public and the media. For this reason, their potential for social conflict is huge.** Conflicts over public goods such as the climate are particularly difficult to resolve, as individual stakeholders, including states, have virtually no incentive to provide the

42 See Chapters 3 and 4.

collectively desirable outcome on their own. It is therefore necessary for all stakeholders to cooperate with one another (see Ostrom et al. 2002 and Renn 2010). Furthermore, conflicts over global public goods are characterized by very diverse interests on the part of the stakeholders involved and by cultural and political circumstances. For example, the conflict caused by the search for a suitable location for $CO_2$ capture and storage (CCS) can be identified as a typical distribution conflict. The public perceives that the distribution of costs and risks is unequal: the risk is borne by a few, while many others, or the community as a whole, reap the benefits (Rosa 1988).

**Some CE technologies may harbor insidious hazards.** To cite one example, the use of sulfur to modify the stratosphere may involve health risks. Experience with environmental contamination resulting from human activity (pesticide residues in drinking water, genetic engineering, etc.) reveals that risks of this kind are intuitively perceived to be particularly severe and are often feared more than comparable risks posed by everyday routines or natural sources. For example, the risk of contracting cancer as the result of being exposed to environmental pollution causes greater fear than the risk of contracting cancer as the result of smoking cigarettes. This is because people fear invisible risks more than the visible risks. Accordingly, it is in line with human psychology for a person to fear the risks posed by genetically modified food and at the same time to indulge in risky behavior like speeding (Renn and Rohrmann 2000).

Potential demands for “zero-risk” approach

**In assessing risks that are not discernible via the senses, people depend on experts for information.** When people do not trust the institutions whose job it is to provide the necessary information, conflicts will result. Most people demand a **zero-risk approach if they do not trust those institutions.** The risk managers responsible are not trusted to weigh up risks objectively. Accordingly, people are not willing to accept any degree of risk at all for the purpose of achieving a given benefit (Renn 2005). **Those who do not trust CE experts will reject any technology they propose, regardless of the actual level of risk involved.**

Trust in controllability of technologies has dwindled

Generally speaking, perceptions of risk are influenced far more by epistemic trust than by social trust (Sjöberg 2008). This means that a general trust in science is more important than trust in a particular scientist or institution. **In Europe, general trust and the associated belief in our ability to control technologies has dwindled dramatically in recent decades** (Scheer and Renn 2010). This fact highlights the significance of scientific communication, both in general and in connection with acceptance issues. In addition to the more technological types of risk, the greatest risk for society is seen to be the eventuality that communication on the subject of climate engineering might lessen the perceived urgency of preventing climate change (moral hazard) and thus exacerbate the actual risk of climate change. In this context, Grunwald (2010) observes that communication of risks must be handled responsibly and very carefully, indeed. He insists that the perceptions and acceptance of the public and the impact of risk perception on people’s behavior should be considered and lessons learned from it for the management of communication and participation processes.

## 5.2 Societal risk discourses and risk perception in the social sciences, the media, and the public sphere

### 5.2.1 The social sciences

Paucity of social science studies relating to climate engineering

**So far, only a handful of social science studies dealing with “climate engineering” or “geoengineering” have been published.** Studies outside the domain of the natural sciences still focus mainly on areas like international relations, governance, ethics, and economic analysis, although current research projects at Heidelberg's Marsilius Kolleg Advanced Research Center do encompass some sub-projects involving sociological perspectives.

**The few existing social science studies on climate engineering mainly consist of articles weighing up the pros and cons of climate engineering on the basis of theoretical considerations or arguments derived from parallels with other sectors of technology.** They also examine the resonance of such arguments in the political sphere and among the wider public. It is generally assumed that public acceptability problems associated with RM technologies, in particular, might actually prevent them from materializing, but some CDR technologies would also be affected. Jackson and Salzmann (2010) doubt whether the public will ever accept RM technologies as reflectors in space and the spreading of nanoparticles in the stratosphere, or CDR technologies such as ocean fertilization. They recommend forest protection and afforestation, the industrial capture of $CO_2$, and the use of bioenergy in combination with CCS as alternative options. But they also remark that actual cases in the Netherlands and Germany indicate that major public opposition to CCS must be reckoned with. Their conclusion is that the CE debate should focus on the technologies with the best chances of being accepted by the public (Jackson and Salzmann 2010).

Concern about risks hinders public acceptance

**The assumption widely held in the current literature is that the factors militating most strongly against the acceptance of CE technologies by the public are (i) concerns about the impossibility of gauging the risks involved and (ii) ethical, legal, governance-related, and geopolitical concerns.** Related to the risks involved, a number of potential risk areas have been identified, ranging from the mere preparation of CE experiments to the political realization of CE technologies, the impact of climate engineering on political stability, the possible interruption of CE deployment, and the misuse of the CE technologies (Grunwald 2010; Scheer and Renn 2010; Corner and Pidgeon 2010). In the context of the political realization of CE technologies and its impact on political stability, the unilateral deployment of these technologies is perceived as particularly critical and potentially disastrous in its consequences (Corner and Pidgeon 2010). It follows that the acceptance of these technologies by the public will depend not only on how it precieves the risks involved, but also on how much it trusts the institutions involved, on how transpart CE activities are, and on the nature of the liability regimes established (Jackson and Salzmann 2010; Bracmort et al. 2010b).

The acceptance of CE technologies is also hindered by potential physical health issues and psychological problems. The latter might materialize if RM deployment caused more vibrant sunsets or duller skies (Scheer and Renn 2010). Moreover, concerns that the prospect of CE deployment might undermine sensitivity to the need for sustainable patterns of production and consumption are a crucial factor for public acceptance. Further, these concerns are not restricted to actual deployment; it has also been asserted that mere CE research itself might be enough to undermine other efforts undertaken to avoid climate change (Corner and Pidgeon 2010). This state of affairs might also be exacerbated by lobby groups who have no interest in reducing emissions (Corner and Pidgeon 2010). However, studies also reveal that the opposite might be the case. Low acceptance of CE technologies or fears that these technologies could actually be deployed might also step up efforts to reduce emissions. Climate engineering would effectively act as a catalyst for a form of social engineering, a process that would be open to criticism on moral grounds (Corner and Pidgeon 2010).

Work carried out by the Royal Society has yielded interesting results on the topic of acceptance and public dialogue. In its report, we find the results of a preliminary study based on discussions between focus groups representing various public attitudes to climate engineering. The focus groups were stratified in terms of environmental beliefs and behaviors and discussed potential risks, benefits, and areas of uncertainty in relation to various CE technologies (Royal Society 2009: 43). The study revealed that the perceptions of climate engineering among the focus groups were largely negative. In the light of these results, the Royal Society recommends that further and more thorough investigations of public attitudes, concerns, and uncertainty as regards climate engineering be conducted parallel to technological R & D work and a public dialogue with citizens. Similar recommendations can also be found in other publications. The American Meteorological Society, for example, has recommended that the scientific and technical exploration of the potential of CE technologies should be accompanied by broadly based studies of their social and ethical implications (AMS 2009).

Necessity for early public involvement

**The acceptance problems arising in connection with CCS demonstrate the necessity of involving stakeholders and affected citizens at an early stage** (Schulz et al. 2010; Bracmort et al. 2010b; Corner and Pidgeon 2010). Such involvement would not only generate acceptance, it would also help in assessing the degree of tolerance present and in pinpointing potential sources of controversy between those who bear more than their fair share of the risks and those who stand to benefit (Schulz et al. 2010). This would call for a dialogue between scientists and academics, political decision-makers, and the general public (Bracmort et al. 2010b). An international public dialogue in the form of a direct participative model should be initiated as rapidly as possible, before large-scale CE experiments are initiated. The public should play an active advisory role throughout the period during which scientific research and development is going on and, even more importantly, before any significant CE intervention materializes that is driven by commercial interests. Deliberative workshops (similar to focus groups) and citizens' juries (similar to planning cells, with a panel of citizens selected on the basis of certain criteria to represent the fundamental spectrum of opinions and attitudes present in the population) have been recommended as formats facilitating such participation (Corner and Pidgeon 2010).

**A dialogue of this kind must be informed by an awareness that risk cultures and world views vary.** Attitudes toward the deployment of technologies such as genetic engineering may differ from one country to the next (Scheer and Renn 2010; Corner and Pidgeon 2010). It is also important to evaluate individual CE technologies in order to determine the scale of the opportunities and risks they pose, the extent to which the public trusts the science involved, and the effects of the technologies on social justice, as these technologies are part of a broader strategy designed to mitigate anthropogenic climate change (Jackson and Salzmann 2010).

### 5.2.2 The media

Increased media coverage of CE debate in the past two years

**The number of articles published in the media show that the CE debate has reached an increasingly wide audience in the last two years and that scientific and political interest in climate engineering is gradually increasing.** This has, however, mainly been the case in English-speaking countries. An international comparison of English-language articles shows that the largest number of newspaper articles (in print and online) on climate engineering have appeared in the UK, followed by the USA, Canada, and Australia (Buck 2010). Asian countries such as Korea and China rank much further down the list. Media debate on climate engineering in Germany has been slow to gather speed, and it has been mainly skeptical and apprehensive. In the USA, by contrast, a number of CE options have been advocated without reservation. The same contrast between US and European attitudes can also be observed in connection with other risk topics, such as green genetic engineering. Over the last few decades, Europeans have rapidly lost confidence in the powers of technology to deal with complex problems, in particular in comparison to US Americans (Scheer and Renn 2010).

The number of articles on climate engineering published in the media increased following the publication of the Royal Society Report in September 2009 and again at the end of October 2010, after the publication of the findings of the 10th Conference of Parties to the Biodiversity Convention (COP 10). The media interpreted the results of this conference as imposing a general moratorium on research into and deployment of CE technologies and as a milestone in the history of climate protection (Mihatsch and Messina 2010). But it is very hard to see why. The conference proceedings merely suggest that the precautionary principle should be applied.[43]

A8
MORATORIUM

**Currently, media coverage on climate engineering is usually triggered by new books, articles in specialist journals, conferences, and scientific experiments.** Most articles quote scientists engaged in climate engineering research or "climate engineers" who have developed or proposed CE technologies. Other articles quote experts from the fields of law, political science, the social sciences, philosophy, or ethics, with a small number of figures from business also receiving a mention, especially Bill Gates (in connection with his investment in a cloud-seeding research project). Politicians and other stakeholders are seldom quoted. Ordinary citizens are almost never quoted, which is rather unusual for media coverage of risk discourses of this kind (compare, for example, the coverage of genetic engineering or electromagnetic fields).

**The injection of sulfur into the stratosphere is the technology most frequently discussed in the media, followed by cloud seeding and ocean fertilization with iron.** Afforestation, reflectors in space, and painting roofs white have been given less attention. The concerns expressed most often in relation to these technologies can be summed up as follows: the technologies are thought to pose incalculable risks and to have the potential to alter ecosystems and thus affect biodiversity. RM technologies are felt to be not only dangerous because they might affect regional rainfall, but also ineffective in addressing the fundamental problem, namely the elevated concentration of greenhouse gases in the atmosphere. The "moral hazard" argument is often advanced: CE technologies might occasion greater carelessness in dealing with greenhouse gas emissions. In addition, concerns have also been voiced that CE technologies might prove too expensive. Concerns about misuse of the technologies and the conceivable social and political impacts resulting from misuse have been conspicuous by their absence.

AC7
RISK ETHICS

A12
ONLY PARTIAL OFFSET

A1/A27
NEGATIVE EFFECTS ON EMISSION ABATEMENT

A13
INDIRECT COSTS UNDERESTIMATED

AC12
GEOPOLITICAL OBJECTIONS

A29
DUAL USE

**Media coverage tends to stress the urgency of finding a solution to the impending "climate catastrophe,"** with CE technologies frequently being seen either as an additional option supplementing mitigation and adaptation or as a necessary lesser evil to be fallen back on if it should prove impossible to impose a limit on emissions. Fairness issues are frequently broached, along with the question of which countries would stand to win or lose if certain CE technologies were deployed. It is frequently assumed that the countries responsible for greenhouse-gas-induced radiative forcing would profit from CE deployment, while developing countries would suffer. Media coverage also touches on the question of how CE deployment could be regulated, controlled, and authorized.

A26
DISTRIBUTIONAL EFFECTS

Media coverage also repeatedly uses metaphors from the field of medicine. The Earth is seen as a "sick patient" who could conceivably be "healed" by climate engineering. Words such as "symptoms", "treatment", "side-effects", and so on are also used. Most reports are couched in a neutral style, although more critical undertones are sometimes to be heard (e.g., "tinkering" or "messing with the planet"). On balance, only a small part of the coverage expresses open and direct opposition to climate engineering. It is, however, true, on the other hand, that the number of articles explicitly arguing in favor of CE technologies or deployment is even smaller.

A16
SICK-PATIENT ANALOGY

Frequent metaphor: the Earth as a "sick patient"

43 See Section 6.5.

**Sometimes media reports also claim that there is a lack of transparency in the CE debate.** The German media leveled this kind of criticism particularly at the LOHAFEX project, although the scientists involved insisted that they had carried out the project in a very transparent manner. While the negative responses to the project dwindled quite quickly in 2009, media reporting in 2010 continued to cite LOHAFEX as a negative example of CE deployment.

An analysis of readers' comments in online articles and blogs shows that their most frequent concern is that as a result of research on CE technologies and their subsequent availability, climate change itself might appear to be less threatening, which would alleviate the pressure on politicians to make further progress in the quest for alternative sources of energy. In addition, many commentators doubt whether the global climate is really changing, often using phrases like "the global warming lie" or "climate myths". On balance, the majority of comments are critical, with only about five percent of them advocating climate engineering.

**A1**
NEGATIVE EFFECTS ON EMISSION ABATEMENT

Climate engineering reduces scare potential of climate change

### 5.2.3 Stakeholders

**Stakeholder analysis is designed to provide an overview of all the internal and external opinion leaders who influence the coverage of a given topic in the media,** even though only a few CE stakeholders have actually presented their views there. In the following, stakeholders are defined as political representatives, nongovernmental organizations (NGOs), individual citizens, and other advocacy groups with an interest in the effects of potential CE technologies.

Few statements from CE stakeholders in the media

The Action Group on Erosion, Technology, and Concentration (ETC Group) is the initiator of the global campaign "Hands Off Mother Earth!" (H.O.M.E.) and is one of the few stakeholders actively opposing climate engineering. Critical comments from this quarter were first heard in Germany when the LOHAFEX project was initiated (ETC Group 2009b). The report that appeared on 18 October 2010, "Geopiracy—The Case Against Geoengineering," also deserves mention (ETC Group 2010c). In addition to the ETC Group, the Green Action campaign has also attempted to heighten awareness of the topic in Germany: "Stop looking the other way! Geoengineering and aerosol crimes!" (Green Action Group 2010).

**Leading NGOs such as Greenpeace Germany, Robin Wood, the German branch of Friends of the Earth (BUND), and NABU, another organization concerned with nature conservation and biodiversity, have not yet issued statements or informative literature on climate engineering.** Criticism of CCS is, however, widespread on German websites (see Greenpeace 2010; Robin Wood 2011; BUND 2010) with only NABU (2011) voicing the opinion that its deployment might be acceptable under certain circumstances. The climate protection organization Germanwatch has drawn attention to the risk of unintentional consequences and the danger that individual countries might misuse the technology for their own purposes. As an alternative to climate engineering it advocates greater efforts to avoid emissions.

No statements from German NGOs on climate engineering

**Greenpeace UK has taken a much more active stand against climate engineering, referring to its hazardous nature and its irreversibility as the reasons for doing so.** The organization argues that research funding should be diverted to other areas of environmental research and that emphasis should be placed on avoiding emissions, for example by the use of solar and wind energy. Greenpeace and other international environmental action groups have publicly criticized the LOHAFEX project, alleging that it pollutes the ocean and contravenes international agreements.[44] Such impressions are fueled by individual politicians insisting that consensus should be reached rapidly on climate engineering and other climate issues or

**AC7**
RISK ETHICS

44 A leading Greenpeace UK scientist wrote: "The scientist's focus on tinkering with our entire planetary system is not a dynamic new technological and scientific frontier, but an expression of political despair." Parr 01/09/2008.

pressing for near-term deployment of climate engineering. Similar impressions result when the effects of CE technologies on human society and the ecosystems of the planet are intentionally left out of consideration and the long-term outlook disregarded. This is true, for example, of statements made by Bjorn Lomborg, a scientist known for his skeptical views on climate change. Broder (2009) summarizes Lomborg's main conclusion succinctly: "The most cost-effective and technically feasible approach is through geoengineering, the use of technology to deliberately alter the Earth's climate."

This conclusion has been fiercely criticized by other scientists. Robock (2009), to name only one, has called it: "A biased economic analysis of geoengineering." Marshall (2009) has advanced similar arguments:[45]

A13
INDIRECT COSTS UNDERESTIMATED

> Lomborg's endorsement immediately made the thesis suspect in the eyes of many environmentalists. The fact that the paper was co-authored by an assistant professor of the Department of Petroleum at the University of Texas and a fellow at the conservative American Enterprise Institute (a bastion of global warming deniers) didn't help its credibility. Nor did the fact that geoengineering was endorsed as a 'political ploy' by a spokesman for the British coal industry, who wrote, the geo-engineering option provides the needed viable reason to do nothing about [human-caused global warming] now.

Lomborg's critics are not convinced of the collective net value of CE deployment for the population. The "real" motivation behind this analysis is perceived as resulting from self-interest and alliances with coalitions close to industry. In addition, this argumentation is close to the slippery-slope argument, which suggests that research and development makes the deployment of a technology inevitable. Accordingly, the optimistic outlook adopted by Lomborg and others is not shared unreservedly in the scientific community. Many scientists still display a cautious wait-and-see attitude, while others are actively skeptical.

A4
UNSTOPPABLE DEVELOPMENT

**On balance, all stakeholders see the CE topic in the broader context of climate and climate change.** Aspects of mitigation and adaptation to climate change are also considered. As CE deployment could take place over a timescale of several hundred years, many actors are reluctant to concede that such technologies could be (or could be seen as) a "bridging technology." At any rate, the subject continues to provide a considerable amount of fuel for political debate among those involved or interested in the topic (Titz 14.01.2011).

Stakeholders see climate engineering in climate context

### 5.2.4 Public perception

**Surveys in the USA have shown that 74 percent of those questioned have never heard of climate engineering and only 3 percent had a realistic idea of what it actually is** (Leiserowitz 2010). As the level of media coverage in Germany is lower, it can safely be assumed that knowledge and awareness of climate engineering are even more limited here. Although comparitive surveys do not yet exist, it is fair to assume that the majority of the German population currently either have no opinion on climate engineering or view it with caution and skepticism. Further, it is likely that increasing media coverage, especially relating to the risks and the moral hazards implicit in CE technologies, will lead to increased skepticism about, and hostility toward, climate engineering. The controversial discussion on the LOHAFEX project has already provided evidence for this claim, albeit on a small scale. The debate and the attitudes of those involved were influenced by critical opinions and opposition to the project voiced online.

Public knows little about climate engineering; attitudes typically hostile

**Questioning focus groups to ascertain public attitudes to climate engineering was part of the work carried out for the Royal Society report and showed that attitudes to CE technologies**

A20
NO IRREVERSIBLE INTERVENTIONS

45 See also the blog entry by Romm (2009).

**in Britain are also predominantly negative**, although acceptance varied dramatically among the participants. The reasons for concern referred to were very diverse and closely geared to the precise technology under consideration. Some of those questioned, for example, had fundamental ethical objections to all forms of climate engineering, while others had none. In addition, a small-scale telephone survey involving 1,000 participants was conducted on behalf of the Royal Society. Responses to this survey were particularly negative whenever the interviewers touched on technologies for the modification of the stratosphere. 47 percent were opposed to the deployment of such technologies. Another 39 percent rejected ocean iron fertilization (Royal Society 2009: 43). Studies carried out by the International Risk Governance Council (IRGC 2006) and the National Environmental Research Council (NERC 2011) show that SRM technologies engender more controversy than CDR technologies because they would have global effects and cannot be deployed in a manner that would only affect specific regions. The fact that RM technologies only tackle the symptoms and do not get to the root of the matter is also seen as a problem. In addition to their potential risks for the environment, the evaluation of CE technologies must also be based on controllability, deployment reversibility plus consequences, cost-effectiveness, whether technologies can be brought on stream in time, and fair regulation of the field of operation.

Public prefers measures with positive side-effects

**Most of those questioned in the above surveys were in favor of afforestation and the production of biochar**, as these tended to be seen as what are often called no-regret measures that would bring other advantages beside climate protection. Methods involving the ocean, such as iron fertilization, were seen as particularly risky with regard to their effects on ecosystems. Participants were in favor of combining various international CE technologies with individual, national, and international efforts to control emissions. In general, adopting sustainable lifestyles was seen as the only possible long-term solution. The results of the public dialogue initiated by NERC suggest that a majority of the population are not opposed to climate engineering in principle, but are deeply concerned about the implications of deploying particular technologies (NERC 2011). Otherwise, opinions on climate change are strongly influenced by the degree to which those questioned perceive climate change to be a serious problem and by how successful they judge emission control efforts to be.

**Acceptance is reduced by the fact that CE technologies are often seen as a substitute for emission abatement.** While economic analysis does show that such substitution is possible under certain circumstances,[46] the Royal Society (2009) also points out that the prospect of CE deployment might sharpen sensitivities for the problem that emissions represent and lead to a redoubling of efforts to avoid them. A number of participants in the Royal Society focus groups were skeptical about climate change and either reluctant to embrace CE technologies or hostile to them. They stated that planned investments in CE technologies and measures had motivated them to act in a more climate-friendly manner (reducing their own emissions, etc.) so as to avert the necessity for climate engineering in future. Corner and Pidgeon (2010: 31) also highlight the current uncertainty about whether and how strongly negative feedback leads to emission abatement. They suggest that representatives from the social sciences should do research to find out how the CE debate influences attitudes towards climate change and individual behavior. While the moral hazard phenomenon has been statistically demonstrated in conjunction with other technical innovations, such as the introduction of seat belts in vehicles, no empirical evidence supporting the moral hazard argument in a CE context has yet materialized. The Royal Society study highlights three particular aspects that might lead to

46 See Section 4.2.1

greater acceptance: (i) transparency about actions, motives, and aims, (ii) absence of commercial lobbies, and (iii) demonstrable interest in, and responsibility for, effects on the environment.

**Deliberative workshops held in the UK and Portugal by the European project Deepening Ethical Engagement and Participation in Emerging Nanotechnologies (DEEPEN) have identified five key positions often associated with nanotechnology.** As there are striking parallels between the development of nanotechnology and of climate engineering, these key positions suggest views that may be advanced in public in the future on climate engineering (Davies et al. 2009):

AC7
RISK ETHICS

AC11
CRITICISM OF TECHNOLOGY AND CIVILIZATION

AC10
RELIGIOUS, EXISTENTIAL AND ENVIRONMENTAL ETHICS-BASED ARGUMENTS

A26
DISTRIBUTIONAL EFFECTS

A32
NO INFORMED CONSENT

- “Be careful what you wish for”: getting exactly what you want may not ultimately be the ideal outcome.
- “Opening Pandora’s box”: interventions in the complex Earth system may lead to disaster.
- “Messing with nature”: redesigning nature so that it more closely suits with our needs occasions moral scruples about destroying the existing order of the natural world.
- “Kept in the dark”: CE measures should be rejected until decision-makers stop leaving the public in the dark about important aspects of the technology and its side-effects.
- “The rich get richer and the poor get poorer”: climate engineering might exacerbate existing inequalities and injustices.

Interestingly, participants in the project tended to reject a vision that technology will continue to advance and will inevitable bring progress with it. The discussion of risk focused on social aspects. Although participants were given background information from the hard sciences, the societal and ethical effects were the central topic of discussion. Based on analogies to other technology-associated controversies, it cannot be expected that social acceptance would be higher if the CE debate were restricted to CE research involving field testing as opposed to a decision on large-scale and long-term CE deployment. This has become evident, for example, in connection with CCS research in Germany. The protest movement in Brandenburg—to mention just one—has protested vigorously against the testing of CCS (Schulz et al. 2010).

## 5.3 Results from the Delphi

**Within the framework of the present study, a Delphi study was carried out in order to obtain current and well-founded opinions from experts in Germany on the potential social and cultural consequences of climate engineering.**[47] Twelve experts from the social sciences, communication studies, and the natural sciences participated. The Delphi method involves the iterative validation of quantitative ratings generated as answers to specific questions (Information Box 2).[48]

### 5.3.1 Potential for conflict

Measures in close geographical proximity are more controversial

**The Delphi participants were united in their opinion that CE experiments have the potential to engender conflict.** Large-scale CE experiments involving research on how the technology works would be particularly controversial if atmospheric modification with sulfur particles were involved. Ocean fertilization would also be controversial, but not quite to the same degree. The participants’ assessment was that cloud seeding had medium potential to generate

47 The most important results from this group Delphi are summarized in the following. More details and the exact questionnaire used can be found in Renn et al. (2011).

48 See Schulz and Renn (2009) for more details on the methodology involved.

## The Delphi method

INFORMATION BOX 2

The classical Delphi involves surveying the same group a number of times in order to gain an understanding of a particular topic (trends or future events). This report used a variation of the Delphi with a discursive approach to developing political visions and planning targets. The aim of the Delphi was to ascertain how in future the potential deployment of particular CE technologies might be perceived and evaluated by individual groups within society, by the media, and by the general public, with a view to deriving political communication and participation strategies from this information.

For the first round in the Delphi, the participants were divided into three groups. Each group received an identical questionnaire requesting estimates about the list of themes below rated on a numerical scale. This indicated whether or not the small group was able to agree on a numerical characterization on a scale from 1-10. If they did not agree, the reasons were discussed in the subsequent plenary session. In addition, the group with the numerical value furthest away from the mean was given the opportunity to present the reasons for its divergent opinion to the whole panel. This made it possible to clarify whether such outliers were a result (i) of ambiguity in the phrasing of the question, (ii) knowledge that other panel members were not aware of, or (iii) a fundamentally different evaluation of the problem.

In a second round, the small groups were reshuffled to ensure that each new group represented the entire range of opinions. Subsequently, a second plenary session assembled the entire panel to explore the remaining differences and gather the arguments on controversial points representing different interpretations of the phenomena discussed.

The Delphi took place on 13 and 14 January 2011 in Stuttgart. Twelve experts from the fields of communication, participation, and climate engineering participated. The interdisciplinary mix proved fruitful throughout the discussion. The questionnaire used dealt with the following topics:

- Perception of the potential risks of climate engineering among stakeholders and the general public; potential for conflict engendered by the deployment of different CE technologies.
- The course of the debate as it has developed in the media; comparisons with other technology debates.
- International research collaboration on the effectiveness, environmental impact, risks, and opportunities bound up with climate engineering; the regulation of climate engineering at a global level.
- The development of political communication and discourse strategies.
- Participation opportunities for specialists, interest groups, and the general public.

The participants explored these questions against the background of a group of specific CE technologies: afforestation, ocean iron fertilization, cloud seeding in the troposphere, and modification of the stratosphere by spreading sulfur particles.

conflict and that the potential of afforestation to generate conflict would be low.[49] The spatial proximity of deployment was judged to be important in the case of all technologies. The closer the geographical ties to the site of deployment, the higher the conflict potential of any given technology would be.

Unilateral or minilateral solutions increase potential for conflict

**Would the specific constellation of actors driving the process influence the potential of climate engineering to engender conflict in Germany?** This question brought forth the same ranking for conflict potential as the question about the acceptability of undertaking climate engineering (in this case: with German participation) for research purposes: modification of the atmosphere by spreading sulfur particles > ocean iron fertilization > cloud seeding > afforestation. The scores for conflict potential were even more striking when the Delphi participants were asked to assume that the respective initiatives took place in or above Germany and against the will of the UN and many developing countries. The ranking was turned on its head when the Delphi participants were asked to consider a scenario in which Germany refused to participate despite international requests to do so. They estimated that the potential for conflict in the event of Germany refusing to participate in CE deployment would be low. One remark made was that Germany is not so seriously affected by climate change that significant potential for conflict would exist in the country. Solidarity protests could be expected, but not on a large scale.

Potential for conflict rests on whether Germany is actively involved in climate engineering

Conflict potential involving environmental organizations

**The greatest potential for conflict according to the Delphi participants would originate from environmental organization.** The organizations can be expected to express the most vehement protest against the modification of the atmosphere with sulfur particles and the least vociferous protest in response to afforestation measures. The spreading of sulfur particles without broad international agreement (for example, within a UN framework) would lead to strong protests from NGOs, and these would receive support from the solar technology sector and organizations with close links to that sector. In the case of afforestation, the potential for conflict would heavily depend on the actual scenario involved, as the use of space and competition for land for food production would vary widely as a function of the areas involved and the intensity of the relevant measures. Differences in evaluation here also result from different levels of knowledge about the method deployed and the associations it would prompt. Intuitively and by tradition, afforestation is seen positively by environmental groups. The opportunity costs for land use that would arise if large-scale, climate-relevant measures were initiated are not immediately visible. However, parallels have been drawn between this and the conflicts arising from the rival aims of using land for food production and for energy production (conversion of biomass). This latter conflict is now widely recognized as such.

In the case of ocean fertilization, the Delphi participants expected protests to emanate from the political opposition. The main differences in assessment here had to do with the evaluation of the likelihood of business organizations, especially in the fisheries sector, being drawn into the conflict. Dissenting views materialized largely because there were conflicting estimates of how much the fisheries sector knew about the possible effects of ocean fertilization on fish stocks. These differences were resolved in the plenary discussion. Participants assumed that in the last resort the fisheries sector would be in favor of ocean fertilization, since it would probably be understood as a welcome opportunity to replenish fish stocks that had been significantly depleted by overfishing. This being the case, the potential of ocean fertilization to cause conflict was given a lower rating.

49 The Delphi did not address any other technologies.

If CE technologies interfere significantly with nature, religious institutions are expected to take a very disapproved view of them and the potential for controversy is correspondingly high. However, the effect of this discussion on society as a whole was not perceived to be especially significant.

**AC10**
RELIGIOUS, EXISTENTIAL AND ENVIRONMENTAL ETHICS-BASED ARGUMENTS

### 5.3.2 Comparisons with other technology discourses

The Delphi participants also compared the CE controversy with earlier debates and their attendant conflicts (genetic engineering, nuclear energy, waste incineration, etc.):

- For the modification of the stratosphere, clear parallels with nuclear energy were drawn, principally because of the fact that the effects span generations.
- For ocean fertilization, parallels with debates over organic agriculture and genetic engineering were drawn, as effects could be expected on biodiversity and ecology.
- For afforestation, parallels were drawn with anti-flooding measures, the designation of flood overflow areas, and general conflicts over land use.

Reference was also made to the controversy over the railway station redevelopment plan Stuttgart 21, with the not-in-my-backyard (NIMBY) effect being seen as a characteristic feature that these debates have in common. This effect is less applicable to other CE technologies, as the physical distance from the deployment site would be greater.

### 5.3.3 Opportunities for public participation in cases of conflict

**Within the framework of the Delphi study, there was discussion of the opportunities open to the public to participate in the debate, and measures for facilitating public participation were explored.** The only opportunities for participation examined were those relating to German involvement in CE deployment. Very different ideas exist about the salient features defining individual measures for facilitating participation. The capacity of a measure to contribute to de-escalation depends on the extent to which a conflict has already pervaded society and contributed to polarization. The format for measures proposed by participants for the communication and elaboration of standpoints at an early stage were focus groups, open and closed Internet forums, and conferences (with public participation). At later stages, when conflicts have already begun to materialize, these formats were assessed as being less suitable for reestablishing communication with a wider public. The Delphi participants felt that currently the public has insufficient knowledge for representative polls to be a suitable way of finding out what the informed preferences of the population actually are.

Plebiscitary participation in decision-making: collision of aims

**Using referendums or plebiscites means confronting the familiar conflict of interest between the supporters and opponents of such formats.** Do we believe that citizens can be trusted to approach highly complex questions responsibly, or is it better to follow the delegation principle of representative democracy and leave matters entirely in the hands of elected representatives? In the case of climate engineering, this translates into the question whether it would not be appropriate for such far-reaching decisions as the deployment of CE technologies to obtain democratic legitimization from the entire population instead of solely by elected representatives? Or should not such decisions—precisely because their consequences are so immense—be left to the volatile will of the people? The Delphi participants discussed these questions intensively, with one group pointing out that normative arguments (the sovereignty of the people) favored more plebiscitary elements, and the other arguing that continuity and consistency could only be maintained on the basis of governance by committees of representatives. This fundamental conflict remained unresolved throughout, a leitmotif running through all the controversies flaring up between the Delphi participants.

The Delphi participants agreed that plebiscitary elements would only be useful in connection with climate engineering if other measures for facilitating participation (such as round tables, citizens' forums, or mediation) were deployed beforehand in order to prepare the ground by ensuring that all relevant arguments received a hearing in public. Combinations of different participation measures would be ideal (hybrid processes). More specifically, participants highlighted the opportunities for combining stakeholder debates (round tables, mediation, arbitration) with formats for citizen participation such as consensus conferences, citizens' forums, or citizens' conferences. Several different suggestions for specific hybrid processes emerged. All groups in the Delphi agreed that such a hybrid process should also include virtual meetings visible to all or closed online conferences. Three of the four groups also suggested focus groups and citizens' conferences or other forms of direct participation by the public with informed preference reporting. One recommendation made was that representative polls should only be carried out after information on climate engineering has been distributed widely, for example through the media, as a measure supporting the direct participation processes. Round tables with stakeholders who could issue policy recommendations to the Federal Government were also considered important. Only a minority of Delphi participants strongly opposed a citizens' plebiscite.

#### 5.3.4 Devising communication and discourse strategies

Increased communication with the public necessary

**The Delphi participants attached major importance to informing the public more intensively about all the different key aspects of climate engineering technologies in order to create a sound basis for a democratic decision-making process.** The communication and discourse strategies used should allow the topic to be presented attractively and in a manner that non-specialist audiences can readily comprehend. The aim should neither be to advertise climate engineering nor to "sell" it to the public. The participants also agreed that the views of stakeholders and non-specialists could contain information valuable in the context of policy formulation, this being a good reason to start informing the public about climate engineering sooner rather than later. The level of uncertainty in our knowledge about climate engineering and particularly its potential side-effects should be clearly communicated. The participants felt that around 30 percent of the information offered should ideally explain the relevant processes and technologies, with the other 70 percent being given over to a discussion of their potential effects and side-effects. A proactive presentation of the facts (i.e., manipulating public opinion) was unanimously rejected.

**It was pointed out that it is difficult to make statements about the pros and cons of technologies and present them in a balanced way when so little is known about the technologies and their likely effects.** At the same time, some participants also drew attention to the problems implicit in a relative over-estimation of risk, recalling in that context the Creationist reaction to the theory of evolution and observing that that particular debate shows how quickly widespread skepticism can be manipulated to engender general hostility. Different evaluations also result when the evaluation is dominated either by a general fairness principle or by the precautionary principle.

Discussing CE technologies as part of a package of measures

**The consensus that emerged among the Delphi participants consulted was that the technologies should be introduced individually before going on to discuss combinations (for example, scenarios with and without emission control measures).** Participants also observed that the climate engineering debate should not be allowed to oust the underlying debate on climate change. The overall topic should be approached against the background of other measures affecting the climate and discussed in the context of climate change and climate protection. More specific measures should only be discussed at a later point. The debate should begin before specific deployment scenarios were known. Context-specific conditions could always be specified later.

**In engaging with unresolved questions in connection with communication strategies, it was notable that the participants were more interested in what communication strategies would be appropriate and less concerned with how these strategies might be implemented.** An open-ended debate was felt to be desirable. It could be initiated by the Federal Government and revolve around the questions whether climate engineering is seen as an option for the future at all, and whether advance investments in the technology should be made, always assuming that the necessary finance would not simply be recouped from other budgets. The opinion of the Delphi participants was that climate engineering is not yet a socially divisive issue. CCS, by contrast, is already proving controversial and forms the substance of a debate conducted between different camps. Ideally, an information campaign on climate engineering should be launched before such a tipping point in the debate is reached and different camps start to form. An early campaign would be more effective. As both LOHAFEX and the CCS experiments have already led to negative reactions, communication strategies in future should aim to be as transparent as possible before battle lines are drawn and fronts become entrenched. The Delphi participants saw the (re)establishment of the public's trust in politics as crucial in relation to the question: "What do you want? Plan A (emission abatement only) or plan B (emission abatement plus climate engineering)?" Plan B would require a more dynamic approach to heightening climate engineering awareness and sensitivity among the wider public. A first step here could be the communication of basic knowledge that would form the foundations for further suitable participative measures. More concretely, participants suggested that a broad and timely information campaign should be followed by participative processes (online communication, citizens' conferences) dealing with the factual basis of the problem (negative effect of greenhouse gas emissions) and seeking to avoid emissions and motivate people to make their lifestyles more sustainable. Against this background, the recommendation was to present climate engineering as a "last resort" option, clearly drawing attention to the risks involved.

## 5.4 Summary of societal aspects

**A search for literature on the current international debate on climate engineering in the social sciences reveals that such literature in German was very scant before 2010.** However, some publications do draw attention to social aspects of climate change, and the importance of dialogue with the public is highlighted.

Little knowledge of climate engineering among population

**The population's current level of knowledge about climate engineering is low.** Even though climate engineering has been discussed more intensively and longer in the USA than in Germany, almost three quarters of the American population had never heard of such technologies in 2010 and only 3 percent had a realistic idea of what they might involve. Representative figures are not yet available for Germany. Media and environmental campaigners have begun to raise the CE topic, but the response from the wider public has been tepid. We may assume that a survey conducted in Germany right now would reveal largely skeptical attitudes to CE technologies. This is also what attitudinal studies on CCS have shown. Here again, knowledge of the CCS technology among the general public is limited, but the majority of those who have already formed an opinion are opposed to its use. It can further be assumed that providing better media coverage of climate engineering or giving the debate on such technologies greater prominence would be likely to bring forth more critical or hostile voices, unless organizations or groupings were to emerge consciously expressing support for CE technologies. Up to now, this has not been the case in Germany. Accordingly, if and when the topic becomes more predominant in public discourse, it is unlikely that a high degree of acceptance for climate engineering will manifest itself. In short, it looks as if in the face of the likely lack of consensus on the acceptability of CE technologies, the potential for mobilization against climate engineering to be expected from the German public is high.

High acceptance for climate engineering unlikely

**NGOs have also shown little interest in the topic of climate engineering.** The ETC Group which has issued a statement entitled "Hands Off Mother Earth" and which attempts to influence UN committees and other bodies, is emphatically opposed to climate engineering. Its main focus, however, is still on activities in America. In Germany, the first evidence of critical attitudes from NGOs took the form of comments on the LOHAFEX ocean fertilization project, which was severely criticized by many environmental groups and in the media. While publicly expressed protests quickly fizzled out, the pilot project has since been cited as a negative example on a considerable number of NGO websites. The potential for mobilization of the private sector against climate engineering is perceived as low, although the potential in particular subsectors, such as solar energy, agriculture, forestry, fisheries, or tourism, could be much higher.

Increased media coverage of climate engineering

**In the media, the response to the subject of climate engineering has increased over the past two years, especially in the UK and the USA.** In the USA, both the opinions of those who are either strongly opposed to or those who are strongly in favor of climate engineering have been covered by the media. The media response in Germany has not only been significantly less marked than in the USA and the UK, but also somehow different. The German media usually focuses on the risks posed by climate engineering which are typically seen as incalculable, notably in relation to their effects on ecosystems and biodiversity. Mention has also been given to concerns that CE deployment could alter precipitation patterns, that individual countries could deploy it independently, and that it could lessens people's willingness to curb emissions.

**In sum, we can say that the future of the CE debate and the public's response to climate engineering are uncertain.** Studies carried out elsewhere have not come up with results that are completely clear-cut, and no empirical research that would permit a forecast about how the debate will evolve in Germany has yet been conducted. Conclusions derived by drawing parallels with other technologies give some indication of how the population might react to climate engineering. Some fruitful comparisons can be drawn by looking at the history of the acceptance problems run into by nuclear energy, genetic engineering, and nanotechnology. What all of these technologies have in common is that the chances and opportunities they held out were presented first, with a degree of euphoria, while the risks that eventually dominated the respective debates only came into perspective more gradually. Taking into account all the sources referred to here, it seems unrealistic to expect a comprehensive consensus about climate engineering to be achieved.

**The participants in the Delphi agreed that conflicts would become more virulent if CE technologies were deployed in or in close proximity to Germany, particularly if international support for such deployment were not forthcoming.** The conflict potential of initiatives being taken in defiance of the will expressed by the UN and many developing countries was perceived to be particularly high. The Delphi participants ranked the probable virulence of potential conflicts as follows: the emission of sulfur dioxide aerosols in the stratosphere would engender the most severe controversy, with ocean fertilization, cloud seeding, and massive afforestation following in descending order. Parallels to other technology controversies do not suggest that a more narrowly-defined debate covering only CE research would generate any greater acceptance than a debate on large-scale and long-term CE deployment, at least not if the research were to involve field studies.

More information should be communicated to the public

**Consensus exists in the literature and among the Delphi participants that even at this early stage in the development of climate engineering, it is already necessary to provide the public with information about the topic.** A comprehensive communication program should examine CE technologies in the light of the wider debate on climate change, emission control, and adaptation.[50] It should also take the precautionary principle into account by placing more weight on explaining effects and risks of climate engineering than on explaining technical details and processes of climate engineering. While information on opportunities and risks should be communicated clearly, the level of uncertainty involved should also be highlighted as an absolutely central issue in the communication on the topic. Dialogue with the public should keep pace with scientific research on the advantages and disadvantages of CE technologies. This way, it would be possible to keep track of the current degree of acceptability accorded to these technologies in the light of the latest research and to evaluate CE technologies within a comprehensive climate protection policy framework. We suggest that a three-stage plan be used to integrate citizen participation in this process:

- Provision of extensive information and communication via the Internet and through public institutions active in the wider context of the climate change debate.
- Organization of round tables or forums with stakeholders to identify the interests and preferences of organized groups in matters relating to CE research and deployment.
- Organization of (web-based) citizens' forums or citizens' conferences to assemble information on the wishes, concerns, and ideas of citizens who are not affiliated with specific organizations and to feed this information back into the formulation of policy.

**When and if concrete CE deployments are considered in the future, specific round tables or other formats should be used to convey informed preferences to decision-makers.** If the CE topic is not to be allowed to gather its own momentum, and in order to adapt political and communicative action strategies to the dynamic progress of the debate, social monitoring of a potential field of conflict would appear to be imperative. Knowledge, attitudes, and mobilization potential should be systematically recorded at regular intervals. The background conditions and the priorities set by actors must be understood better as they progress over time and in the complex, dynamic context of opinion-formation and mobilization mechanisms. For that reason, the interplay between the parameters of information reception, understanding of risk, and uncertainty should be investigated intensively in order to gain a clear idea of (i) the degree to which consensus is possible, (ii) where the opportunities actually lie for participating in deliberative decision-making on CE technologies, and (iii) what restrictions there are on participation.

50 See also Figure 2 in Chapter 1.

# 6
# Instruments and Institutions of International Law

**Due to the largely transboundary nature of the technologies involved, the legality of climate engineering is primarily to be assessed according to the rules of the partial legal system of public international law.** As a consequence, the following discussion of the legality of climate engineering must begin by examining the sources of international law. Analysis is required, above all, of the applicability, scope and legal consequences of international treaty law and customary international law; particular attention should be paid to the decisions of the International Court of Justice (ICJ) and other international dispute resolution bodies in regard to its substance and interpretation. Based on the definition of international law as the law applicable between states, the level of international relations—represented, for example, by the Conferences of Parties to the applicable treaties—should be the focus of discussion.

Legality is primarily to be assessed on the basis of international law

Currently international law does not contain norms addressing the research and deployment of climate engineering in a direct and comprehensive manner. No international treaty has ever been adopted with the intention of regulating such activities. That individual CE technologies are nonetheless covered by existing treaties can be attributed, at least in part, to the framework approach commonly found in international law, which is applied particularly in connection with global environmental issues (climate, ozone layer, biodiversity protection) (Durner 1999: 365). It is characteristic of this approach that a specific issue is comprehensively regulated in a multi-stage process: While a framework convention contains general principles and rules for the peaceful resolution of disputes, specific rights and obligations are codified in annexes to the convention or in subsequently adopted protocols. This often allows the rules contained in the framework convention to be applied to new phenomena that were unknown at the time the treaty was negotiated. In addition—not least due to the need to compromise in international relations—treaty provisions that address specific issues are often "openly" formulated that so that factual developments, which were not part of the treaty's original intentions, can nonetheless be covered by treaty norms.

No rules in international law address the research and use of climate engineering directly

**No general and binding definition of climate engineering exists under international law.** The 10th Conference of Parties (COP) to the Convention on Biological Diversity (CBD) included a preliminary definition of the term in a footnote to Decision X/33 on Biological Diversity and Climate Change. This definition is not legally binding, however, and refers only to the CBD's scope of application. Although the distinction between SRM and CDR was made here for the first time in the context of an international treaty, no concrete legal consequences can be drawn from this. The legality of climate engineering must instead be judged separately for each individual technology on the basis of international treaty and customary law.

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No binding definition of climate engineering in international law

**Provided that special legal prohibitions or obligations are not applicable, it can be assumed as a basic principle that international law allows everything that it does not explicitly prohibit (ICJ 2010: § 84).** In order to ban climate engineering as a whole or to ban individual CE technologies, a legally binding moratorium is necessary. Nothing of this nature currently exists.[51] Against this background, the following will examine the legality of CE technologies on the basis of potentially and factually applicable international treaties. In the first instance,

51 This also applies to ocean fertilization methods using iron, phosphorous, and /or nitrogen.

instruments will be highlighted that are or could potentially be comprehensively applicable to climate engineering (Section 6.1), and then individual CE technologies will be examined on the basis of special agreements (Section 6.2). Finally, customary international law (Section 6.3) and international rules on liability (Section 6.4) will be examined, concluding on the basis of these findings with an outlook on future legal developments (Section 6.5).

## 6.1 Cross-sectoral instruments

ENMOD Convention is not applicable

**The United Nations Convention on the Prohibition of Military or Any Hostile Use of Environmental Modification Techniques (ENMOD) is not applicable to climate engineering.** This can be concluded based on the specific objective of regulating the use of the environment as a weapon or as part of a military operation contained in the title of the Convention, as well as the seventh recital of its preamble, which expresses the intentions of the contracting parties to effectively prohibit the military or otherwise hostile use of environmental modification techniques (Zedalis 2010 a: 19). The ENMOD Convention establishes that "[e]ach state party to this Convention undertakes not to engage in military or any other hostile use of environmental modification techniques [...]"(Art. I ENMOD Convention). The Convention contains a legal definition of the term "environmental modification techniques" in Art. II ("changing—through the deliberate manipulation of natural processes—the dynamics, composition or structure of the Earth, including its biota, lithosphere, hydrosphere and atmosphere or of outer space"). As CE technologies also intervene in natural processes, they could be regarded as "environmental modification techniques" in terms of the ENMOD Convention. However, the contracting parties made clear in an understanding, which must be taken into consideration when interpreting the Convention, that the Convention does not address the question "whether or not a given use of environmental modification techniques for peaceful purposes is in accordance with generally recognized principles and applicable rules of international law" (GAOR 1976: 92). This would be a different case if one were to deem—some or all—CE activities as environmental modification techniques for military or other hostile use. The connection between military uses, on the one hand, and other hostile uses, on the other hand, contained in the wording of Art. I ENMOD Convention suggests that the term "other hostile use" cannot be examined in isolation from the qualification of an activity as military, though. Even if the adverse environmental impacts listed in Chapter 3 could potentially result from CE activities, it cannot be easily concluded that a potentially hostile use as seen from an ecological standpoint constitutes "other hostile use" in terms of the ENMOD Convention. Expanding the treaty's scope beyond environmental modifications for military purposes cannot be considered in particular in light of the close connection between the subject matter of the ENMOD Convention and the concept of armed conflict, which is decisive for the applicability of international humanitarian law. As a consequence, the ENMOD Convention does not provide a general starting point for the international legal appraisal of climate engineering.

UNFCCC and Kyoto Protocol are not fundamentally opposed to climate engineering

**The United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol qualify the reduction of greenhouse gas emissions through sinks as a means of combating global warming and are not fundamentally opposed to climate engineering.** The UNFCCC is the primary legal instrument for regulating the protection of the Earth's climate. It aims to counter adverse effects on the climate system caused by increasing anthropogenic greenhouse emissions. The UNFCCC is a framework convention that contains comparatively broad obligations. These obligations are mainly limited to procedural requirements such as the obligation to document and communicate information concerning emissions, national policies and best practices. The UNFCCC is given more concrete form through the provisions of the Kyoto Protocol. It requires the industrialized countries listed in Annex 1 of the UNFCCC to ensure that their greenhouse gas emissions do not exceed the individually determined reduction commitments contained in Annex B to the Kyoto Protocol.

CDR falls under the UNFCCC definition of sinks

In order to satisfy the reduction commitments contained in the Kyoto Protocol, Art. 3 (3) sets out two different strategies: the reduction of greenhouse gases through sinks, on the one hand, and, on the other hand, the reduction of emissions at their source, with the latter strategy as the primary objective of the Kyoto Protocol. The UNFCCC defines a source as a "procedure or an activity, through which a greenhouse gas, an aerosol or a precursor of a greenhouse gas is released into the atmosphere" (Art. 1 (9)), whereas a sink is a "procedure, an activity or a mechanism, through which a greenhouse gas, an aerosol or a precursor of a greenhouse gas is removed from the atmosphere" (Art. 1 (8)). Accordingly, CDR falls under the definition of sinks (and consequently, within the concept of mitigation), as they specifically further the objective of removing greenhouse gases from the atmosphere. In this sense, they are not only in line with the objectives of the Framework Convention on Climate Change, but also represent an implementation mechanism specifically contained within the Convention for achieving this objective. However, only land-based sinks (land-use and forestry projects) can contribute to national emissions balances in accordance with the Kyoto Protocol.

Marrakesh Accords restrict the Kyoto Protocol's definition of sinks

In accordance with the Marrakesh Accords (UNFCCC 2002) adopted by the parties to the Convention in 2001, only such activities "other than afforestation, reforestation and deforestation" which can be qualified as "revegetation, forest management, cropland management, and grazing land management" come into consideration. In order to integrate other CDR activities such as marine $CO_2$ storage enhancement or the acceleration of carbonization into the Kyoto Protocol's so-called flexible measures (Joint Implementation, Clean Development Mechanism, emissions trading), it would be necessary to revise the Protocol or introduce an expanded definition of sinks into the successor agreement to Kyoto. The Kyoto Protocol's restrictive approach results only in the inapplicability of these mechanisms in regard to CDR activities, which are not otherwise addressed. This does not mean, however, that such activities are prohibited in general.

## 6.2 Legality of specific CE technologies under international law

### 6.2.1 Legality of RM technologies under international law

#### Reflectors in outer space

**The legality of installing reflectors in outer space is judged according to the international treaties governing the protection and use of outer space, in particular the 1967 Outer Space Treaty (OST).** This treaty is applicable as all RM technologies for the reduction of solar radiation with reflectors are to take place at a distance of more than 120 km from the Earth, thus, in line with all views put forward on the delimitation of outer space, in outer space rather than in airspace subject to the sovereignty of states. The OST guarantees the freedom of outer space, which encompasses both research and the use of outer space. Due to the factual irreversibility of RM technologies in outer space, it must generally be assumed that they represent use of outer space rather than scientific research. "Use" in terms of the OST encompasses both the economic and non-economic uses of outer space (Hobe 2009: margin note 36), but is subject to legal limits.

Outer Space Treaty can prohibit modifications in outer space

**Because the common interest clause contained in Art. I (1) OST qualifies the research and use of outer space as the "province of all mankind", CE activities in outer space may not adversely impact other states.** This would be the case if the introduction of reflective materials would not only lead to a reduction in global temperatures but also to further unintended consequences such as intensified El Niño events, which particularly impact specific countries.[52] In this respect, there is a good case to argue that a unilateral CE deployment would only be in the interest of all states if it would be combined with a benefit sharing mechanism. Because such benefit sharing mechanisms do not (yet) exist for unilateral CE deployment, it appears unlikely that a unilateral CE deployment in outer space would be compatible with the common interest clause (Zedalis 2010 a: 24). Considerable uncertainty exists, however, in regard to the binding character of that clause. It is argued by some that Art. I (1) OST contains only a general objective which is not binding on the contracting parties (Bhatt 1973: 273; Hobe 2009: margin note 56). However, in as far as the contracting parties are bound by the principle of due regard contained in Art. IX OST to conduct outer space activities "with due regard to the corresponding interests of all other states parties to the Treaty", this constitutes a limitation on the freedom of outer space. In principle, a state may only install sun shields or reflective materials in outer space when there is no reasonable doubt that another treaty party could be expected to be adversely affected as a result.

**RM activities in outer space are further restricted by the environmental impact clause contained in Art. IX Sentence 2 OST, from which, in conjunction with sentences 3 and 4, elements of precaution can be derived.** In accordance with the environmental impact clause, which substantiates the common interest clause, the contracting states must conduct research and use outer space[53] in such a way as to "avoid their harmful contamination and also adverse changes in the environment of the Earth resulting from the introduction of extraterrestrial matter". In regard to the stipulation that all "contamination" of outer space is to be prevented, this applies not just to the contamination itself, but also includes every negative modification of outer space, the moon and the celestial bodies. It is a matter of interpretation, however, at which point a negative modification can be established. In this respect, different perspectives on the harmfulness of space debris have emerged. As a starting point, it can be considered on the one hand whether a concrete hazard for future space projects exists, which can be partially demonstrated through a risk of collision with debris (Kolossov 1980: 104). Alternatively, space debris can be qualified as harmful contamination per se (Marchisio 2009: margin note 29). If these alternatives are applied in the context of climate engineering, the lenses forming a potential sun shield increase the amount of space debris on the one hand if they unexpectedly fail to serve intended objectives. On the other hand, the installation of a sun shield itself could represent harmful contamination in terms of Art. IX sentence 2 OST. Even though the manifestation of risk is unlikely, all activities in outer space are considered ultra-hazardous per se as the potential for damage is that much larger in scale (Marchisio 2009: margin note 28).

To the extent that Art. IX sentence 2 OST is intended to protect outer space from contamination as well as protect the terrestrial environment from negative impacts as a result of the introduction of extraterrestrial matter (back contamination), this norm addresses all modifications through materials which have an impact on the Earth from outer space (Marchisio 2009: margin note 28), for example those of reflective materials in outer space. It is, however, unclear in this regard, at which point such modifications are to be considered harmful in terms of this norm. In particular, its wording does not establish that a modification is harmful only when it affects all states. Neither the wording nor customary international law—due to the lack of state practice—provides an answer in regard to the correct interpretation of this provision.

52 See Chapter 3 for further discussion of regional climate effects.

53 It is not yet unanimously agreed that the use of space is also covered by Art. IX, sentences 2 – 4, OST. Because the parallel provision in the Moon Treaty explicitly places research and use at the same level and the moon is directly referred to in Art. IX, sentence 2, OST [in addition to "other celestial bodies"], it can be assumed that the omission of a reference to "use" is an editorial oversight.

As significant uncertainty exists both in regard to harmful contamination of outer space as well as in regard to the adverse nature of changes in the terrestrial environment in relation to climate engineering, the interaction between sentences 2 through 4 of Art. IX OST can be regarded as reflecting an element of precaution. Even though the precautionary principle was unknown in international law at the time the Outer Space Treaty was adopted in the 1960s, central characteristics of this principle—scientific uncertainty, environmental hazard, duty to consult—can be identified in Art. IX OST. Therefore, particular attention should be paid to the effects of the precautionary principle in the context of potential CE activities (see Section 6.5) also with regard to activities in outer space.

Relevant treaties on the use of outer space contain liability provisions

**The pertinent treaties concerning the use of outer space contain liability provisions, which can also be applied in the event CE technologies are used.** Art. VI OST extends the general customary rules on state responsibility in such a way that the contracting parties are also responsible for outer space activities of international organizations and private actors (Wins 2000: 142ff). This indicates, in particular, that a state must ensure that precautionary measures are taken and international legal obligations are respected in the course of the activities it carries out (Gerhard 2009: margin note 1, 12). While international legal responsibility exists for national activities in outer space according to Art. VI OST, liability only arises according to Art. VII OST when damage occurs as a result of outer space activities. In such a case, the operator and the launching state are liable for all damages an object or its individual components cause to another state party or its natural or legal persons on Earth, in its airspace or in outer space, including the moon and other celestial bodies. A specific basis for liability for damages in connection with activities in outer space can be found in the 1972 Convention on International Liability for Damage Caused by Space Objects (Space Liability Convention, SLC). Art. II SLC establishes absolute liability for damages caused by a space object on the Earth's surface or an aircraft in flight, while Art. III SLC establishes limited liability for damages to space objects of other states in locations other than the Earth's surface. In accordance with Art. I (a) SLC, the term "damage" encompasses "loss of life, personal injury or other impairment of health: or loss of or damage to property of states or of persons, natural or juridical, or property of international intergovernmental organizations." Damage to the environment, as such, or damage to areas beyond the limits of national jurisdiction such as the high seas and outer space cannot automatically be included under this definition (Frantzen 1991: 619 ff). Thus, the question of liability for damages caused by space-based CE activities cannot be definitively answered. Global climate impacts, particularly in areas beyond the sovereignty of states, could be among the unintended consequences of reflective materials in outer space.[54] Although somewhat controversial, this problem can be minimized by subsuming environmental damage, which directly impacts the environment of a contracting party and consequently its territorial integrity, under the term "damage" (Gehring and Jachtenfuchs 1988: 107).

#### Reflectors in the stratosphere

The legality of introducing reflective aerosols or particles into the stratosphere is judged in accordance with the requirements of international law relating to the prevention and reduction of air pollution. Even if the international law applicable to outer space in general and the Outer Space Treaty in particular do not distinguish between outer space and air space, no method has been discussed for their demarcation which determines that outer space begins below a level of 60 km (Khan 2004: 637). Because modifications in the stratosphere are currently only being discussed at a level below 30 km, the norms of outer space law are not applicable for

54 See Chapters 3.

the international legal examination of the introduction of sulfur particles and other reflective materials into the atmosphere. Rather, the Convention on Long-Range Transboundary Air Pollution and the Vienna Convention for the Protection of the Ozone Layer are relevant in this respect.

CLRTAP and Vienna Convention for the Protection of the Ozone Layer relevant for RM measures in the stratosphere

**According to the Convention on Long-Range Transboundary Air Pollution (CLRTAP), the contracting parties shall refrain from discharging substances and materials into the stratosphere if and to the extent to which adverse environmental impacts can be detected.** The Convention, which, with only 51 contracting parties, is not universally binding, was negotiated at the end of the 1970s in reaction to increasing air pollution and the phenomenon of acid rain. In spite of this, the "open" nature of its norms provides scope for its application in the legal assessment of the introduction of chemical aerosols or other reflective particles into the stratosphere as RM. Air pollution is defined as the "introduction by man [...] of substances or energy into the air" (Art. 1(a) CLRTAP). This includes not only sulfur particles, but also all other particles or aerosols which are under consideration for introduction into the stratosphere. The materials must, however, "result [...] in deleterious effects of such a nature as to endanger human health, harm living resources and ecosystems and material property and impair or interfere with amenities and other legitimate uses of the environment" (ibid.). The Convention is thus based on the impacts of the introduced substances, which must be deleterious for specific, but not necessarily specifically listed, legal objects, in order to be qualified as air pollution in accordance with CLRTAP. In the absence of reference to aspects of precaution, it is necessary that the negative environmental impacts caused by the introduction of aerosols or particles into the stratosphere are verified before the prohibition contained in CLRTAP can become applicable.

**In addition, the three of the eight protocols to CLRTAP addressing sulfur emissions or establish maximum emissions levels cannot be considered universally binding.** In regard to sulfur emissions, the 1985 Protocol on the Reduction of Sulfur Emissions or their Transboundary Fluxes by at least 30 percent, the 1994 Protocol on Further Reduction of Sulphur Emissions and the 1999 Protocol to Abate Acidification, Eutrophication and Ground-level Ozone are applicable. These have only 25 (1985 Protocol), 29 (1994 Protocol) and 26 (1999 Protocol) contracting parties, respectively. In the most recent and most extensive 1999 Protocol, Germany recognized a 90 percent reduction commitment by 2010 in comparison to the base year 1990, which represents a maximum emissions level of 550,000 tons of $SO_2$ per year (see Annex II to the Protocol). Based on the amounts determined by Crutzen (2006: 213), 1 – 2 megatons (Mt) of sulfur are required annually worldwide to increase sulfur-particle retroreflectivity in order to sufficiently compensate for greenhouse gas-associated radiative forcing. Only 5 percent of this sulfur would reach the stratosphere where it would form $SO_2$, however. If one takes these figures as a basis, the established upper limit, which is only applicable to Germany, would in all likelihood not be exceeded. Meanwhile, the estimated amounts have been corrected significantly upwards; values of up to 75 Mt are now possible (Klepper and Rickels 2011), which is likely to change the calculation of the established upper limit.

Vienna Convention for the Protection of the Ozone Layer is applicable

**A CE technology involving the introduction of sulfur particles into the stratosphere falls within the scope of the Vienna Convention for the Protection of the Ozone Layer.** With 196 contracting parties, the 1985 Convention is meanwhile universally binding. According to its Art. 2 (2), the contracting parties are to "adopt appropriate legislative or administrative measures and co-operate in harmonizing appropriate policies to control, limit, reduce or prevent human activities under their jurisdiction or control", in as far as these activities adversely impact, or have the potential to impact, human health as a consequence of an actual or probable change in the ozone layer. Sulfur is not mentioned in Annex I to the Convention. Here, chemical substances are listed, which are "thought to have the potential to modify the chemical and physical properties of the ozone layer." This does not indicate, however, that only the substances named in the Annex are covered within the scope of the Convention. Instead, it is decisive that the substance in question has sufficient potential to cause harm in terms of Art. 2 (1) of the Vienna Convention. This can be assumed in the case of sulfur, as sulfur inputs can lead to a significant depletion of the ozone layer (Tilmes et al. 2008; Keith 2010).

**At this point the inherent conflict between the objective of climate engineering to mitigate the process of global warming and other environmental objectives comes to the fore.** On the one hand, climate engineering aims to reduce the negative consequences of climate change and thus serve the objectives of climate protection. On the other hand, one of the consequences of the introduction of aerosols into the stratosphere that cannot yet be ruled out is that these accelerate chemical processes that degrade ozone and can therefore lead to a corresponding depletion of the ozone layer; adverse impacts on human health can result as a consequence of this.[55] This raises the question how the formulation "adverse effects" and respectively "likely adverse effects" used in Art. 2 of the Vienna Convention should be handled.

In this regard Zedalis suggests a motivation-based interpretation, which emphasizes climate engineering's intention to protect human beings and the environment (Zedalis 2010 a: 23). While such an intention would not allow climate engineering to be conducted under the auspices of the Vienna Convention per se, in order for the Convention to be applicable, a causal connection between the human activity and the adverse effect in question would have to be established. As long as this has not occurred, the Convention is not applicable and does not prohibit the relevant CE technologies according to this view. Wiertz and Reichwein (2010: 22) support this approach and regard as decisive whether significant adverse effects can be expected or not. In this respect, the objectives of climate engineering could be taken into account. In the end, however, these proposals are not fully convincing. An interpretation of the Vienna Convention that places the objectives of climate engineering at the forefront and disregards the explicitly formulated objectives of the Convention violates the generally recognized rules of treaty interpretation. Adverse environmental impacts from the introduction of aerosols into the stratosphere that cannot currently be scientifically ruled out cannot be lowered below the threshold of significance contained in Art. 2 (1) of the Vienna Convention with the argument that such CE activities are intended to reduce the negative impacts of climate change. If the introduction of aerosols causes significant negative impacts to these protected legal interests, these cannot be offset within the specific treaty regime by referencing the objectives of the CE activities. A different result can only be arrived at through a cross-functional approach or a comprehensive approach beyond the scope of the given Convention (see Section 6.5).

#### Modification of marine stratus and cirrus clouds

Legality of cirrus cloud modification subject to its potential to cause damage

**The legality of cirrus cloud modification is to be judged on the basis of the Vienna Convention for the Protection of the Ozone Layer and of the CLRTAP in the same manner as the injection of aerosols into the stratosphere.** According to the CLRTAP, the contracting parties should refrain from introducing substances and materials into the stratosphere if negative environmental impacts can be confirmed. If the modification of cirrus clouds leads to an actual or likely change in the ozone layer and this change has an actual or likely negative impact on human health, field research and operations are forbidden under the Vienna Convention for

55 See Section 2.4 and 3.2.2.

the Protection of the Ozone Layer. This applies irrespective of the fact that bismuth(III) iodide used for the modification is not listed in Annex I of the Convention.

**The deployment of cloud-seeding vessels for the purpose of marine cloud formation in a foreign state's internal waters and territorial sea requires that state's approval.** The vessels foreseen for cloud seeding operations are ships in legal terms. This poses the question which states—and where—are entitled to operate ships for climate engineering, and if and to what extent their freedom of navigation is subject to coastal state approval. Waters on the landward side of the baseline[56] are considered internal waters (Art. 8 (1) UNCLOS) subject to the full territorial sovereignty of states. The coastal state's laws are therefore applicable in their entirety to the operation of cloud seeding ships. The same applies to the territorial sea, which extends up to 12 nautical miles seawards from the baseline (Art. 3 UNCLOS). The coastal state's sovereignty over its territorial sea is limited by the right of innocent passage (Art. 17 UNCLOS). According to this, the ships of all states enjoy the right to navigate the territorial sea provided that this passage is innocent, that is, that it does not interfere with the peace, good order or security of the coastal state (Art. 19 (1) UNCLOS). Art. 19 (2) UNCLOS substantiates when such an occurrence can be considered to have taken place. Expressly mentioned are research and surveying activities (Art. 19 (2) (j) UNCLOS) and other activities not having direct bearing on passage (Art. 19 (2) (l) UNCLOS). Thus, cloud seeding activities for the purpose of researching this CE technology require the consent of the coastal state. Additionally, it seems doubtful whether such activities can be considered "passage" at all. According to Art. 18 (2) UNCLOS, "passage" can only be deemed to have taken place when navigation through the territorial sea is continuous and expeditious. In contrast, cloud seeding is not limited to the mere navigation of a body of water, but instead, in view of the fact that seawater is injected into the atmosphere to stimulate or intensify cloud formation, aims at more extensive presence at specific locations in the territorial sea appropriate for this purpose as well as traversing the coastline.

Deployment of cloud seeding vessels requires approval under certain circumstances

**Cloud seeding activities are not qualified as marine scientific research in terms of UNCLOS; the deployment of such vessels in another State's Exclusive Economic Zone (EEZ) is therefore not subject to the consent of the coastal state, but is instead permissible subject to the principle of due regard, which also reflects customary international law.** In the EEZ, which extends up to 200 nautical miles seawards from the baseline, the coastal state is only entitled to exercise specific functionally limited sovereign rights and jurisdiction (Art. 56 UNCLOS). The coastal state is only entitled to grant permission in regard to cloud seeding vessels when these are deployed for purposes of marine scientific research (Art. 56 (1)(b)(ii) in conjunction with Art. 246 UNCLOS). The term marine scientific research was not defined in the UN Convention on the Law of the Sea, but is generally understood to encompass all activities undertaken in the oceans, which seek to expand human knowledge of the marine environment and its processes (Tanaka 2005: 938). Art. 243 UNCLOS suggests that this only covers activities concerning phenomena in the marine environment (Bork 2011: 31f). Based on this, while there is a case to argue that activities could be included which are not conducted in the water column or on the seabed or subsoil, but instead in the atmosphere directly above the water (Tanaka 2005: 939; Soons 1982: 177), the injection of seawater into the atmosphere to stimulate cloud formation cannot be qualified as marine scientific research, even when the activity takes place experimentally or on a trial basis.

56 The baseline constitutes the outer boundary of the internal waters; the extent of a coastal state's territorial sea, contiguous zone, exclusive economic zone and continental shelf are measured from it. The normal baseline is the low-water line along the coast as recorded in the coastal state's official nautical charts.

Cloud seeding operations are not marine scientific research

Since cloud seeding activities are not qualified as marine scientific research, the coastal state cannot make the corresponding deployment of ships in its EEZ subject to its consent. It cannot be concluded from this, however, that a CE activity conducted by ships of a third state would be automatically permissible. Whether or not third states are to be considered as being privileged rather depends on whether the activity concerned is in sufficiently close connection with the freedoms of navigation, overflight or laying of submarine pipelines and cables mentioned in Art. 58 (1) UNCLOS (Kwiatkowska 1989: 203; Attard 1987: 66). This could be seen in the affirmative as cloud seeding activities at sea can only be conducted by ships. Upon closer examination, however, navigation is merely the means by which cloud seeding is to be performed. In this case, the CE activity itself is the dominant activity, that is, the injection of seawater droplets into the air, which speaks against a sufficient connection with the freedom of navigation contained in Art. 58 (1) UNCLOS. The principle of equity contained in Art. 59 UNCLOS supports that cloud seeding activities in another state's EEZ can be deemed permissible subject to the principle of due regard, which is also valid under customary international law. Therefore, it seems inevitable that specific navigational standards are guaranteed so that international commercial shipping is not significantly impaired as a consequence of the CE operation. In light of Art. 211 (5) UNCLOS, which places coastal state measures for the prevention of pollution by foreign ships in the EEZ subject to the approval of the International Maritime Organization (IMO), it is submitted that rules for guaranteeing safety at sea would have to be established by the IMO also in the context of cloud seeding.

**In light of the potential influence of cloud seeding activities on ocean circulation as well as the risk of pollution of the marine environment from condensation nuclei, a potential conflict of objectives exists for operations conducted on the high seas between that of mitigating climate change as pursued by the CE method and the potential hazards for the marine environment ensuing from such an activity.** Due to the fact that the high seas cannot be made subject to any state's claims of sovereignty, all states can exercise the non-exhaustive list of freedoms contained in Art. 87 UNCLOS. The deployment of cloud seeding ships on the high seas is therefore permissible in principle. The limitations on these freedoms are found in the other rules contained in the Law of the Sea Convention and public international law, as a whole. Relevant above all in this regard are—in addition to other states' freedom of navigation—the stipulations contained in Part XII UNCLOS (Art. 192 et seq.), which comprehensively address the protection and preservation of the marine environment. However, the Law of the Sea Convention does not provide a clear answer to the question as to how the potential conflict between the objectives included in Part XII UNCLOS on the one hand and those pursued with cloud seeding on the other could be resolved (see Section 6.5).

#### Modification of the Earth's surface

Modification of the Earth's surface is subject to CBD restrictions

**The permissibility of painting buildings and streets white for the purpose of increasing their albedo is judged according to the requirements of national law.** In order to achieve significant results, however, multilateral cooperation—ideally in the form of an international treaty—would be necessary.

**The artificial modification of desert and steppe landscapes, for example by installing reflective plastic sheeting, is subject to the restrictions contained in the Convention on Biological Diversity.** The 1992 Convention on Biological Diversity (CBD) also guarantees the protection of desert and steppe landscapes. In addition to the complete range of living genetic information and species diversity, the concept of "biological diversity" also encompasses landscapes such as forests and deserts as well as the functional interconnection between living species and their habitats (Art. 2 CBD). Covering existing deserts and steppe areas would be contrary to this objective.

**The protection of desert areas in accordance with the Convention on Biological Diversity is subject to the restrictions of the United Nations Convention to Combat Desertification (UNCCD).** For parties to both instruments—and in as far as the planting of vegetation with higher reflectance values is under discussion—it must be kept in mind that it is the UNCCD's objective to combat desertification. As long as it is suitable for this purpose, the planting of flora with higher albedo does not violate the Convention on Biological Diversity.

### 6.2.2 Legality of CDR technologies under international law

**Increasing oceanic carbon uptake through fertilization with iron, phosphorous, and/or nitrogen**

London Framework

**In regard to the legality of ocean fertilization, UNCLOS refers indirectly to the legal framework established by the London Convention and Protocol.** In light of the definition contained in Art. 1 (1)(4) UNCLOS, whether the introduction of a substance is to be qualified as pollution of the marine environment must be judged not according to the characteristics of the substances, but instead based on its effects in the marine environment (Rayfuse et al. 2008: 308). This also applies to the case of ocean fertilization. Part XII UNCLOS distinguishes between different types of pollution and designates corresponding legal obligations for each. In view of the fact that fertilization of a specific marine area could also be seen as dumping, Art. 210 UNCLOS comes into consideration as the pertinent protection norm. Art. 210 (6) UNCLOS, in turn, refers to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Convention, LC) as well as the Protocol to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Protocol, LP). The latter replaces the London Convention for its contracting parties.

Ocean fertilization is subject of international negotiations

**In order to assess the legality of ocean fertilization it is necessary to establish whether iron, phosphorous, and/or nitrogen are being introduced for purposes other than mere disposal and whether these do not conflict with the objectives of UNCLOS and the London agreements.** In accordance with Art. III (1)(a) LC and Art. 1 (4.1.1.) LP (as well as Art. 1 (5)(a) UNCLOS), the term "dumping" concerns the deliberate disposal of wastes and other matter. Even if the fertilizers introduced into the marine environment are not deemed to be "waste", they nonetheless constitute "other matter". Because these substances are intended to remain in the ocean, this constitutes "disposal". In accordance with the exception clauses to these norms, the depositing of fertilizer does not fall under the definition of dumping when it occurs for reasons other than mere disposal and, in addition, does not conflict with the objectives of the applicable treaty. The objective of ocean fertilization is to stimulate the primary production of phytoplankton in order to scientifically examine this process and its consequences, and, if appropriate, subsequently use it as a CE method for increasing the ocean's $CO_2$ storage capacity.[57] Thus, a different objective other than the mere disposal of fertilizer is being primarily pursued. Nonetheless, the question is not yet answered whether ocean fertilization activities contradict the objectives of the London Convention and Protocol framework and the Law of the Sea Convention. The objective of these treaties is to prevent the pollution of the marine environment through the disposal of wastes or other substances (Art. 194, 210 UNCLOS; Art. II LC; Art. 2 LP). It can therefore be assumed—at least at first glance—that it conflicts with the objectives of the treaties when the introduced substances have potentially negative effects on human health, living resources or marine species (Art. I LC; Art. 2 in conjunction with Art. 1 (6.10) LP). It cannot currently be ruled out that ocean fertilization entails such negative consequences.

57 See Section 3.3.3.

**A8**
**MORATORIUM**

**On the basis of the current interpretations of the Conferences of the Parties of the Convention on Biological Diversity and the London Convention, it may be assumed that ocean fertilization experiments, provided they are "legitimate", do nonetheless not contradict the objectives of the previously mentioned agreements.** While the 9th Conference of the Parties of the Biodiversity Convention introduced a de facto (though legally non-binding) moratorium on fertilization experiments in its Decision IX/16 on Biodiversity and Climate Change in May 2008, requiring "in accordance with the precautionary approach, to ensure that ocean fertilization activities do not take place until there is an adequate scientific basis on which to justify such activities [...]; with the exception of small scale scientific research studies within coastal waters"[58], the 10th Conference of Parties modified the requirements for research experiments authorized on an exceptional basis in October 2010 in its Decision X/33 on Biodiversity and Climate Change. In this way, the "coastal waters" criterion was abandoned. Research experiments should be carried out only "in a controlled setting in accordance with Art. 3 of the Convention". In addition, they should also be justified by the need "to gather specific scientific data" and subjected to "thorough prior assessment" in regard to their potential environmental impacts. In November 2008, the contracting parties to the London Convention adopted Resolution LC-LP.1 (2008) on the regulation of ocean fertilization, which, although equally not legally binding, must be taken into consideration when interpreting the scope of both London agreements. The central message of this document is that ocean fertilization activities contradict the objectives of the London framework when they cannot be classified as "legitimate scientific research." In order to judge whether ocean fertilization experiments are "legitimate", the Resolution requires the preparation of an assessment framework by the London Convention's scientific groups. Such a framework was adopted in October 2010 by the Conference of Parties with its Resolution LC-LP.2 (2010), two years after the adoption of Resolution LC-LP.1 (2008).

Legitimate scientific research on ocean fertilization is permitted

**The assessment framework imposes rigorous requirements to prove the existence of "legitimate scientific research", and contains, in connection with the decision-making process regarding the permissibility of iron fertilization experiments, first steps toward a comprehensive resolution of conflicts between objectives.** As a consequence, a research team must provide an extensive range of information before the responsible national authorities can make a decision approving the project. Precise details must be supplied regarding the financing of such research, which poses an additional hurdle for privately sponsored projects. The reason for this is that projects of a purely commercial nature do not fall under "legitimate scientific research" (Resolution LC-LP.2 [2010], para. 2.2.2). The rigorous requirements are relativized by the responsible authority's decision-making requirements in accordance with national law. Without explicitly referring to the objective of the Framework Convention on Climate Change, the decision-making process prescribed by the assessment framework is not exclusively concerned with the adverse impacts of ocean fertilization. Instead, it states: "[i]f the risks and/or uncertainties are so high as to be deemed unacceptable, with respect to the protection of the marine environment, taking into account the precautionary approach, then a decision should be made to seek revision of or reject the proposal" (para. 4.3).[59] If an experiment is incompatible with the objectives of the London Convention and the London Protocol, it should additionally be determined whether "environmental disturbance and detriment would be minimized and the

58 The meaning of the term "within coastal waters" is unclear. If the Conference of Parties based this on geographical proximity to the coast, the exemption clause would have ultimately been unusable because the artificial increase of the ocean's uptake capacity is unlikely to be successful due to the nutrient concentrations present in waters near the coast [see Section 3.3.3].

59 In view of the precautionary principle, a project can only be rejected or modified if the risks and uncertainties for the marine environment appear unacceptable.

scientific benefits maximized" (para. 4.1). The decision-making process thus allows room for weighing the risks to the environment stemming from ocean fertilization experiments against their potential benefits in regard to mitigating the negative consequences of climate change.

#### Increasing oceanic carbon uptake through pump systems in the high seas and Exclusive Economic Zone

The use of pump systems enhances ocean upwelling in order to bring nutrient-rich deep sea water to the surface. This CE method increases biological carbon storage in the ocean through fertilization and, at the same time, promotes short- and medium-term cooling effects. The use of pump systems also enables an increase in natural downwelling, through which water with relatively high carbon content is transported into the deep sea. With this CE method, the physical storage of carbon in the ocean is increased.

CE deployment on the high seas require due regard for the interests of other states

**As emphasized by the non-exclusive character of Art. 87 UNCLOS, the use of pump systems on the high seas is, in principle, covered by the freedom of the High Seas.** As in the case of cloud seeding activities, this freedom is, however, to be exercised "under the conditions laid down by this Convention and by other rules of international law" (Art. 87 (1) UNCLOS). This is particularly relevant in light of the due regard principle contained in Art. 87 (2) UNCLOS. The use of pump systems may not unduly interfere with the freedom of other states to use the high seas, for example, for navigation. Assuming that such an operation is deemed reasonable, the development of operational guidelines to reduce the risk of conflicts between the freedom to use the high seas and the other high seas freedoms could be appropriate. The UNESCO Intergovernmental Oceanographic Commission (IOC) and its Advisory Board of Experts on the Law of the Sea would be an appropriate forum.

Experiments on pump systems may require coastal state approval

**Because the testing of pump systems qualifies as marine scientific research, their operation in the EEZ is consequently subject to the coastal state's jurisdiction.** The coastal state enjoys the exclusive right to establish, approve and regulate the establishment, use and operation of artificial installations and structures (Art. 56 (1)(b)(i) in conjunction with Art. 60 UNCLOS). All categories of installations share the common feature that they are man-made constructions. An installation in terms of Art. 60 UNCLOS is characterized by its relative size, as well as the fact that the object remains fixed at one location (Kwiatkowska 1989: 108); this is thus applicable to pump systems fixed to the seabed. In regard to free-floating pumps, these can only be considered as equipment. The term "equipment" is not mentioned in Part V of UNCLOS concerning the EEZ, but is rather used in connection with marine scientific research. According to Art. 258 UNCLOS, their installation and use is subject to the rules governing marine scientific research in the area in question. In as far as the operation of pump systems can be qualified as marine scientific research (which can only be assumed in the trial phase), the coastal state exercises jurisdiction over such equipment in the EEZ. According to Art. 246 (3) UNCLOS, the coastal state is to grant its consent in normal situations. In the event of a conflict between the coastal state's sovereign rights and jurisdiction contained in Art. 56 (1) UNCLOS, on the one hand, and the freedoms of other states found in Art. 58 (1) UNCLOS on the other, a rebuttable presumption exists in favor of the coastal state's legal position. This presumption derives from the sui generis character of usage rights in the EEZ and only applies if and to the extent to which the conduct of the coastal state cannot be considered as constituting an abuse of rights (Art. 56 (2) UNCLOS) (Proelss 2006: margin note 273; Proelss 2010 a: 361ff).

#### Chemical processes for marine carbon uptake

**In light of the fact that the increasing alkalinity of the oceans calls for the introduction of specific substances into the marine environment, the same international legal standards are applicable as in the case of ocean fertilization.** The legality of such CE activities is determined on the basis of the UN Convention on the Law of the Sea, supplemented by the framework established by the London Convention and Protocol. The Biodiversity Convention also comes into consideration in regard to potential impacts on marine ecosystems.

Ocean-based chemical CDR may be compatible with international law

**Despite uncertainty in regard to its scientific basis, there is currently no indication that the introduction of substances to increase ocean alkalinity is illegal or represents dumping in contradiction to the objectives of the applicable treaties.** In order to determine whether the introduction of substances constitutes dumping, it is necessary to determine in accordance with Art. III (1)(a) LC, Art. 1 (4.1.1.) LP and Art. 1 (5)(a) UNCLOS whether the introduction of the substances contradicts the objectives pursued by these treaties. Because their purpose is, at least in part, to prevent the pollution of the marine environment, a contradiction with the objectives of the treaties can be deemed to exist when the introduced substances have potentially damaging effects on human health, living resources or marine life. However, unlike iron fertilization, activities to increase the alkalinity of the ocean can specifically be designed to counter increasing ocean acidification and its negative consequences for marine ecosystems.[60] In addition, these seek to increase the ocean's absorption of atmospheric carbon dioxide. This suggests compatibility with the objectives of the relevant treaties. None of the calcium-containing substances is covered by the exemptions listed in Annex 1 to the London Protocol, particularly not those applicable to inert, inorganic geological substances. From a systematic point of view, this supports that the introduction of such substances does not constitute dumping. Nonetheless, in the event of large-scale introductions by a number of ships, the obligation of due regard under the law of the sea must be respected so that other states' freedoms of use are not unduly impaired.

**Provided that the alkalinity of the ocean is increased through the electrolytic removal of hydrochloric acid in special water treatment facilities, there are no additional restrictions.** Both the UN Convention on the Law of the Sea and the London Convention/Protocol are based on the terms pollution and dumping. However, these concepts are not affected by electrolytic treatment. While the UN Convention on the Law of the Sea obliges its contracting parties to protect and preserve the marine environment (Art. 192 UNCLOS), this is not an absolute obligation to leave the marine environment untouched. Instead, the general obligation contained in Art. 192 UNCLOS, irrespective of its legally binding character, is to be interpreted in light of the specific rules contained in Part XII UNCLOS as well as the complete spectrum of rules contained in other parts of the treaty (Proelss 2004: 77). Existing rights to explore and exploit marine resources as well as other potential uses of the ocean make clear that Part XII UNCLOS concerning the protection and preservation of the marine environment does not seek "zero impact" on the ocean. The construction and operation of electrolysis facilities is otherwise subject to the requirements of national environmental law so that—irrespective of the general rules of customary international law, which will be presented in more detail (see Section 6.3)—no further international legal restrictions are applicable.

#### Increasing $CO_2$ sequestration on land through afforestation and forest management

Ecosystems are protected under the CBD

**It is largely the responsibility of individual states to regulate questions of afforestation, reforestation and forest management on the basis of national law.** In order for such CDR

60 See Section 3.3.2 and 4.3.1.

activities to make a significant contribution toward the mitigation of global warming, coordinated action would be necessary, ideally in the form of a multilateral treaty. As long as combating desertification is not the subject of discussion, which would open the scope for the application of the UNCCD[61], the Convention on Biological Diversity restricts the afforestation of deserts and semi-deserts, as well as the creation of the necessary conditions for reforestation, as it protects these landscapes and their ecosystems.

**Acceleration of natural weathering through the spreading of olivine**

The legality of spreading olivine on the territory of individual states is primarily to be judged according to national law. International legal restrictions derive from the provisions of the Convention on Biological Diversity. These protect landscapes such as forests, on whose soils olivine could be spread, as well as the functional interconnections between living species and their habitats. No restrictions can be found in the 1999 Protocol to Abate Acidification, Eutrophication and Ground-level Ozone to CLRTAP,[62] as the weathering of olivine is specifically intended to counteract the acidification of the soil and thereby contribute to the realization of the Protocol's objectives. If, however, part of the absorbed carbon is to be fed into the ocean via rivers, this would lead to increased $CO_2$ levels in the ocean, which in some circumstances (fertilization effects brought about by the simultaneous introduction of silica) cannot be counteracted by increasing alkalinity. The potential for negative impacts on the marine environment resulting from this could have the consequence that the acceleration of natural weathering is to be treated as legally analogous to ocean fertilization (see this section concerning ocean fertilization with iron, phosphorous and/or nitrogen).

In the event of negative impacts on the marine environment, the extraction of olivine is to be evaluated in accordance with the legal requirements concerning ocean fertilization

**Chemical air capture of carbon**

Irrespective of the technology for air capture under discussion, devices are necessary which must be installed on the territory of individual states. These, as well as the geological storage of captured carbon on national territory, are therefore subject in their entirety to the requirements of national law as they are not apparently of transboundary nature. The parallels to afforestation suggest that air capture should be incorporated into the UNFCCC's flexible mechanisms in the future.

## 6.3 Rules of customary international law

**In connection with climate engineering, the customary rights of neighboring states are particularly important for the resolution of conflicts arising from activities, which take place within the territorial jurisdiction of a state ("state of origin") and damage the environment of another state ("victim state").** In such situations, a balance must be struck between the sovereign interests of states, which are reflected in the territorial sovereignty of the state of origin and the territorial integrity of the victim state. Two principles of customary international law provide a balancing mechanism: the prohibition on significant transboundary environmental harm and the obligation to equitably use of transboundary resources. In the specific context of climate engineering, only the prohibition on significant transboundary environmental harm, which has developed into a general obligation of prevention (ICJ 2010: § 101), provides clarification. It only becomes applicable when environmental damage has already taken place or when the consequences of a particular activity can clearly be associated with such environmental damage. The ICJ has meanwhile extended this principle to the protection of the environment in areas beyond the sovereignty of states (ICJ 1996: § 29; ICJ 2010: § 101).

Climate engineering with the potential to cause significant transboundary environmental harm are prohibited

61 See Section 3.2.5.

62 See Section 6.2.1 concerning reflectors in the stratosphere.

**The principle of prevention does not represent a "no harm rule".** It becomes applicable in situations in which environmental damage is likely to occur. The objective of the principle of prevention is to ensure that measures are taken to prevent adverse consequences of environmental damage or to reduce these to the greatest extent possible (Jiménez 1996: 392). The mere possibility of environmental damage, however, does not yet activate the principle of prevention. This is frequently the case in regard to the CE activities described here. Scientific certainty is, on the whole, lacking in regard to the causal connection between the implementation of a CE activities—an activity, which is potentially damaging to the environment—and potentially adverse environmental impacts. It should be specifically noted that not all forms of environmental damage—whether in the context of neighboring states or in regard to the global commons—are violations of international law. Otherwise the sovereign right of states to use their own resources would be undermined. According to the prevailing opinion, the obligation of prevention does not amount to more than an obligation to act with "due regard/ diligence" (Birnie et al. 2009: 147ff). Among other obligations, this establishes that the use of environmentally damaging technologies requires that the most environmentally sound available technology must be selected and that the interests of other affected states as well as the areas beyond the jurisdiction of states must be respected. Birnie et al. (2009: 147, 150) understand the principle of prevention therefore as an "obligation of conduct" rather than an "obligation of result". The ICJ has confirmed this view in the Pulp Mills case. In the event that the principle of prevention is evoked in the context of the prohibition on significant transboundary environmental harm, the Court insisted on the necessity to provide evidence of the existence of environmental damage (ICJ 2010: § 101). Sufficient likelihood of damage occurring is enough in this regard (ICJ 2010: § 228). Corresponding to the principle of prevention is "an obligation to act with due diligence in respect of all activities which take place under the jurisdiction and control of each party" (ICJ 2010: § 197).

Interventions in natural processes require mutual consideration

**In regard to CE activities, states wishing to undertake such activities must satisfy the requirements arising from the obligation of due diligence under customary international law.** As a precondition for this, the ICJ has found that an environmental impact assessment (EIA) must precede activities for which there is sufficient likelihood that damage will occur; the exact structure of this is not specified in customary international law (ICJ 2010: § 205). It can be assumed that the requirements the EIA must satisfy increase proportionally to the hazard posed by the measure planned by the given state. In order to establish a breach of the obligation of due diligence, on the other hand, it is necessary to provide "conclusive evidence" (ICJ 2010: § 265).

**Ultra-hazardous activities cannot be automatically included under the prohibition of significant transboundary environmental harm.** There is a lack of state practice and opinio juris that could provide a basis for the automatic application of the prohibition of significant transboundary environmental impacts to high-risk activities undertaken close to state borders, or to those with the potential for transboundary harm. For this reason, the prohibition of (significant) transboundary environmental damage is only applicable to CE activities when it can be proven with sufficient likelihood that either a state has caused damage in an unlawful manner, or that it has willfully disregarded the obligation of due diligence arising from the principle of prevention. This demonstrates that the principles of customary international environment law with origins in the rights of neighboring states are only of limited appropriateness for regulating activities with potentially global impacts.

## 6.4 General rules on responsibility and liability under international law

No general liability for lawful activities involving the risk of transboundary environmental harm

**There is no liability of states for activities that are allowed but involve a variety of risks under international law.** In order to establish the international legal responsibility of a state in accordance with the ILC Articles on Responsibility of states for Internationally Wrongful Acts (2002), which represents customary international law in large part, it is necessary to establish, in addition to the breach of an international legal obligation, that an act or omission is attributable to that state (Art. 2 Articles on state Responsibility). The international legal obligation can be any part of an international norm as defined in Art. 38 (1) ICJ Statute, which was binding for the state in question at the time the act to be attributed occurred. In regard to CE activities, this can easily be proven in most cases when the measure in question was conducted at state level. An argument against the extension of the concept of state responsibility, which always requires a breach of international law, to include activities that are allowed but involve risk is that treaty-based rules on strict liability have been established only in very few individual cases[63]. In as far as a CE activity is in conformity with international law, an obligation to provide compensation can thus not be founded (Bedjaoui 2000: 214ff).

**State responsibility can only be invoked by the state "victim" to the breach of an international legal obligation.** For this to occur, it is necessary that a state is directly affected by the illegal act of the injuring state and that the international legal obligation that was breached was owed to that state (Art. 42 Articles on state Responsibility). When erga omnes obligations[64] are violated (e.g., the protection of the marine environment; Ragazzi 1997: 158ff; Lagoni 1991: 147ff; Proelss 2004: 79ff), Art. 48 of the Articles on state Responsibility additionally recognizes the legal interests of states, which were not themselves directly affected, to invoke the responsibility of the injuring state. It remains disputed, however, whether this norm represents customary international law. Even if one affords erga omnes effect to the protection of the marine environment in areas beyond state sovereignty, misgivings remain in regard to the existence of standing (*ius standi*) for other states (Talmon 2006: 293ff; Proelss and Müller 2008: 677ff; Ragazzi 1997: 212; for another view, Tams 2005: 161ff; Birnie et al. 2009: 232ff) when these are not directly affected by the breach of the pertinent international obligation. In light of the on-going doubt as to the acceptance of the actio popularis[65] in international law (ICJ 1966: § 88; ICJ 1970: § 91), even if one recognizes every state's legal interest in invoking the responsibility of the "injuring state", this does not establish that this responsibility can be enforced by judicial process.

## 6.5 Future developments

Conferences of the Parties are currently appropriate fora for CE negotiations

**Even if newly emerging phenomena are included within the scope of an international treaty or customary international law, this does not mean that they are reasonably and effectively regulated.** This suggests that it is appropriate to cast a glance at future legal developments—particularly in light of the supplementary contribution of customary international law. Reforms are also needed from an institutional standpoint due to the specific characteristics of climate engineering. Developments up to now indicate that for the time being, the debate surrounding the legality of research and deployment of climate engineering will continue in

63 See Section 3.2.1.

64 Obligations *erga omnes* ("toward all") refer to the commitments of a state, which exist not solely toward other individual states, but instead toward the community of states as a whole.

65 The *actio popularis* ("collective action") refers to proceedings brought by a legal subject which is not directly affected.

the sovereignty-friendly form of conference diplomacy. The appropriate fora continue to be the Conferences of the Parties to the existing multilateral treaties, above all the UNFCCC, the CBD and the London Convention/Protocol. Compromises and concessions will remain necessary in the future, potentially to the detriment of the effectiveness of a future CE regime. The international system lacks a world legislator that could establish uniform standards for the research and deployment of climate engineering. The UN Security Council, the institution that would come into consideration at first glance, can only adopt legally binding decisions in fulfillment of its primary responsibility for the maintenance of international peace and security (Art. 24 (1) UN Charter). A concrete mandate to take action on the basis of Chapter VII of the UN Charter requires that the Security Council determine the existence of a threat or breach of the peace or an act of aggression (Art. 39 UN Charter). It cannot be ruled out that the consequences of climate change for security policy could ultimately entail that a threat to the peace could be established in the terms of Art. 39 UN Charter in the event of drought-induced transboundary refugee flows, grave human rights abuses or other similar situations (Podesta und Ogden 2008). This could eventually require a revision of the existing rules for the maintenance of peace and security. There are currently no indications, however, that such reforms will be undertaken.

**The precautionary principle provides a potential approach to the resolution of conflicts between objectives in the context of activities, which may have negative effects at the regional or local level, but nonetheless have the potential to stabilize global warming at a level acceptable for human beings and the environment.** This principle, whose status as customary international law continues to be debated (Cameron and Abouchar 1996: 36ff), can be found in at least rudimentary form in many of the instruments examined here; it therefore comes into consideration as a "lowest common denominator" (Proelss and Krivickaite 2009: 444) in the international law applicable to CE activities (Proelss 2010b). In the international context, its core elements were reformulated in Principle 15 of the Rio Declaration (ILM 31 [1992], 874) adopted in June 1992 at the Earth Summit in Rio de Janeiro. According to the Rio Declaration, states are to widely apply the precautionary principle according to their capabilities. In situations where there is a risk of significant or irreversible damage, the lack of full scientific certainty may not be used for discontinuing environmental protection measures that have already been taken. The lack of complete scientific certainty is a centrally important element in the context of international environmental law. In regard to hazard potential and the consequences of a measure potentially damaging to the environment, for example the introduction of certain substances into the marine environment, it will only rarely be the case that full scientific certainty exists at the point in time in which the particular measure will be implemented. This is that much more the case for global environmental phenomena like climate change which are influenced by a variety of different factors.

A15
LESSER EVIL
A26
DISTRIBUTIONAL EFFECTS

Precautionary principle offers a potential starting point for the resolution of conflicts between environmental objectives

**Although the precautionary principle itself does not issue specific authorizations to act, it nonetheless influences actions taken on the basis of other authorizations.** In regard to the CE technologies examined above and their associated and potentially significant risks, the precautionary principle appears at first to argue for the protection of the part of the environment specifically addressed in the treaty provision, which is potentially affected by CE research or deployment. A conflict between objectives becomes evident, however, when the Framework Convention on Climate Change, which is also based on the precautionary principle, is examined in a cross-sectoral manner. According to the Framework Convention, states should take precautionary measures to counter climate change and mitigate its negative effects. Art. 3 (3) UNFCCC clearly states that "[w]here there are threats of serious or irreversible damage, lack of full scientific certainty should not be used as a reason for postponing such measures". In the context of climate protection, the precautionary principle thus provides an argument in favor of CE measures when these measures are understood as part of a mitigation strategy (Bodle and Kraemer 2010: 45). This is also seen in Art. 4 (1)(d) UNFCCC where the contracting parties "promote and cooperate in the conservation and enhancement [...] of sinks and reservoirs [...], including biomass, forests and oceans as well as other terrestrial, coastal and marine ecosystems". Ultimately, there is no apparent reason why the precautionary principle should not be applied to specific categories of intervention into natural systems like climate engineering.

**As the ultimate consequence, an isolated understanding of the precautionary principle could hinder the move toward sustainable use of the environment and its resources.** If the scope of the precautionary principle is limited to the legal interests protected by a particular treaty, situations could arise in which a specific human activity is prohibited due to a lack of scientific certainty in regard to its potential negative impacts on the environment, and scientific field experiments designed to rectify the lack of scientific information are not authorized due to the potential for negative environmental impacts. There is a danger that scientific uncertainty will be perpetuated in such situations.

**As a legal principle, the precautionary principle can be used as a procedural instrument to substantiate and more effectively structure states' material obligations in the field of climate protection.** The precautionary principle is a legal principle in the sense of the theoretical distinction between rules and principles (Proelss 2010b: 80ff; for a different view Beyerlin 2002: 56). It is characteristic of principles that they do not establish specific legal consequences and can instead be satisfied in various ways. They call their addressees—primarily states in international law—to realize a "target ideal" to the greatest extent possible (Alexy 1995: 177ff). In view of their formal structure as "obligations to optimize" (Alexy 2002: 70) they express normative values, which depending on the given factual and legal conditions, can be realized to varying degrees through the optimized balancing of conflicting principles using the principle of proportionality as a benchmark. In this sense, the precautionary principle does not require behavior of a specific content and scope from its addressees (Marr 2003: 13). Its application is much more situation-bound, which prevents its content from being realized in an "all-or-nothing manner". Its situation-specific character and resulting structural indeterminacy as well as its openness regarding content (Birnie et al. 2009: 161ff) which cannot be resolved solely through interpretation, reveal themselves above all in the element of lack of scientific certainty.

Precautionary principle as an instrument of cross-functional risk balancing

**The resolution to be reached by balancing conflicting interests and values is based on the idea that the precautionary principle, as a legal principle, can be satisfied to different degrees.** The extent of the expected environmental damage, the degree of scientific uncertainty in regard to the negative consequences of climate engineering, as well as the structure of the precautionary principle in the relevant treaties should be included as part of the weighting in each case. The risks, which first exist during research and later during the potential deployment of CE activities and threaten specific areas of the environment depending on the CE technology in question, can be weighted according to their relationship to the potentially climate-relevant advantages of climate engineering arising from the objectives of the Framework Convention on Climate Change and the Kyoto Protocol. It may ultimately prove necessary to accept a certain degree of environmental damage in this process in order to advance the comprehensive goal of climate protection. For the purpose of harmonizing these objectives of international environmental law, the possibility of balancing protected interests emerges as a third pillar in addition to the coordination mechanisms known in treaty law (recourse to collision clauses and treaty interpretation) and the mechanisms of institutional cooperation. Such an understanding can be considered in this regard as the precautionary principle is expressly or implicitly included in the pertinent treaties and thus serves as their common denominator (Proelss and Krivickaite 2009: 444ff; Erben 2005: 225).

**There are first indications that this proposal for the resolution of conflicts between protection objectives based on the precautionary principle will feed into the practice of international law.** It can be argued, however, that the proposal presented here for the cross-functional operationalization of the precautionary principle, which seeks a preliminary legal appraisal of all CE activities (research and deployment), cannot lead to the development of clear solutions or provide legal certainty. In individual cases, it is likely that a focus on the balancing of theoretical principles alone will not adequately address the need for rule-making at the transnational level. However, provided that a comprehensive ban of climate engineering is not negotiated (which would only be effective if all states with the necessary technologies were to participate), the decision for or against CE research and/or deployment ultimately will have to be based on a balancing of risks due to the existence of scientific uncertainty. The example of ocean fertilization confirms that the question of the legality of a specific CE method cannot fully be determined at the international level, but must instead be resolved by the appropriate national authorities—even though the decisions of the competent domestic bodies will be incorporated within the existing international framework. Thus the assessment framework adopted in 2010 within the scope of the London agreements,[66] which is intended to provide a basis for the evaluation of the legality of iron fertilization experiments, was amended in the final negotiating round to include procedural rules, which enable a weighing of the potential environmental risks of ocean iron fertilization experiments against their potential benefits in regard to the mitigation of the negative effects of climate change. In this regard, the approach presented above is based on the factors that would form the core of any future rule.

## 6.6 Summary of international legal issues

**Due to the largely transboundary nature of the CE technologies involved, the legality of climate engineering is primarily judged according to the rules of the partial legal system of international law.** Because international law is first and foremost defined as the law applicable between states, efforts to regulate these activities should focus on the level of international relations—represented, for example, by the Conferences of Parties to the applicable treaties. International law does not currently contain comprehensive norms specifically addressing the research and deployment of climate engineering. No international treaty has ever been adopted with the intention of normatively restricting such activities.

Framework approach ensures applicability of existing treaties to individual CE measures

**That individual CE technologies are nonetheless covered by existing treaties can be attributed, at least in part, to the framework approach commonly found in international law, which is applied particularly in connection with global environmental issues (climate, ozone layer, biodiversity protection).** It is characteristic of this approach that a specific issue is comprehensively regulated in a multi-stage process: while a framework convention contains general principles and rules for the peaceful resolution of disputes, specific rights and obligations are first codified in annexes to the convention or in subsequently adopted protocols. As a result, the rules contained in the framework convention are often applicable to new phenomena that were unknown at the time the treaty was negotiated. In addition—not least due to the need to compromise in international relations—factual requirements are often “openly” formulated in

66 See Section 6.2.2 on ocean fertilization with iron, phosphorous, and/or nitrogen.

treaties that address specific issues so that developments, which were not part of the treaty's original intentions, can nonetheless be covered by treaty norms.

Legality of CE technologies must be individually assessed

**No binding definition of climate engineering exists under international law.** The 10$^{th}$ Conference of Parties to the Convention on Biological Diversity included a preliminary definition of the term in a footnote to Decision X/33 on Biodiversity and Climate Change. This definition is not legally binding, however, and refers only to the CBD's scope of application. Although the distinction between SRM and CDR was made here for the first time in the context of an international treaty, no concrete legal consequences can be drawn from this. The legality of climate engineering must instead by judged separately for each individual measure on the basis of international treaty and customary law.

No general prohibition of climate engineering under international law

Concerning legal uncertainties, which are, above all, attributable to scientific uncertainty in regard to the risk of environmental damage as a result of CE activities, it can first be established that, **particularly against the background of the Framework Convention on Climate Change, a general prohibition of climate engineering does not exist under international law.** Second, closer examination of individual CE technologies supports the **conclusion that CDR measures tend to elicit fewer legal objections than RM measures.** This is particularly true in regard to the acceleration of carbonization by increasing the alkalinity of the ocean as well as the acceleration of natural weathering. Unlike in the case of iron fertilization, a contradiction to the protection objectives of the applicable international legal instruments cannot—or can only minimally—be seen with regard to these CDR technologies on the basis of currently available scientific knowledge. Third, the vast majority of all CE technologies requires **that due regard be paid to the existing rights and territorial integrity of other states.** As this cannot normally be assumed in the case of a purely unilateral action, it is submitted that a refutable assumption of unlawfulness is assumed for such measures. Fourth, in regard to RM measures, in particular, legal assessment depends, above all, on **how the phenomenon of conflicting environmental objectives is handled in the future.** This refers to situations in which a human activity, which may have potentially negative consequences for part of the environment, has the potential to positively influence the condition of another part of the environment at the same time.

Development of international environmental law with regard to climate engineering requires balancing of environmental risks

In regard to the future development of international environmental law, it is important that the decision for or against CE research and/or CE deployment always requires that a balancing of the risks involved is performed due to the existence of scientific uncertainty. The example of ocean fertilization and the recently adopted assessment framework confirms that the question of the legality of a specific CE technology cannot be conclusively answered at the international level, but must instead be resolved by the appropriate national authorities, which then ought to take into account the international legal requirements. The situation would only be different if one or more CE technologies had been specifically prohibited or allowed at the international level. There are, however, no indications that this has occurred.

Because scientific uncertainty in regard to both the potentially negative impacts of climate engineering on the environment and the consequences of climate change is unlikely to be resolved for the time being, regulatory approaches are necessary, which enable a flexible approach to new knowledge and developments. This cannot be accomplished by creating (putatively unambiguous) norms of obligation or prohibition—a proposition which is already unrealistic due to the divergence of interests existing in the international community. If one accepts that it will be necessary in the future to answer the question on a case-by-case basis, which potential environmental impacts are acceptable in regard to a CE activities potentially suitable for mitigating the negative consequences of global warming, particular attention should be paid to the procedural safeguards of the risk balancing process upon which that decision is based. In addition, the general customary duties to conduct consultations and perform environmental impact assessments in the context of the specifically and "most likely" impacted treaty are to be adapted to the specifics of the CE technology in question and effectively implemented at the international level.

# 7 International Coordination and Regulation

**In addition to considerations of effectiveness and economic efficiency, the extent to which CE research and deployment is possible is determined in particular by the international political circumstances.** In contrast to the analysis of international law, which is concerned with existing legal conditions, this chapter focuses on the forms of international cooperation that are necessary and desirable for researching and, if appropriate, implementing CE technologies. To this end, this chapter examines, on the one hand, the international political conditions CE technologies face and, on the other hand, the regulatory requirements for research into and any possible implementation of CE technologies that result from these conditions.

**AC8**
OBJECTIONS RELATING TO JUSTICE AND FAIRNESS

**AC2**
RESEARCH SIDE-EFFECTS

In general, social and political problems arising from cross-border activities can only be tackled effectively through international cooperation and international institutions. Even if an individual state were able to reduce its $CO_2$ emissions to zero, climate change and the problems it creates would continue virtually undiminished if not at least the most important emitters of greenhouse gases were to jointly reduce their emissions. Anthropogenic climate change is therefore a prime example of a global problem that requires a global solution. International regulation of climate engineering should therefore ideally (i) encompass an incentive system that solves the free-rider problem, (ii) create a compensatory mechanism between CE winners and losers, and (iii) limit the side-effects of research as far as possible by establishing rules for the investigation of CE technologies.

Practical implementation of an international CE regulation encounters a variety of difficulties

The practical implementation of such a regulatory framework is admittedly likely to encounter a large number of difficulties. Climate negotiations to date have shown that, for example, a rapid and effective implementation of measures to control emissions often fails due to the principle of consensus in international politics. In the case of an international regime such as the UNFCCC, all parties to the treaty must agree to regulations unanimously, as there is generally no majority decision-making process at the level of treaty negotiations. Agreement to an effective international climate regime is, in addition, made more difficult by considerable distributional problems. For example, agreement needs to be found as to who is to bear the costs of abating $CO_2$ emissions. Even in the event that an agreement were reached, the question would remain as to how the rules and regulations, once determined, could actually be imposed in the absence of any central enforcement agency. This problem is augmented further by the precarious legitimacy of international institutions.

On the one hand, climate engineering could possibly be implemented unilaterally …

In view of these structural and so far more or less insuperable difficulties regarding the creation of an effective international climate regime, climate engineering might at first glance appear to be a revelation due to the possibility of it being implemented by a single state. Nobel Prize winner Tom Schelling succinctly stated that in his opinion, the possibility of unilateral CE deployment turns the political logic of negotiations on an international climate regime on its head (Schelling 1996: 305). Instead of global agreement, decisive action on the part of a single state or a small coalition of states would suffice, while the costs of deployment could be shared. Schelling (1996: 306) concludes: "Primarily the issue is who pays for it? And this is an old-fashioned issue; we have dealt with it before".

… on the other hand, this will also entail difficulties

However, the global problem structure of climate engineering also entails complications: Effects of CE technologies impacting differently on different regions and unforeseen side-effects are one aspect of this, the danger of significantly diminished efforts to reduce emissions another.

In its report on the subject, the Royal Society therefore writes that "[t]echnical, legal, ethical, economic and other concerns need to be balanced carefully in a policy and governance framework which is international in scope and remains flexible in light of fresh evidence" (Royal Society 2009: 37). Against this background, three aspects of the debate are dealt with in this chapter: Firstly and most basically, to what extent is Schelling's thesis valid that climate engineering can be deployed unilaterally or minilaterally? Secondly, what would be the social and political consequences of such a unilateral or minilateral deployment? And thirdly, what requirements would have to be considered in developing a multilateral solution?

The first question must therefore be whether it is possible and likely that a single country or a small group of countries might deploy CE technologies. To answer this question, the following aspects must be examined:

A10
DO-IT-ALONE ARGUMENT

- In the absence of international cooperation, which CE technologies would be suitable for research, funding, and implementation by a single state (or a small group of states)?
- Could the application of these technologies be supported by arguments drawing on existing international law?

In order to answer these questions, reference must be made to the scientific, economic and international law assessments made in the previous chapters. The central issue is to insert these "external" data into the political analysis of international cooperation. It becomes apparent that some CE technologies—but by no means all of them—can indeed be applied uni- or minilaterally from a scientific, financial and legal point of view.

**Even if a uni- or minilateral application of some CE technologies would appear to be technically feasible, in view of potential (non-intended) consequences the question as to the desirability of such a CE deployment and associated uncoordinated CE research would remain.** The following aspects must be considered in this regard:

AC7
RISK ETHICS
A25
SOCIO-POLITICAL UNCERTAINTIES

- Can CE technologies be effective in the long term in the absence of any international regulations?
- What are the likely effects on the UNFCCC process?
- Could a unilateral deployment of climate engineering lead to global tensions in view of uneven regional impacts?
- What political reactions could unilateral research into CE technologies provoke, in particular in view of global efforts to reduce emissions?

Discussing this second set of questions results in an expansion of perspective and methodology, as sociological and political logics beyond the assumption of states as unitary, rational actors now come into consideration. It becomes apparent that a uni- or minilateral approach to climate engineering could unleash a number of problematic consequences that make it seem advisable to integrate research and deployment of climate engineering into a multilateral negotiating process.

**This leads to the question of which requirements are necessary for a suitable form of international regulation to ensure effective and legitimate governance of research and deployment of CE technologies.** This essentially entails the development and use of CE technologies in such a way that sufficient political and social legitimacy is generated and the negative effects on emission control remain limited. Which preconditions have to be fulfilled such that an interface with the UNFCCC process can be established to ensure that the endeavors to secure reductions in emissions are not impaired? This involves both dealing with already existing international committees, institutions, actors and regulations, to which reference could be made in the opinion formation on and the regulation of climate engineering, as well as considering possible institutional innovations in this area.

## 7.1 International cooperation requirements for research and deployment

**Schelling's central thesis concerning the simple logic of implementing climate engineering activities from a political perspective in the end rests on the assumption that such technologies are extremely effective from an economic point of view and that they can easily be implemented uni- or minilaterally, both in technical and legal terms.** Accordingly, the first thesis which is to be assessed states:

> Thesis K7.1: Most CE technologies can either be financed and implemented unilaterally or by a coalition of a few resource-rich states and do not entail any clear breach of international law.

Schelling's thesis about the cost-effectiveness of CE technologies and the possibility associated with this of solving the climate problem unilaterally is put forward in transparent terms in an article by Scott Barrett, titled "The Incredible Economics of Geoengineering". Barrett announces programmatically: "In contrast to emission reductions, this approach [climate engineering, the authors] is inexpensive and can be undertaken by a single country, unilaterally" (Barrett 2008: 45).

Schelling's thesis regarding the possibility of solving the problem of rising global mean temperatures unilaterally rests on two sub-theses:

> Thesis K7.1a: CE technologies exist which are so cheap and effective that they are easy to implement, either unilaterally or minilaterally.

> Thesis K7.1b: No explicit, legally binding prohibitions are in place at the level of international law, so that a justification for researching and deploying climate engineering appears possible.

For Thesis K7.1a the costs of such tehnologies must be so low and their efficacy so high, that they can be implemented by a single state or by a small group of states, without the question of cost-sharing becoming an insurmountable hurdle. In addition, the technologies, if they can should be implemented uni- or minilaterally, must be capable of being performed on the territory of an individual state, on a limited number of state territories or in common spaces outside national jurisdiction. For Thesis K7.1b international law must not formally have the authority to block such a solution.

Some CE technologies can be implemented effectively on a uni- or minilateral basis

**The first sub-thesis, K7.1a, can be confirmed based on the outcomes of Chapters 3 and 4: CE technologies do exist which appear so effective and cheap that they can easily be implemented either unilaterally or minilaterally.**[67] We assume (i) that a technology is considered as highly effective if it is capable, as a single measure, to avoid any further increases in global mean temperatures;[68] and (ii) that it is considered as cheap if it can be financed within the governmental budget of a large state. In terms of the Schelling Thesis, with reference to the

67 In Section 3.2, it was shown that, at least in theory, particular technologies exist, which allow for a large-scale manipulation of the radiation budget. In Section 4.1, it was shown that the implementation and pure operating costs for these technologies appear in part to be considerably below the costs of conventional emission control measures. These results are, however, still subject to considerable uncertainty and the sub-thesis is only confirmed subject to the uncertainty expressed by the corresponding estimations.

68 Ideally, it should also be possible to reach this result within a relatively short period of time. The determination of effectiveness is based here like in Chapter 4, on whether a technology can achieve the goal of climate stabilization on its own.

question of the extent to which a CE technology can be financed, only those costs are taken into account which arise from unilateral implementation (research, investment and operating costs), but not potential external costs which can occur on a global scale. Technologies which are highly effective and cheap in this sense are regarded as highly efficient. On the basis of this operationalization, a typology of CE technologies can be established (Table 6). This reveals that the Schelling Thesis is de facto only fulfilled for the technologies of putting aerosols into the stratosphere, marine cloud modification, and cirrus cloud modification. And this only holds if these technologies will deliver in terms of cooling which their proponents hope for.

| | Efficiency[A] | |
|---|---|---|
| | High | Low |
| Can be implemented centrally[B] | Stratospheric aerosols<br>Marine cloud modification<br>Cirrus cloud modification | Ocean fertilization<br>Space reflectors<br>Enhancement of natural weathering in the ocean or land<br>Biochar<br>Air capture |
| Decentralized implementation necessary[C] | | Large-scale afforestation<br>Increased urban albedo<br>Increased desert albedo |

A Effectiveness relates to the costs, at which an increase in the global average temperature can be prevented through the respective technology. If the potential of any technology is inadequate for this or if the costs required for this cannot be financed within the framework of the governmental budget of a very large state, then its effectiveness is rated as low. Classification is based on current estimations (which are still subject to a high degree of uncertainty).

B Central implementation is possible if a technology can be implemented by a state (or a small group of states) either within its own territory or in common spaces outside national jurisdiction.

C Decentralized implementation requires deployment on a variety of state territories.

TABLE 6: Typology of CE technologies in terms of how far they can be achieved on a uni-/minilateral basis

Source: Own representation.

International law does not provide a general prohibition of climate engineering …

**The second sub-thesis (K7.1b) can be confirmed given the results from Chapter 6: international law does not lay down any general prohibition of CE activities.** Against the background of the UN Climate Framework Convention, there is no general prohibition of climate engineering under international law. To this extent, Virgoe's statement (2009: 109) is true that: "No existing treaty deals explicitly with geoengineering", and further: "None of these treaties was drafted with geoengineering in mind, and none of them clearly prohibits or regulates relevant activities" (Virgoe 2009: 111). In a similar way, Zedalis (2010b: 31), formulates the view that "[...] next to nothing is present in any of the agreements that constitutes an iron-clad prohibition on geo-engineering." The Royal Society (2009: 45) therefore rightly arrives at the view that: "While no single international instrument applies, there are a number of existing treaties and customary rules which could be brought to bear, depending on where the activity and its effects occur."

**Thus the key issue is the interpretation of existing treaties under international law.** In this regard, closer analysis of individual CE technologies has revealed that CDR technologies tend to encounter fewer legal reservations than RM technologies.[69] This especially applies to technologies such as increasing the alkalinity of the ocean, with reference to which a contradiction of protection goals under international law on the basis of the scientific information currently available does not exist or exists only to a limited extent.

69 See Section 6.6.

**Nevertheless, controls do exist under international law, which could impede a unilateral deployment of climate engineering**, possibly also irrespective of context-specific agreements. The vast majority of CE technologies require due regard to be given to existing laws and the territorial integrity of other states. In the case of proceeding unilaterally, the possibility of impermissibility is correspondingly higher than in the case of a coordinated, minilateral implementation by a group of states. Particularly with regard to RM technologies, legal assessment depends above all on how the phenomenon of conflicting environment-related objectives is handled in the future. In this process, a collision of objectives related to the environment describes situations in which the deployment of a CE technology, which is supposed to mitigate climate change, can possibly have a negative effect on another legally protected environmental resource (such as the marine environment, biodiversity, inland waters, etc.). Against this background as well, carrying out CE technologies within the framework of a minilateral coalition of a small group of states appears less controversial than an individual state proceeding in a purely unilateral manner.

… there are, however, restrictions under international law regarding unilateral climate engineering

**In addition to the safeguard under international law, theoretical arguments with respect to cooperation also speak for a CE technology being easy to implement by means of a minilateral solution.** Should a small group of states, for example, decide to jointly carry out a manipulation of the stratosphere, expressed in terms of cooperation theory this would represent a coordination game with distributional conflict. In the case of such interest constellations, several options for cooperation are available, containing particular distributional conflicts with regard to the solution to be chosen, without the wish to cooperate itself, however, being put into question because of this. As all Pareto optima are also Nash equilibria, there is no incentive to deviate from an agreement once made (Schelling 1960). Achieving a cooperative solution within the framework of such an interest constellation is generally likely. In this specific case, in view of the high level of uncertainty with regard to the distributional effects of a CE deployment, there is the additional fact that already by being part of the implementing consortium creates an opportunity to constantly influence the actual deployment of technologies in such a way that the distributional effects do not run counter to one's own interests. Should such a consortium exist, it can therefore be presumed that the states affected would also like to be a part of the same, so as to be able to exert influence on the actual deployment of technologies. A bandwagoning effect can accordingly be expected to occur.

## 7.2 Social and political side-effects of uni- or minilateral policies

The thesis regarding a uni- or minilateral solution to the problem of rising global mean temperatures through climate engineering is based on the rationalist theory of cooperation in international relations (Keohane 1984; Zürn 1992; Koremenos et al. 2001). The relatively simple version of this theory from which the Schelling criterion is derived is based on two premises. On the one hand, it assumes that states are the key actors in international politics and that they are able to act in a relatively autonomous manner, without having to consider transnational norms and actors or changing domestic political interests. On the other hand, it assumes that the interests and preferences of states are relatively stable with regard to a certain issue and are not influenced by international negotiation processes. Adopting such an approach means that existing inter-governmental constellations of interests can be precisely worked out; however, it also carries the danger of disregarding the dynamic component of political interaction processes and the role of transnational actors. Both aspects are considered in more detail in what follows.

In order to analyze the social and political consequences of a uni- or minilateral CE policy, reference is made to other elements of the theory of international institutions. In this process, transnational actors and norms, domestic political interests as well as the dynamics at work in negotiations and conflicts come into view. Two clusters of factors can roughly be distinguished.

Unilateral climate engineering would lead to a comprehensive politicization of climate policy

**On the one hand, unilaterally deploying climate engineering could lead to a comprehensive politicization of climate policy.** Decision-making processes are considered politicized if they lead to strong social mobilization with a high degree of contestation.[70] For example, transnational norm entrepreneurs[71] such as Greenpeace are capable of mobilizing high levels of political resistance in the area of environmental politics by appealing to internationally recognized norms (Finnemore and Sikkink 1998). At the same time, the North-South conflict over international climate policy would be intensified, as climate engineering could easily be interpreted as an expression of a policy of exclusion or ruthlessness on the part of the Hegemonic West. Within the framework of the Conference of the Parties of the Convention on Biodiversity, the international community has thus partially already bowed to the pressure exerted by some transnational organizations. In one decision, the following was established:

> [The Conference of the Parties [...] invites Parties and other Governments [...] to [...] ensure] that no climate-related geo-engineering activities that may affect biodiversity take place, until there is an adequate scientific basis on which to justify such activities and appropriate consideration of the associated risks for the environment and biodiversity and associated social, economic and cultural impacts, with the exception of small scale scientific research studies that would be conducted in a controlled setting [...] (UNEP/CBD/COP 10 Decision X/33).

This extremely vague formulation concerning the deployment conditions for climate engineering as well as the legally non-binding character of the Decision mean that it is not impossible for any state to deploy CE technologies. The introduction of the topic of climate engineering into the discussions in the context of the Conference of the Parties provides evidence, however, that increased attention is being paid to this issue on the part of political actors.[72] This makes it likely that political conflicts will arise on an intensified scale with the advance in research on CE technologies.

Growing societal opposition to climate engineering

The beginnings of a growing social resistance to climate engineering are already visible. It was shown in Section 5.2.3 that, for example, the transnational non-governmental organization ETC Group is involved in the CE area in a variety of ways. In doing this, it refers to a number of arguments against climate engineering, whereby the global effects of climate engineering are an important aspect of their reasoning. For example, reference is made to the inequitable global distributional effects which a deployment of climate engineering is likely to entail (ETC Group 2009a). Further arguments relate to the possibility of a military deployment of CE technologies as well as the influence which private sector interests could exercise on the development and the deployment of CE technologies (ETC Group 2010c: 37ff). In rejecting CE technologies, reference is also made to international law (e.g., ENMOD Convention, see ETC Group 2010b).

70 On the politicization of international institutions see Zürn et al. (2011).

71 Norm entrepreneurs are persons or social groups who possess "strong notions about appropriate or desirable behavior in their community" (Finnemore and Sikkink 1998: 896). They play a key role in establishing and validating norms by naming, interpreting and dramatizing issues of importance to them (ibid.).

72 The Decision has met with wide-spread agreement in the community of transnational environmental groups, which have expressed views on climate engineering to date (ETC Group 2010a).

A politicization of climate engineering, the beginnings of which can already be witnessed, may be expected to occur for the following reasons. Firstly, climate engineering fulfills all the requirements for mobilizing social resistance against high-risk technologies and technocratic approaches to problem-solving.[73] Strong links are thus to be expected between social movements in those countries which introduce climate engineering unilaterally and a corresponding transnational protest movement. Secondly, the unclear distribution of climate effects and the side-effects of CE deployment would evoke the North-South divide to its full extent due to the non-involvement of states which do not possess the technical means required to participate. This would damage the UNFCCC process by making it a target of anti-hegemonic resistance (Rajagopal 2003).[74] Thirdly, both forms of resistance, social as well as political, can appeal to general principles of international law (UNCLOS, Art. 195; Outer Space Treaty, right to be consulted; Antarctic Treaty, peaceful purposes; specific prohibitions contained in the Montreal Ozone Protocol, CBD, London Protocol etc.). These general norms would provide a suitable "political opportunity structure" (Tarrow 2005; Tarrow and Della Porta 2005) for such resistance. Finally, unexpected environmental damage in third states could possibly give rise to high follow-up costs.[75]

A1 / A27
NEGATIVE EFFECT ON EMISSION ABATEMENT

**On the other hand, unilaterally deploying climate engineering is expected to lead to political effects are likely which could prove to be counter-productive independently of a comprehensive politicization.** In countries deploying significant resources for CE technologies, the costs of abatement strategies would be considerably more difficult to justify due to budgetary considerations alone. This is one aspect of what has also been referred to as the moral hazard problem. The preparedness to engage in a joint global effort to achieve emission reductions would accordingly be undermined. Additionally, if individual states signal their preparedness to limit climate change by the deployment of a climate engineering technology, then this could bring with it a reduction in the readiness of other states to exercise control over emissions. Put simply, the "rest" of the world would then rely on those states having CE technologies ready to be deployed to limit a rise in temperatures. The "rest" of the world would then correspondingly choose lower efforts to control emissions than would optimally be the case in view of the possible occurrence of serious consequences arising from climate change (e.g., Moreno-Cruz and Smulders 2010).[76] In addition, the conclusion of an ambitious post-Kyoto agreement presupposes that in the medium term a change in preferences will occur with regard to the laggards in the UNFCCC process. This can only be achieved via a strong international norm supported by a transnational epistemic community (Biermann et al. 2010). This mechanism would lose its effectiveness if the pioneers in the reduction of GHG emissions were to support climate engineering.

An escalation of conflict within the political process can develop from this deferral of economic incentives. Third states affected negatively by unilateral climate engineering (CE losers) could tend to exercise radical opposition and in extreme cases even resort to taking counter-measures—what Lane calls "Counter-CE" (2010). Lane identifies countries which both have an interest in an advance in warming and also possess the means to be able to oppose a CE

73 See Section 5.2.1.

74 In this context external costs also have to be considered, as these include the costs arising in third party states as a result of CE deployment and thus allow an overview of the extent to which these countries are affected (in economic terms).

75 As regards the possible applicability of the rules of state responsibility and liability under international law, see Section 6.4.

76 In making this estimation, however, account must be taken of the fact that different regions are affected in different ways by the deployment of climate engineering. CE losers accordingly have an incentive for increasing their efforts to ensure the control of emissions, so as to prevent a CE deployment. This effect can thus lead to a situation in which the abatement of emissions is higher than without the option of climate engineering being available (Moreno-Cruz 2010; Goeschl et al. 2010). This reaction is, however, subject to very many presuppositions.

deployment. In order to achieve the desired counter-effect, particle filters could, for example, be removed from coal-fired power plants. The thawing of permafrost soil and the agriculturally productive land gained from this may possibly offer an economic incentive for not slowing any further warming or counteracting a targeted intervention by another country. The second general thesis of this chapter can accordingly be formulated as:

> Thesis K7.2: Uni- or minilateral CE deployment can lead to social and political consequences which undermine their chances of success.

It should be noted in this regard that no negative physical impact through climate engineering is necessarily required for this deferral of incentives or for the possibility of a conflict escalation to occur. These implications also emerge if countries evaluate the same damages or effects occurring through CE deployment very differently. This case can, for example, occur if a given society evaluates climate engineering more strongly than other societies as a massive interference with nature and rejects it for moral or ethical reasons.

AC10
RELIGIOUS, EXISTENTIAL AND ENVIRONMENTAL ETHICS-BASED ARGUMENTS

A further typology of different CE technologies is required for a differentiated evaluation of the second thesis (K7.2). From a political/legal point of view, CE technologies can initially be distinguished according to whether their implementation occurs in so-called spaces outside national jurisdiction or on a limited number of sovereign territories.[77] In addition, CE technologies can be distinguished according to whether undesired side-effects are likely to remain restricted to a local area or will have the tendency to assume a global character (Table 7).

| | Undesired side-effects have the tendency to have only a regional impact | Undesired side-effects have the tendency to have a global impact |
|---|---|---|
| Common spaces outside national jurisdiction | Ocean fertilization<br>Acceleration of natural weathering in the ocean | Space reflectors<br>Stratospheric aerosols<br>Marine cloud modification<br>Cirrus cloud modification |
| Sovereign territory | Air capture<br>Acceleration of natural weathering on land<br>Increased rooftop reflectivity<br>Biochar manufacture<br>Decentralized afforestation | Large-scale afforestation<br>Modification of deserts |

TABLE 7:
Typology of CE technologies according to the extent of their social and political consequences in the event of unilateral deployment

Source: Own representation.

On the basis of this typology, two sub-theses can be derived from Thesis K7.2.

> Thesis K7.2a: The more the use of common spaces outside national jurisdiction is required and the more cross-border side-effects of a CE technology deployed uni- or minilaterally occur, the more social and political consequences can be expected to arise resulting in a lower probability of success for the CE technology.

**Precisely those technologies which were identified in Section 7.1 as being capable of being deployed uni- or minilaterally possess the highest potential for generating politicization and opposition.** This is already revealed in the statements of CE opponents. An amalgamation of various organizations forms the campaign "Hands Off Mother Earth" (H.O.M.E.), which is devoted to the opposition against CE technologies.[78] Their objective is stated as being "[...] to

CE technologies which can be carried out unilaterally also possess the greatest potential for creating resistance

77 On the concept of the non-sovereign space, see Wolfrum (1984).

78 The H.O.M.E. campaign currently lists 107 organisations as "allies and endorsers" on their Internet site (H.O.M.E. 2011b).

build a global movement to oppose real world geoengineering experiments [...]" (H.O.M.E. 2011c). The CE measures listed on the H.O.M.E. website, against which the protest is directed, are the production and storage of biochar, the introduction of sulfuric particles into the stratosphere, cloud modification and the storage of $CO_2$ in the ocean by fertilization with nutrients (H.O.M.E. 2011d). With the exception of the production and storage of biochar, these are all measures which have strong cross-border effects and which have to be implemented in common spaces outside national jurisdiction. By implication of the above, it holds true that:[79]

> Thesis K7.2b: Those CE technologies which are likely to cause less opposition and politicization are not amenable to uni- or minilateral deployment.

The modification of rooftops, the acceleration of natural weathering and air capture appear by comparison to offer little potential for public conflict. There have not been any social mobilization activities on a larger scale against any of these proposals up to now. In addition, for these CE technologies the possibility exists of accrediting investments in corresponding projects to reduction commitments within the framework of a Kyoto follow-up agreement.

**As an interim summary, the following may be stated: Precisely those technologies which can be carried out effectively on a uni- or minilateral basis can be expected to produce especially vehement politicization and considerable social and political opposition with far-reaching consequences for the UNFCCC process.** Other CE technologies present fewer problems in terms of their social and political consequences, but require broad-based international implementation in order to achieve a comparable temperature effect or a reduction in greenhouse gas concentrations. Against this background, it is necessary to draw up the foundations of an institutional design for dealing with CE technologies on a multilateral basis.

## 7.3 Proposal for an institutional design to multilaterally regulate climate engineering

**A1/A27**
NEGATIVE EFFECTS ON EMISSION ABATEMENT

**A4**
UNSTOPPABLE DEVELOPMENT

**A18**
TERMINATION PROBLEM

Multilateral solution preferred

The central demand posed by transnational NGOs is that a greater role should be given to multilateral international organizations, so as to avoid matters being dealt with exclusively by Western States and large private corporations. This can be seen when examining the statements issued by these NGOs regarding the Decision issued by the Conference of the Parties of the Convention on Biodiversity: "On 29 October 2010, the [COP 10] of the [CBD] adopted a decision that amounts to a de facto moratorium on geoengineering and, almost as importantly, affirmed the UN's leadership in addressing these issues" (ETC Group 2010d), and: "[Scientists] have no right to do real-world experiments without any prior inter-governmental discussion and agreement [...]" (ibid.). Irrespective of this, a legally binding effectiveness of the decision cannot be assumed.[80]

**The analysis presented in Section 7.2 of the likely social and political consequences of a uni- or minilateral deployment of climate engineering suggests the desirability of a multilateral solution.** There are only a few CE technologies carried out on a uni- or minilateral basis which can effect globally the climate, and precisely these technologies possess the greatest potential for generating opposition and conflict. Two objectives in particular are of significance, which can only be achieved by dealing with climate engineering on a multilateral basis. On the one hand,

79 The opposition to the production and storage of biochar which can be observed is primarily justified by the large surface which is required for the deployment of this technology: "The biggest danger of biochar for geoengineering, however, is scale. Hundreds of millions of hectares of land likely needs to be turned over to new plantations in order to produce the quantities of biochar many talk about" (H.O.M.E. 2011a).

80 See Section 6.2.2.

for research and deployment to proceed, a sufficient degree of social and political acceptance must be generated to avoid intergovernmental and transnational tensions. Otherwise, negative political and social consequences could under certain circumstances lead to an important technological option being spoiled or obstructed, which could help in dealing with unforeseen and accelerated climate change. On the other hand, climate engineering needs to be embedded within the UNFCCC process in order to avoid long-term damage to emission reduction efforts and also to avoid any self-reinforcing implementation dynamic (the slippery slope argument). In this context, it is also of importance that a termination of a CE deployment must be possible without thereby producing irreparable climate damage. The option of terminating a deployment must remain in place, which in turn requires a continuation of the efforts to reduce emissions.

> Thesis K7.3: CE research, as well as CE deployment, requires an institutional embedding which creates sufficient international and transnational social acceptance and links it to the existing international environmental regulations in such a manner that counter-productive effects are avoided.

A series of proposals have been developed in the literature on dealing with climate engineering in institutional terms. Although none of these proposals have been explicitly developed with regard to both the terms cited, the existing considerations provide a good foundation for developing a proposal for an international regulation.

**In accordance with the line of reasoning developed up to this point, any successful regulation of climate engineering must prevent moral hazard and the slippery-slope dynamic from manifesting themselves while keeping open the option of terminating a CE deployment**. On the other hand, conflictive political and social consequences of research on and possible deployments of CE technologies must be kept to a minimum level. For this reason, in examining existing proposals, only those studies will be considered which provide a concrete proposal for a multilateral solution. The proposals for a uni- or minilateral solution have been discussed and rejected above.

We follow the basic line of analysis provided by Carlin (2007). He regards possible ways of dealing with climate engineering from the perspective of ideal objectives, which should be pursued by an organization which is entrusted with the regulation of climate engineering. Basically, Carlin (2007: 57) cites three options for dealing with climate engineering: (i) unilaterally, (ii) within the framework of a coalition or an alliance (e.g., OECD or NATO) or (iii) within the framework of the UN. On the basis of the great advantages of high legitimacy, Carlin pleads for a multilateral solution within the framework of the UN, but does not, however, describe any concrete ways of dealing with climate engineering within the UN framework. He thus lays the foundations for tackling CE regulation within the framework of the UN but does not contribute any concrete proposal for regulation.

**Most of the proposals for regulation advanced in the literature, which present a concrete institutional elaboration for a potential CE regime, support a solution within the UN** (Barrett 2008, Barrett 2009, Barrett 2010; Virgoe 2009; House of Commons 2010). Only Bodansky (1996: 318ff) criticizes the low level of authority of those existing institutions of relevance for the issue and considers a fundamentally new international organization as desirable. At the same time, he regards the establishment of such an institution as fairly unlikely and fears that in place of this a prohibition of climate engineering is inevitable—even if it should turn out that this would not be justified. In any case, he also regards a multilateral solution as being imperative.

Barrett (2008; 2009; 2010) proposes a regulation of RM within the framework of the UNFCCC. In the case of his proposal, however, it is noticeable that he hardly addresses the problem of the moral hazard and the logic of the slippery-slope argument. According to Barrett, the fear that research into RM could lead to reduced efforts in emission reductions is unfounded. He argues that hardly any efforts have been made to reduce emissions up to now anyway. On the contrary, fears with regard to the risks associated with climate engineering could even strengthen the efforts to reduce emissions further (Barrett 2009: 23). In addition, a less strong reduction of emissions would in any case make sense in economic terms, if it should be established that RM can be deployed without any great difficulties (Barrett 2010: 3). Barrett argues in a similar way with regard to the fear that research into RM could already generate pressure towards its further development and eventual deployment (slippery slope dynamic). He assumes that such a development would only occur if research into RM were to reveal that a safe deployment of RM is possible. In this case, a deployment would be desirable anyway. If research into RM were to reveal that deployment would have serious undesirable side-effects, then RM would not be deployed on the basis of this knowledge (Barrett 2010: 6).

A1
NEGATIVE EFFECTS ON EMISSION ABATEMENT

A4
UNSTOPPABLE DEVELOPMENT

Virgoe's (2009) considerations on the international regulation of CE measures come closest to the proposal presented in the following section. He sees the danger of strong international tensions emerging in the event of a unilateral deployment, which would result from the lack of legitimacy inherent to such a solution. A consortium of states on the other hand would be exposed to a conflict of objectives between the ability to act on the one hand and the requirement of achieving a high degree of legitimacy on the other, and would be unstable in the long run.

## 7.4 Requirements for international regulation

On the basis of the considerations presented in the literature and the results of the above analysis, the six requirements for an international regulation of climate engineering can be derived:

Requirement 1:
International coordination of research and technical evaluation

Requirement 1: Research into, and the technical evaluation of, climate engineering should be coordinated internationally so as to prevent the process from gathering its own momentum as much as possible. The goal in this is to form a coalition of states, which is prepared to finance corresponding research and to carry it out, to support research activities elsewhere and to disseminate research outcomes in a transparent manner. **The institutional embedding of such a coalition could occur within the framework of the UNFCCC process, as climate engineering would in this way become a part of the international climate regime.** Such embedding would allow for the avoidance of any negative influence being exerted by research into climate engineering on the efforts to reduce emissions. One option for this coordination task would be the creation of an international CE agency, which is institutionally embedded into the UNFCCC process.

A1
NEGATIVE EFFECTS ON EMISSION ABATEMENT

A4
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Requirement 2:
Independent supervisory authority

Requirement 2: The evaluation of options, costs and dangers of climate engineering should take place in two stages. The CE agency discussed above should summarize research and interpret the outcomes in a practically relevant manner. As a second step, **the evaluation and classification of the research outcomes should then be undertaken by an independent supervisory committee.**[81] The supervisory committee would be assigned the coordination of research and would take on an advisory role, and in this sense have a similar function as the Intergovernmental Panel on Climate Change (IPCC), or could be placed directly under the

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UNSTOPPABLE DEVELOPMENT

81 We presume that the efforts to create a global environmental organization will not lead to any success in the short term. Our proposal therefore follows the "clustering strategy" for improving the coordination of various international and transnational environmental institutions, as it exists, for example, in the area of chemicals control (Simon 2010: 24-26).

latter.[82] This supervisory authority would accordingly be a further environmental assessment agency (Mitchell et al. 2006). Three reasons speak for an independent supervisory authority: (i) due to the enhanced consultation commitments of the supervisory body, the range of the actors involved is considerably wider than in the proposed CE agency, the members of which are to be drawn especially from countries actively involved in research, which would increase social acceptance; (ii) the evaluation of the research outcomes would occur in an integrated manner, considering climate policy alternatives and the overall problem of climate change; (iii) the institutional interest to be expected of a CE agency, which could increase its own standing with positive recommendations, would be avoided.

Requirement 3: On the basis of the supervision carried out by the independent committee, the member states of the UNFCCC would make decisions about norms and rules, while taking into account the precautionary principle.[83] The norms and rules lay down

Requirement 3: Definition of international norms and rules

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- which technologies are to be developed further and made ready for deployment in emergencies such as the transgression of critical threshold values,[84]
- which field research will be allowed for this purpose, and
- which technologies are deployed under which conditions.

**Part of these norms and rules could also set an upper level for the large-scale CE deployment which is not to be exceeded when altering the radiation balance** (e.g., 1 W/m²). This would defuse the termination problem to a certain extent and, in addition, reduce the potential extent of negative climatic side-effects.

Requirement 4: Within a regulatory framework, a definition should be provided as to how the expenditure of resources for the control of emissions on the one hand and CE deployment on the other can be compared.[85] On the one hand, effective, decentralized incentive mechanisms for emission control need to be maintained, but, on the other hand, incentives may need to be set for climate engineering. A price conversion mechanism must accordingly be created, which compensates for the higher effectiveness of CE technologies (as appropriate). **The contributions by states to the costs arising from CE deployment should therefore not be measured in terms of their direct climatic impact, but rather according to how much the same deployment of resources would have achieved when invested in the reduction of greenhouse gases.** This would create cost equivalence (and not effectiveness equivalence), meaning that a systematic preference for RM technologies over emission control or CDR technologies, and accordingly a one-sided focus on RM and the neglect of reduction measures, could be avoided. In principle, the climatic effect of a measure should be in the foreground in this process. As a result, it would be possible to extend the portfolio of climate-effective measures whose implementation can be accredited, according to a uniform metric, to the reduction targets laid down in the Kyoto process in the future. Within this uniform metric, it would be possible (in the same way as applies to the conversion of the climate impact of other greenhouse gases such as $CH_4$ or $N_2O$) to select $CO_2$ as a uniform reference value. The implementation of decentralized air capture, the acceleration of natural weathering and the increase in the reflective power of rooftops could, as is already the case with afforestation,[86] be accordingly accredited to international

Requirement 4: Comparability of emission control and CE deployment

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82 The Intergovernmental Panel on Climate Change will deal with climate engineering in some chapters of its Fifth Assessment Report (IPCC 2011b).

83 See Section 6.5.

84 See Section 3.1.4.

85 See Section 4.3.2.

86 National afforestation measures can be offset against emission reduction commitments within the framework of the Kyoto Protocol. Should an international accreditation scheme emerge, this should also apply to afforestation measures being financed in other countries.

reduction targets.[87] In order to supervise the effects on traditional means of abating emissions, which would result through price effects from the additional offer of $CO_2$ certificates, a lower level could be set for the certificate price with the reduction targets being adjusted if a figure below this level was achieved.[88]

Requirement 5: Parallel with the institutional embedding into the UNFCCC process and the establishment of an independent supervisory authority, additional regulations should also be created, which are capable of reducing the slippery slope problem in climate engineering research. **One element of such a regulation could be a time-limited moratorium** for the deployment of individual CE technologies. Those technologies which can be carried out on sovereign territory and the consequences of which remain restricted to a local area would need to be exempted from such a moratorium. The moratorium should be time-limited, so as not to prescribe an institutional blockade for the deployment of CE technologies prematurely.[89] However, so as not to initiate the slippery-slope logic after the moratorium has expired, deployment would still require a positive decision by the responsible international committees.

Requirement 5: Coordination of research with regard to the slippery-slope problem

A4
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Requirement 6: In the event of a state unilaterally abandoning a CE technology being carried out on a multilateral basis, this state should be obliged to increase its emission reduction efforts significantly. **The aim of such an obligation consists of counteracting the drastically accelerated climatic warming which could occur in the event of a CE technology being terminated.** The costs which are associated with the avoidance of negative side-effects of an abrupt abandonment of climate engineering could thus be imposed on those countries which have driven the CE technology. This would counteract the termination problem.

Requirement 6: Definition of terms for phasing out the use of CE technologies

A18
TERMINATION PROBLEM

## 7.5 Summary of the aspects of international coordination and regulation

In this chapter, an examination was carried out as to which political and regulatory aspects must be taken into account in the CE debate. In particular, an analysis was conducted into the extent to which climate engineering could be implemented by individual states and which political and social implications this would have. It was shown in the process that the Schelling Thesis, according to which CE technologies do not involve any clear breach of standards under international law and can be financed and implemented either unilaterally or through a coalition of a few resource-rich states, can only be proven to apply to very few of the CE technologies. It is true that there are no legally binding prohibitions for deploying CE technologies under international law. The position under international law is, however, so uncertain that its further development will largely be determined by political debate, the outcome of which is open-ended. Regarding the possibility of a uni- or minilateral development and implementation of CE technologies, only the introduction of aerosols in the stratosphere, marine cloud modification and possibly the modification of cirrus clouds are in accordance with the Schelling Thesis.

The consideration of the social and political consequences of a unilateral deployment of climate engineering reveals that it appears to be confronted with an insoluble dilemma. The promise of a quick and highly effective technological solution, which is so effective that it can be carried out

CE dilemma: the most effective CE technologies carry the greatest conflict potential

87 A similar view is expressed by the Royal Society (2009: 41): "A question for all CDR methods is whether they will be eligible for certification under the KP (or its successor instrument) under the clean development mechanism or joint implementation".

88 Rickels et al. (2010, 2012) show with the example of the integration of $CO_2$ certificates from large-scale iron fertilization in the southern ocean into a global trading system that an adjustment of reduction targets would be needed.

89 This distinguishes it from the proposal for a moratorium made by Krämer (2010), who sees this as a component of a political strategy for necessary prevention.

by only one state or a small number of states acting, as it were, on behalf of all humanity, can only be delivered by the small number of technologies which were found to be in accordance with the Schelling Thesis. These are, however, precisely those CE technologies which can be expected to generate particularly vehement politicization and far-reaching social and political opposition with possibly devastating consequences for the UNFCCC process. Against this background, an international coordination of climate engineering appears desirable.

Climate engineering without multilateral cooperation not desirable

Approaches to dealing with climate engineering which do not aim at producing a multilateral process of cooperation can hardly be described as second-best solutions: only a multilateral regulation within the framework of a global climate regime will allow for climate engineering to be linked to the commitment of reducing emissions in such a way that moral hazard and the problem of termination can be dealt with. Additionally, the existence of the slippery slope problem in connection with research into CE technologies requires any regulation to follow a multilateral approach. Research and deployment outside of a global climate regime would accordingly not be a second-best solution, but rather the worst case scenario. A minimal solution which operates outside the proposed regulatory framework could possibly be an amalgamation of a group of states in an institution the membership of which is open. This would mean that not all members of the UNFCCC would have to participate in the coordination process for climate engineering.

As an outcome, it can be concluded that an institutional embedding of CE research and CE deployment is desirable. It would allow for adequate international and transnational social acceptance and it would link climate engineering to existing environmental regulations in such a way that counter-productive effects are avoided. The requirements for an institutional embedding of climate engineering are as follows: (i) international coordination of research and technical evaluation through a CE agency, (ii) the creation of an independent supervisory authority, (iii) the definition of international norms and rules on the deployment of CE technologies, (iv) comparability of emission control and CE deployment, (v) coordination of research with regard to the slippery-slope problem, and (vi) the definition of terms for phasing out the use of CE technologies.

# 8 Summary and Implications

**The present report has traced the structure of the debate on climate engineering and summarized the relevant findings from the scientific and academic literature on the subject,** drawing on expertise from the disciplines of ethics, the natural sciences, economics, sociology, law, and political science. Given the complexity of the CE debate and the effects climate engineering could have on nature and societies across the globe, a broad interdisciplinary approach of this kind is essential. Accordingly, this document is an attempt to examine climate engineering from many perspectives within the framework of a single integrative report.

Report based on analysis of the CE debate

**Argument maps have been used to chart the macrostructure of the debate and identify interrelated sub-controversies,** thus paving the way for systematic analysis of this complex issue and facilitating the identification of interdependencies between individual disciplines. As the macrostructure indicates, the debate has been evolving around the two key questions of whether the deployment of CE technologies is desirable and whether research on these technologies should be undertaken. The argument clusters supporting or seeking to refute the relevant theses and sub-theses need to be evaluated on the basis of information drawn from a wide range of disciplines.

Major uncertainty and knowledge gaps

Across all disciplines, it has become clear that considerable uncertainty still persists about many aspects of climate engineering. At present, the potential effects and side-effects of most CE technologies, the economic costs that would result from a deployment of CE technologies and the consequences of this deployment for society and the political sector cannot be assessed with the requisite precision. The potential range of unintentional consequences and of the economic costs associated with deployment is extremely broad. The main reason for this is that the Earth system itself is highly complex and has yet to be fully understood. The present state of our knowledge is certainly inadequate for accurate modeling. The unpredictability of individual and societal reactions is a further contributing factor. Uncertainty about the potential for social and geopolitical conflict stems mainly from the fact that any CE deployment would globally affect the environment of all of humanity on an unprecedented scale. We have no experience from the history of humankind to indicate how societies might react to such changes to their environment, changes which after all could be triggered by individual states or a small group of states. Nor do we have any conclusive agreement about how management of the Earth system could be globally organized. Existing international regulatory structures probably do not, as yet, provide an adequate framework for this purpose. The degree to which these—currently uncertain—issues might possibly be resolved by further research is a matter for speculation.

In Section 8.1, the two fundamental questions—how desirable is it for climate engineering (i) to be deployed and (ii) subjected to research?—are discussed against the background of the major arguments that inform the ongoing CE debate. To this end, the conclusions arrived at in the individual chapters are summarized from an interdisciplinary perspective. In Section 8.2, the results materializing from the different levels of analysis are summarized separately for each individual CE technology. Section 8.3 is an assessment of the current state of CE research.

## 8.1 Questions for the evaluation of climate engineering

**Much like the discussion within the individual chapters, the argumentative structure of the CE debate as a whole can serve as a framework for summing up the most important arguments in the debate.** The questions are derived from individual arguments (or argument clusters). The answers to them are equally important for the public debate on climate engineering and the political decision-making process. The overall evaluation of the answers depends to some extent on the CE technologies discussed, but rests mainly on the assumptions held by individuals and the subjective significance they attribute to particular arguments. Accordingly, the next section of this report makes no claim to provide a definitive overall evaluation. Instead, it summarizes the informational basis that is pertinent to the assessment of arguments and helpful in arriving at subjective answers to the initial questions. The overall structure of the summary is a natural spin-off from the two key questions in the debate: Should a particular CE technology be deployed on a large scale? And should research into a particular CE technology be carried out?

### 8.1.1 Should CE technologies be deployed?

**Can ambitious climate targets be achieved without the deployment of CE technologies?**

The question as to whether ambitious climate targets such as the 2°C target can be met without deploying climate engineering itself rests on another question: Will the control of greenhouse gas emissions suffice in future to keep anthropogenic climate change to levels that would enable us to meet that target? Leaving aside for a moment the normative issues involved in defining such acceptability and tolerance thresholds, we can say that such estimates are currently hampered by the high degree of uncertainty about how much remains of the "emissions budget" within which the global rise in temperatures could be limited to an acceptable value. We cannot say how global warming will develop as a result of the current (and already elevated) levels of greenhouse gases, as the expected rise in temperatures will depend on feedback loops in the Earth system that are not yet understood well enough. Individual studies (e.g., Hansen et al. 2008) go so far as to postulate that maintaining the rise in temperature within "safe" levels might involve stabilizing the acceptable $CO_2$ concentration in the atmosphere not at 450 ppm but at a maximum of 350 ppm.

**AC6**
350 PPM/2°C TARGET
Uncertainty on residual emissions budget

Model calculations show that using both bioenergy and CCS or using CSS on a large scale in power generation could, in theory, make this lower target achievable. But if we recall that current concentrations are already markedly higher than this figure, it quickly becomes apparent that our society and our economy would require massive restructuring in order to achieve such a target. Estimates of the aggregate economic costs of such a restructuring process have yet to be undertaken.

**In view of the rate at which $CO_2$ concentrations are currently increasing in the atmosphere and the lack of progress that has been made by international emission control, even a target of 450 ppm might be considered ambitious.** If no greater efforts to limit emissions are undertaken and the expected growth of the world economy is factored into the predictions, annual global emissions of greenhouse gases could reach about 71 Gt $CO_{2equiv}$ by the year 2050 and by the end of the century, atmospheric greenhouse gases might reach a concentration of 1,000 ppm $CO_{2equiv}$ (IEA 2010).[90] The rise in temperature triggered by these processes is estimated to be close to 6°C (IEA 2010). It follows that achieving ambitious climate targets solely by reducing

90 These emissions are projected on the basis of the current policy scenario contained in the World Energy Outlook 2010, which is based on a continuation of the political situation as it was in mid 2010 (IEA 2010).

emissions can only be done via the application of considerable technical ingenuity and at an economic cost that is by no means insignificant. Even estimates restricting themselves to the extra investment required to reduce emissions so that a long-term atmospheric $CO_2$ concentration of 450 ppm $CO_{2equiv}$ can be reached come up with USD 18 trillion for the period 2010 to 2035 (IEA 2010). Quite apart from the question of what emission control may cost, it is not even clear whether it can be implemented effectively. Sufficient storage space would have to be found for $CO_2$ from coal-fired power stations with CCS technology, and long-term storage would have to be provided for, with all the political and technical challenges that implies.

450 ppm target attainable

**However, on the basis of what we know today, a target of 450 ppm does seem realistic.** The technical and economic prerequisites are available. However, agreement on a global climate regime would have to be reached in order to facilitate the successful international implementation of the measures required. Medium-term stabilization of the atmospheric greenhouse gas concentration at 350 ppm represents a distinctly different scenario that would pose considerable technical and economic challenges, not to mention the political challenges involved in securing an international agreement.

Consensus between rich and poor states

**At all events, whether the global community sets a target of 350 or 450 ppm, it will be necessary to arrive at a consensus between poor and rich countries if an international climate treaty with extensive emission control measures is to materialize.** This means that the legitimate aspirations of developing countries to increase incomes must be reconciled with the need to invest in climate protection. Failure to achieve such a consensus and to impose the corresponding emission reduction obligations would mean that the global community could anticipate climate change in excess of the targeted 2°C limit.

### How effective are individual CE technologies?

AC4
EFFICIENCY AND EASE OF IMPLEMENTATION

What does climate engineering aim to accomplish?

At this point, it is important to clarify exactly which aspects of climate change individual CE technologies are intended to remedy. This is the key to any analysis of the effectiveness of a given technology. It is important to distinguish between attempts to influence global temperatures only and approaches geared to other variables as well, such as the concentration of $CO_2$ in the atmosphere, the acidity of the oceans, or the quantities and volatility of precipitation. It is also important to bear in mind that any CE deployment might potentially make it possible to achieve climate targets defined in terms of global averages, while at the same time failing to compensate for climate change at the local level. The most important question in assessing the effectiveness of CE technologies is whether their effectiveness is measured in terms of their potential to prevent drastic climate change (resulting from the triggering of tipping points) or in terms of their potential to limit climate change in the long term by reducing or stabilizing the concentration of $CO_2$ in the atmosphere.

Rapid temperature reduction

**RM technologies may be effective for quick temperature reduction.** Current radiative forcing, induced largely by greenhouse gases, could be rapidly offset by RM technologies reducing incoming solar radiation, increasing the planetary albedo, cutting down the absorption of solar radiation in the atmosphere, or even increasing the thermal radiation emitted by the Earth. All of these technologies would have an immediate impact on the temperature of the Earth. It might indeed be necessary to react this quickly if the Earth system appeared to be on the brink of reaching critical tipping points (Caldeira and Wood 2008; Irvine et al. 2009). However, these RM technologies would need to be continually deployed over very long periods of time (several hundred or thousand years), as concentrations of greenhouse gases can only decline naturally at a very slow rate (e.g., Brovkin et al. 2009). RM technologies could only be discontinued earlier if they were flanked by efforts to reduce $CO_2$ concentration. RM technologies do not significantly reduce the effects of other aspects of climate change (changes to precipitation, acidification of the oceans, etc.).

$CO_2$ concentration

CDR technologies, by contrast, attack the root causes of climate change more effectively. However, they only take effect very slowly, so that in an acute crisis they would not be suitable for putting a stop to the rise in temperature within a short space of time.

Unilateral effectiveness advantage of CDR

CDR deployment might have an effectiveness advantage over unilateral or minilateral emission control. It avoids the free-rider problem that results if regionally limited emission control inadvertently leads to international carbon leakage. States not engaged in climate protection activities are both spared the costs incurred by climate protection measures and also attain competitive advantages in the energy-intensive production of goods into the bargain. Instruments such as emissions trading or taxes on $CO_2$ or energy focus solely on the demand side of the equation and do not factor in the likely reactions of fossil fuel suppliers. The price impact of reduced demand for fossil fuels and potential strategic effects on the supply side could lead to the long-term consumption of fossil fuels simply being shifted closer to the present rather than actually being reduced (Sinn 2008; Edenhofer and Kalkuhl 2009). CDR deployment would help circumvent effects like these, as it would not affect the supply of fossil fuels or the demand for them.

Consideration of effectiveness in isolation

**One problem in analyzing the effectiveness of individual CE technologies at present is that the effectiveness of individual approaches is often viewed in isolation, focusing on one goal only.** CDR technologies are examined primarily in terms of their potential to sequester carbon, while RM technologies are examined primarily in terms of their potential to influence the Earth's radiation budget. Potential side-effects, such as the albedo effects of CDR technologies or the feedback effects of RM technologies on natural carbon uptake, have rarely been considered. Nor have the effects of different CE technologies on the acidification of the oceans been investigated adequately. These indirect negative and positive effects should be included in any comprehensive evaluation of the effectiveness and economic efficiency of CE technologies. However, the gaps in current scientific knowledge make this analysis a difficult matter.

#### How much uncertainty is there about the unintentional side-effects of CE deployment?

AC7
RISK ETHICS

Understanding of Earth system limited

**Scientists are still far from certain whether and to what extent the mechanisms climate engineering would exploit might have side-effects.** With our current understanding of the Earth system, the potential range of unintentional consequences can only be quantified to a limited extent. While some of this uncertainty could be reduced or even eliminated by research, the system is inherently variable, and its complexity can only be reduced to a limited extent. This means that it is particularly difficult to determine the effects and side-effects climate engineering would bring about at regional levels. We have no reliable assessments of possible regional effects at present. Against the background of "natural" climate variability, it would also be difficult to demonstrate such effects reliably via statistical analysis.

Development of climate variables differs from region to region

However, knowing more about the development of various climate variables in different regions is one of the fundamental preconditions for any detailed evaluation, whether economic, political, or legal. For example, the economic costs of CE technologies can only be determined if we can assess the monetary impact of changes to regional climates. But even with this information, evaluation would yield results with a high margin of uncertainty. Accordingly, what we know at present enables us solely to assess side-effects on the basis of scenarios mapping out potential cause-effect relationships. Currently, we do not have estimates that would permit the detailed definition of such scenarios.

Naturally, deficits in our knowledge of the scale of potential side-effects and the form they would take in particular regions make it difficult to estimate the potential for conflict that could result. The impact this uncertainty could have on international negotiations depends on the concrete situation. It may even be easier to reach a consensus on aspects that are not tremendously well-defined than on aspects of which we have detailed knowledge. The level of uncertainty surrounding climate engineering is one of the key factors influencing societal discourses on the topic. Strong risk aversion in societies would exacerbate the rejection of climate engineering.

Scale of CE deployment

**Given the deficits in the current state of our knowledge about the Earth system, scientists are far from certain about the side-effects of CE deployment. But we can safely assume that these side-effects would be amplified by scaling up CE deployment.** This also applies to the economic, political, and social repercussions associated with these side-effects. If CE technology were deployed on a large scale, market prices for the materials and investment goods needed for CE deployment would be affected dramatically, with clear consequences for upstream and downstream industries. At the same time, uncertainty about the distributional effects of CE deployment and general hostility toward the large-scale deployment of technology can be expected to cause an escalation of social and political conflicts in connection with climate policy.

### Can we measure the effectiveness of deploying a particular CE technology?

AC7
RISK ETHICS

Uptake of atmospheric $CO_2$

**Measuring the effects of CDR technologies requires empirical quantification of carbon captured from the atmosphere.** This could be achieved either by measuring the actual amounts of $CO_2$ captured or by relying on appropriate indicators or statistical modeling. This is relatively unproblematic in the case of some technologies, such as air capture or afforestation. CDR technologies such as iron fertilization pose greater challenges. Measuring the flow of $CO_2$ over the surface of the ocean and changes in oceanic $CO_2$ concentrations is technically difficult and produces results that are hard to assess against the background of natural variability.

Radiation balance and temperature

**The effectiveness of RM technologies can only be measured in terms of the development of global temperature or of the Earth's radiation budget.** The change in temperature observed needs to be attributable to the effects of an RM technology. The current state of climate research clearly shows that temperature signals can only be filtered out of the noise resulting from natural variability by means of repeated measurements over long periods of time. Satellite measurements show that natural global variability in shortwave radiation over a year can be as high as 0.3 $W/m^2$ (Hansen et al. 2005). In order to isolate a CE effect of this magnitude, current satellite systems would need to take measurements over 10 – 15 years (Loeb et al. 2007). Even then, global temperature effects could only be identified with statistical methods.

**Mathematical simulations cannot calculate the effects of RM technologies precisely either.** Models cannot resolve all the relevant processes (aerosols, clouds, radiation) with the necessary detail, and parametric modeling of such relationships involves uncertainty. In addition, small-scale disturbances can influence the dynamics of the atmosphere and the ocean, so that minor errors at the beginning of a simulation could lead to high levels of uncertainty in the simulation of the climate signal.

Model-based estimates of the effects of anthropogenic aerosols on the Earth's radiation budget since 1750 have an uncertainty range of over 100 percent.[91] By contrast, RM technologies would be extremely precise about the quantities and the qualities of the particles disseminated.

91 Direct effect -0.5 (-0.9 to -0.1) $W/m^2$, indirect effect -0.7 (-1.8 to -0.3) $W/m^2$ (Forster et al. 2007).

In addition, local effects could be verified by flight observations. A higher degree of precision could thus be expected from the modeling of precisely defined RM technologies. However, in the majority of cases truly precise quantification of the effects of RM technologies will not be feasible, at least in the near future.

**How high are the costs of deploying CE technologies?**

AC4
EFFICIENCY AND EASE OF IMPLEMENTATION

Estimates of operating costs

The information currently available on the costs of deploying particular CE technologies displays major gaps and considerable uncertainty factors. Existing estimates confine themselves in the main to the operating costs of particular technologies. For most technologies, explicit estimates of the research, development, and capital costs required to bring these technologies to deployment-readiness are conspicuous by their absence. Moreover, the scale and price effects that would result if these technologies were deployed on a large scale have also been ignored. Where particular CE technologies draw on existing sectors of industry such as mining infrastructure, shipping, or air transport, we can assume that price effects would dominate scale effects, and that operating costs have thus been underestimated. In the case of new technologies, though, it is quite plausible to predict that operating costs could be reduced significantly by scale effects.

No estimates of economic costs available

**Estimates of the economic costs exceeding the scope of these data and taking the potential side-effects of climate engineering deployment into account are not yet available.** Given the inherent variability of the Earth system and the difficulty of matching interventions with results, some regional effects cannot be accurately predicted, so it is entirely conceivable that comprehensive evaluations of the economic costs will also prove to be impossible in future. The summary of the potential effects of CE deployment below is no more than a tentative initial approach requiring validation from further scientific investigation.

CDR technologies

**The costs of CDR technologies can be compared with the costs of controlling $CO_2$ emissions, as both are calculated on the same basis.** However, the estimates available for individual technologies vary widely. The assessment of operating costs given here is based on the average of the range of available estimates for the operating costs of each technology. Technologies involving physical carbon sequestration in the ocean, oceanic macro-nutrient fertilization realized by nutrient supply from land, and artificially enhanced upwelling are omitted from the discussion because they are either ineffective CDR technologies or are not, strictly speaking, CDR technologies at all.

- The estimated average operating costs for the manufacture of biochar and for iron fertilization in the Southern Ocean are low (< USD 50 per ton $CO_2$). The production of biochar will presumably not have any significant impact on the prices of the materials involved, as alternative uses for materials such as garden and agricultural waste and sewage sludge scarcely exist. It is likely that the economies of scale of the use of pyrolysis will compensate for these effects. In the case of iron fertilization, the small quantities required are unlikely to affect prices significantly. The economic costs resulting from external effects of producing biochar are probably low. In the case of iron fertilization, the economic costs have yet to be established. It remains to be seen whether the negative effects on marine ecosystems or the positive effects on fish stocks would predominate.
- The estimated average costs for spreading pulverized olivine are also low (< USD 50 per ton $CO_2$). It is, however, probable that the investment expenditures involved would be high. Due to the extensive infrastructure required for processing and spreading the material, the

failure to consider price effects has probably led to an underestimation of the operating costs. The economic costs resulting from external effects are probably low.

- The estimated average costs of decentralized afforestation are comparable to the expected costs of $CO_2$ emission control (USD 50–100 per ton $CO_2$). The investment expenditures would be low. Scale effects are unlikely to materialize. Price effects and economic costs resulting from external effects will be determined by land scarcity factors or the extent to which ecologically sensitive tracts of land are used. In the case of continental afforestation, the estimated average operating costs are prohibitively high, even before capital costs are considered (>USD 1,000 per ton $CO_2$).
- The estimated average operating costs for spreading pulverized calcium oxide/hydroxide or pulverized lime are also comparable to the costs expected for $CO_2$ emissions control (USD 50–100 per ton $CO_2$). But the investments required for large-scale deployment are estimated to be prohibitively high, given that intensive processing and/or calcination of the raw material would be required. Moreover, the costs have probably been underestimated as a result of capital costs and price effects not being considered. The economic costs resulting from external effects are probably low.
- Estimates of the average operating costs for air capture are currently high (USD 100 – 500 per ton $CO_2$), but these figures include the capital costs. With this technology, we can expect scale effects to dominate price effects, so that future operating costs have possibly been overestimated. Storing of adsorbed $CO_2$ might however reverse this effect. The economic costs resulting from external effects are probably low.

RM technologies

**The costs for RM technologies cannot be properly compared with the costs of emission control, as the comparison requires the definition of references for atmospheric $CO_2$ concentration and period of time.** If anthropogenic radiative forcing were to be tackled using RM technologies alone, their deployment would have to be sustained over very long periods, so that the cumulative costs of RM technologies over time might exceed the costs of emission control or CDR technologies, even if the annual costs of RM were very low. At present we do not have a comparative analysis of different emissions and compensation scenarios that takes the positive feedback effects of RM on natural $CO_2$ absorption into account. Accordingly, only the running costs of RM technologies can be evaluated; an assessment of cumulative costs over time is impossible. Technologies for increasing the albedo of towns and green areas are not listed in the following summary, as these technologies are too limited in their potential to have any significant influence on the Earth's radiation budget.

- The estimated annual operating costs for the modification of marine stratus clouds and cirrus clouds are very low (<USD 1 billion per $W/m^2$). The available estimates do not, however, reflect the current state of knowledge, and it seems likely that the costs here have also been underestimated as the price effects have not been factored in. It is true, however, that only very small quantities of material would be required to modify cirrus clouds. Both technologies are expected to generate extensive external effects with correspondingly high economic costs.
- If specially manufactured airplanes or airships are used to deliver the material, the estimated annual operating costs for adding aerosols to the stratosphere are low (< USD 10 billion per $W/m^2$). If existing flight technology is used, they will be several times higher (< USD 50 billion $W/m^2$). Unlike the cost estimates for the technologies previously discussed, these cost estimates are current. Here again, we can expect price effects to dominate potential

scale effects. This technology is expected to generate extensive external effects with correspondingly high economic costs.

- The estimated average operating costs for the modification of desert areas with a view to changing the Earth's albedo and for installing reflectors in space are prohibitively high (>USD 1000 billion per W/m$^2$).

Taken as a whole, the research findings available at present are clearly insufficient to determine with any satisfactory degree of accuracy either the cost of acquiring and deploying CE technologies or the economic costs that would result from such deployment.

### What conflict potential might be unleashed by the deployment of CE technologies?

AC12
GEOPOLITICAL OBJECTIONS

Regional impact

**The geopolitical conflict potential of climate engineering depends largely on the distribution of regional effects and on whether CE deployment is organized unilaterally or multilaterally.** Potential for conflict would result from the unequal distribution of the changes to be expected in temperatures, precipitation, and other climate variables. In some regions, climate engineering might lead to climate developments that would incur economic losses higher than those that would arise without CE deployment. The distribution of these regional side-effects affecting areas such as agriculture could lead to international conflicts. The problem is compounded by the fact that climate-related damage like poor harvests or weather-related catastrophes can neither be causally linked to specific CE deployments nor causally disassociated from them (Leisner and Müller-Kliesner 2010).

Unilateral or minilateral deployment

**The very technologies that could be deployed relatively easily—in technical terms—are precisely those technologies that are most likely to engender political and social implementation problems if deployed unilaterally.** This applies both to the spreading of aerosols in the stratosphere and to the modification of marine stratus and cirrus clouds. These RM technologies could lead to significant regional side-effects that could make climate engineering unacceptable for some states. The social and political resistance would be highest if the RM technologies were to be deployed unilaterally or minilaterally.

Hardly any binding regulations at present

This geopolitical conflict potential results from the fact that the applicability of existing binding international agreements to climate engineering is at least questionable in many instances. It is however necessary to add that customary international law has an indirect effect on distribution policies, as it prescribes that the most environmentally friendly technology of those available should be used in the context of potentially environmentally hazardous activities, and that the interests of other states and internationalized territories potentially affected by the activities in question must be respected.[92] In the context of technologies for reducing insolation via reflectors in outer space, Article I of the Outer Space Treaty (OST) arguably implies that a unilateral deployment of climate engineering would have to be linked to a compensation mechanism, as the use of outer space must be carried out for the benefit, and in the interests, of all countries. Other CE technologies also require due regard for the existing rights and territorial integrity of other states. In the light of this general obligation, a rebuttable presumption exists according to which any purely unilateral deployment of climate engineering is a violation of international law. In all other cases, and in particular with regard to RM technologies, the legal evaluation depends mainly on how the phenomenon of conflicting environment-related objectives will be handled in future.

92 Internationalized territory is not subject to the territorial sovereignty of any one state but is open to use by all states. Examples are the high seas, the deep seabed and outer space.

This international relations perspective is closely associated with the problem of intergenerational equity. Although not legally binding, the Rio Declaration establishes environmental protection, intergenerational equity, and appropriate economic development as key components of the concept of sustainable development. Whether climate engineering is compatible with the requirements of intergenerational equity depends on the arguments used to justify their investigation or deployment. While not legally enforceable, these requirements prohibit activities that threaten the survival of future generations or their ability to live their lives with dignity.

Intergenerational equity

Climate engineering can only be implemented without engendering significant conflicts if the technology selected is deployed within a framework of multilaterally agreed procedures and if the technology is widely accepted by society.

#### What potential for social conflict does climate engineering have in Germany?

**Attitudes to climate engineering in Germany are currently very heterogeneous, but media reports on the topic are typically critical or negative.** Empirical studies facilitating predictions about the way the debate will develop in future are few and far between. One reason for this is that climate engineering is still practically unknown to the public at large. The history of the acceptance accorded to other technologies (nuclear energy, genetic engineering, nanotechnology) suggests, however, that the significance accorded to the risks will increase as the debate proceeds. Sociological research shows that the general public in Germany at least is doubtful about the deployment of RM technologies. The fact that their long-term effects on social systems and ecosystems are largely unknown (and are hence are not being evaluated appropriately) lies at the heart of this skepticism.

Experience with other technologies

According to the experts consulted, the potential for social conflict in Germany is conditioned by a variety of factors. If Germany were to take part in a CE initiative, either at an operative level or as a financial backer, this would raise the potential for conflict more appreciably than if Germany were merely a passive observer of such initiatives. Experts agree that the potential for conflict would increase with the implementation of CE technologies in close proximity to Germany. At the other end of the scale, a German refusal to participate in an international CE initiative would lead to less intensive conflicts, as Germany is not one of the countries affected most strongly by climate change and the urgency of adaptation measures would not be perceived as a priority by most observers. Protests expressing solidarity with others could be expected, but not on any very large scale. If CE technologies were to be deployed against the will of the United Nations and many developing countries, the resulting potential for conflict would however be severe.

Different levels of participation

The experts consulted felt that German participation in an international CE research program without any definite obligation to test the technologies investigated would be much less likely to engender controversy than active participation in a major experiment or large-scale CE deployment.

#### Would the deployment of CE technologies lead to a reduction in emission control?

AC9
DEPLOYMENT SIDE-EFFECTS

Any attempt to answer this question must take account both of (i) analyses based on economic models and (ii) analyses of political and social processes. In economic models, CE technologies are viewed as substitutes for conventional emission control. Three different economic mechanisms suggest that climate engineering research or deployment could lead to a reduction of conventional emission control.

First, when CE technologies are perceived to be more economical than emission control—as is often the case when only the operating costs are taken into account, as opposed to the full

Costs assumed to be lower

economic costs—then a simple substitution mechanism applies. RM technologies, in particular, may appear to be cheaper than conventional emission control in terms of operating costs. But this argument ignores external costs, so this substitution mechanism loses its relevance once the economic costs are factored in.

Lower $CO_2$ price

Second, substitution is inherent in theoretical economic modeling of measures designed to control emissions. In these neoclassical models, the introduction of a new technology will always lead to some kind of substitution of technologies previously applied when the marginal abatement costs for the new technology are low. This applies whether the new technology is an emission control technology or a CE technology. Substitution of this kind is also a function of the decentralized realization of CDR technologies in response to a new incentive mechanism ($CO_2$ certificate market). $CO_2$ certificates from CDR increase the supply of such certificates and result in a new, lower equilibrium price, which in turn implies that some other emission control measures will be scaled back. An exception would only be conceivable if the fixed costs for research, development, and putting a technology on the market were high. In that case, though, the CE technology would not be introduced anyway.

Rapid reaction possible with RM

Third, the substitution mechanism does not only result from the cost advantage but also from the ability of RM technologies to affect temperature quickly. RM technologies lower the risk of abrupt climate change, as they could be deployed to great effect in the short term. The capacity for deploying RM technologies would reduce the necessity to extend emission control to a level where it would provide protection against implausibly sudden and abrupt climate change.

Weighting of climate change and climate engineering

**This argument figures in the public debate on the topic.** The evaluation of readers' letters and blogs has shown clearly that the deployment or the mere availability of climate engineering is seen as possessing a worrying capacity to make climate change seem less threatening and hence slacken the pressure on politicians to implement emission control and promote renewable energies. The reverse may however also be the case. A study carried out by NERC (2011) shows that the efforts made by the population to reduce emissions may increase when climate engineering is increasingly seen to be a realistic option, since avoiding emissions may then be perceived as being the lesser of two evils.

So far, we have been considering the interactions between climate engineering and emission control within a single state. But such interactions can also take place between states. If one state acts unilaterally to introduce climate engineering, other states could assume that climate change is already under control and dispense with their emission control. On the other hand, states facing a welfare loss as a result of climate engineering might equally well redouble their efforts in the field of emission control in order to reduce the incentive for other states to implement climate engineering.

#### Are the consequences of deploying a particular CE technology irreversible?

AC7
RISK ETHICS

There is no scientifically precise definition of irreversibility for the debate on the irreversibility of CE technologies to refer to. Interventions in the climate system are fundamentally irreversible as a matter of principle. When a CE deployment is discontinued, the Earth system cannot return to precisely the state it was in before the CE deployment was instituted.

Duration and intensity of intervention

**The reversibility of interventions in the climate system depends on the intensity and the duration of the intervention.** A solar eclipse has a marked influence on the weather, but the system returns to normal very quickly. At the other end of the spectrum, interventions lasting for decades or for hundreds of years lead to changes in the system that can only be compensated for by processes operating over similarly long timescales. It is important to note that bifurcations can occur in the Earth system (Thompson and Sieber 2011). These could make it impossible to return to a balance that is similar to the way things were initially, or cause the climate to go through several long hysteresis loops before such an equilibrium can reassert itself (Rahmstorf 2001).

Hence it is unclear how great the influence of a CE intervention on the Earth system would be and how long it would last. The deployment of air capture with secure storage, for example, would affect relatively few material cycles. In particular, it would have little effect on sensitive biological cycles.

Any discussion of the potential reversibility of CE interventions in the climate system should take into account the fact that undiminished $CO_2$ emissions would also lead to presumably irreversible changes. So an assessment of the irreversibility of the consequences of the deployment of CE technologies must also address the question of the alternative scenario against which the effects need to be regarded. The assumed emission path while CE deployment is ongoing is of decisive importance, particularly in the case of long-term RM deployment.

#### What would be the consequences of discontinuing the use of a particular CE technology?

**AC7**
RISK ETHICS

Strategic exit or unplanned discontinuation

**It is crucial to distinguish between sudden discontinuation and planned phase-out.** All CE technologies could be phased out gradually without any severe repercussions. During the phase-out period, adaptation and mitigation measures could be implemented so that slow climate change with adaptation would be simulated. This process could be quite lengthy if an RM technology were deployed on a large scale without parallel measures to reduce the atmospheric concentration of greenhouse gases.

RM discontinuation triggers major temperature response

If extensive RM deployment was shut down too quickly or disrupted in an unplanned manner for some time, rapid reduction in the compensation of radiative forcing could lead to runaway climate change, with more drastic changes in temperature than might have occurred without previous RM deployment.

No temperature response if CDR abandoned

The deployment of CDR technologies, by contrast, could be interrupted without triggering any rapid temperature response. Over and above this, the consequences of discontinuation would depend on the extent to which the particular CDR technology influenced different material cycles. As we have said, a technology such as air capture would not affect many material cycles and would, in particular, have little effect on sensitive biological cycles, so for the climate system the impact of canceling such a deployment would be minimal.

Significance of capital costs

However, there are various CDR technologies that it might be economically inefficient to relinquish in view of the investments made in the technology. One practical example is the case of CDR technologies based on chemical processes geared to raising oceanic carbon uptake. Depending on the technology used (e.g., spreading of calcium hydroxide or pulverized lime), the mining of the lime alone would require an industry on the scale of between 1/8 and 2/3 of the global coal-mining sector. Furthermore, a fleet of ships equivalent to 1/8 of the totality of current global shipping would be required for the spreading of the chemicals. Exiting from this CE technology would mean that huge investments would have to be written off. Moreover, the discontinuation of individual CDR technologies such as iron fertilization in the ocean or afforestation would have negative effects on the sustainability of carbon sequestration. It follows that these extra emission sources would have to be factored into plans for the future control of anthropogenic emissions.

Withdrawal from international treaties

Desisting from the application of CE technologies, especially those shored up by international agreements, must also be seen in connection with the question of exit options from international treaties. The possibilities existing in international law to withdraw from or terminate a treaty largely depend on the provisions of the respective treaty itself. Treaties may expire after a period of time, provide for withdrawal or termination options, or define a framework within which they can be terminated with the consent of all parties involved (Art. 54 of the Vienna Convention on the Law of Treaties (VCLT)). The withdrawal of one party from a treaty without the consent of the others is only possible under the narrowly defined conditions laid down in Art. 60 VCLT et seq. These allow one party to terminate a treaty (i) if another commits a severe breach of that treaty, for example by unilateral action incompatible with the object and purpose of the treaty, (ii) if the fulfillment of the treaty has become impossible, or (iii) if circumstances have changed fundamentally in a manner that was not foreseeable at the time of the conclusion of the treaty. All these eventualities are governed by stringent requirements. Whether attempts to exit from a CE activity could be prevented on legal grounds would depend solely on the formulation of the international treaties governing the deployment of climate engineering.

### 8.1.2 Should there be research on CE technologies at all?

The preceding sections raised a series of factual issues relevant to the question of whether particular CE technologies should be deployed. Time and again, it became apparent that it is difficult to arrive at soundly justified decisions on the topic for several reasons. One of the most important of them is the absence of precise scientific statements about so many aspects of CE technology and its probable impacts. This is the point of departure for the second central question in the debate: Should research be carried out on CE technologies? The next section summarizes important findings from the scoping report that have a bearing on this question.

#### What types of CE research are currently being carried out?

**It is apparent—not least from the interdisciplinary approach that the complexity of the relevant topics demands—that there is no such thing as** definitive CE research. A better understanding of different aspects of the CE debate can only be obtained by using radically different research approaches. They also differ in terms of the problems they raise. The spectrum of research contributing directly or indirectly to our understanding of the effects of climate engineering ranges from theoretical analysis to mathematical modeling, laboratory experiments, and field studies. All these activities can be geared either to the research and development of CE technologies and/or to the direct measurement of the effects of CE activities.

Research on Earth system

All research on CE technologies and their effects is ultimately founded on the scientific study of the Earth system. Understanding the workings of the Earth system is essential in order to forecast how the system will continue to develop and how it might react to interventions. The objective of this is to come up with models of the Earth system that provide a basis for predicting the effectiveness and the side-effects of the potential CE deployment. At present, however, these models can only generate forecasts featuring substantial uncertainty margins, particularly with regard to the local impact of global developments.

Field work and laboratory work

It would be impossible to improve these models and verify their results without field studies. In RM research, long-term, large-scale experimental approaches would be required to observe statistically significant effects, given the difficulty of separating the climate signal from statistical noise. Many CDR technologies would also call for a kind of testing that would allow robust prediction of their effects via large-scale experiments. This is particularly true in connection with the ecological impact of these technologies. At present no research projects of this nature are being pursued. Research on the basic processes and mechanisms underlying possible CE technologies can be carried out in the laboratory or as relatively small-scale field studies without any risk of side-effects on a global scale. They would be suitable for detecting local changes to the radiation budget or $CO_2$ flows that are not in themselves likely to impact significantly on the climate

Parallels between natural and anthropogenic influences

Over and above work of this kind, the investigation of the way the climate is affected by natural influences (volcanic eruptions, iron fertilization from islands/sediments, etc.) or anthropogenic effects (such as those on clouds in the proximity of shipping and flight routes or changes to terrestrial vegetation) can be used to estimate the effectiveness of CE technologies exploiting the same mechanisms.

Assessment of cost aspects and economic effects

In contrast to these scientific approaches, economic research on climate engineering and research in other disciplines to be discussed in the following is currently almost entirely theoretical, although it is founded on insights gained by scientists. Economic research on climate engineering can be divided into two main fields. One of these is predominantly concerned with estimating the various costs associated with climate engineering. The other makes use of dynamic optimization approaches or game theory to explore the economic impact of the deployment of climate engineering on existing emission control and adaptation measures and to analyze mechanisms that might prove useful in elaborating international treaties. The estimation of costs includes (i) estimation of the costs of infrastructure and raw materials for particular CE technologies, along with the operating costs of such technologies, (ii) the estimation of price effects that would potentially result from the large-scale CE deployment, and (iii) so-called integrated impact assessment studies, which estimate economic costs on the basis of the effects of individual CE technologies predicted by scientists. The bulk of the literature currently available focuses on estimating the operating costs of CE technologies. The other aspects are only gradually coming into focus. In the examination of the effects of CE deployment on existing emission control and adaptation measures, broad conceptual approaches currently dominate over detailed studies on well-defined CE approaches.

International consequences and cooperation requirements

Similar trends are identifiable in current political-science approaches. The principal question currently under discussion here is whether (and to what extent) the unilateral deployment of CE measures would be possible and what kind of impact this would have on the UNFCCC process. There are also investigations on the question of how international cooperation could be organized to facilitate the multilateral deployment of individual CE technologies and on the expectable political and social consequences of unilateral deployment.

Public perception

Current sociological research on the impact of the CE debate on society and on public perceptions centers on media analysis, evaluation of readers' letters and blogs, and interviews with focus groups and experts.

Legitimacy within the framework of existing treaties

Current legal analysis is principally concerned with the legality of individual CE technologies within the framework of existing treaties. Given the predominantly transboundary nature of climate engineering, the subsystem of international law is of the greatest relevance here. The applicability, scope, and legal consequences of existing international agreements and international customary law are presently being investigated, and judgments passed by the International Court of Justice and international arbitration are also attracting attention.

Climate ethics perspective

In philosophy and ethics, the topic of climate engineering is gradually coming into focus, Discussion here takes place in the framework of climate ethics, with particular regard to general moral principles (intergenerational equity or the polluter-pays principle).

#### Is it likely that research on particular CE technologies will reach a "point of no return"?

AC 2
RESEARCH SIDE-EFFECTS

Concerns of the general public articulated

Research on any new technology will never be entirely exempt from the danger that the actors involved (scientists, regulatory bodies, etc.) may go ahead with research on and implementation of the technology, even if from an objective perspective the knowledge thus gained makes this seem inadvisable. Concern that the process of developing CE technologies could generate a self-perpetuating momentum is frequently expressed by members of the public. Analysis shows that the scientific community, bloggers, and the media are concerned that research on and the development of CE technologies are likely to lead automatically to the future deployment of those technologies. This concern results primarily from observations on the course taken in the past by the development and introduction of other technologies (nuclear energy, genetic engineering, nanotechnology). Opportunities and potentialities initially dominated the debate, while risks only came into focus gradually. From that point of view, it is plausible to assume that there is a likelihood of CE technologies being deployed before their effects have been adequately investigated.

Political regulation and momentum

**From an economic point of view, the only incentive the private sector has to invest in CE research is if it can deploy the resulting technology.** On that basis, it could be argued that the momentum already accumulating in the development process may well prove unstoppable. But an argument to the contrary can also be advanced. The expected profitability of research and development for enterprises can only be assured if states permit the implementation of CE technologies and provide appropriate incentives for their deployment. On balance, the argument that the process might become self-perpetuating rests entirely on the political momentum that research on CE technologies generates.

#### Is it likely that research on specific CE technologies will have a detrimental effect on efforts to control emissions?

AC 2
RESEARCH SIDE-EFFECTS

Decisions not taken in isolation

Decisions made on CE research and emission control cannot be seen independently of each other. Influence is reciprocal. The type of research involved determines the degree to which this is the case. Basic research or research on side-effects (i.e., any kind of research that does not lead to immediate readiness to deploy a particular technology) is likely to have only a tangential effect on emission control. In fact, such research might even give it a boost. If research were to show that the outlook for CE deployment is more pessimistic than had previously been thought, this could lead to increased efforts to control emissions, as the option of a quick fix through RM would be either less freely available or at the price of greater negative external effects than initially anticipated.

Type of research

**Application-oriented research aiming to bring CE technology to the point of deployment-readiness makes it more likely that emission control efforts will be negatively affected.** In the case of RM technologies, this view can be explained by the fact that these technologies can be used quite directly to modify the Earth's radiation budget and to respond quickly to catastrophic climate change. Accordingly, they may function as an insurance against abrupt climate change that could otherwise only be prevented by adequate emission reduction. In the case of CDR technologies, the situation is even more clear-cut, since these technologies could remove existing $CO_2$ emissions from the atmosphere, which means reduce the negative impact of emissions that have already occurred. Putting CDR technologies on-stream via research would reduce the necessity for controlling emissions. Consequently, there is indeed a very real risk that attempts to control emissions could be scaled back as a result of application-oriented research into CE technologies.

**Research on CE technologies might not lead to reduced emission control if decisions on such research were to be taken decentrally.** Parties with objections to climate engineering would have an interest in demonstrating that the future deployment of climate engineering is avoidable, so they might increase their own efforts to control emissions. The assumption voiced by some CE supporters that inadequate emission control makes the deployment of CE inevitable could thus be disproved.

Different effects on CE critics and CE advocates

Sociological research indicates that CE critics would act in a more climate-friendly manner if advances were made in the development of CE technologies. At the same time, CE advocates would tend to adopt a more carefree attitude than before towards greenhouse gas emissions. But the extent to which increased awareness of CE technologies in society might lead to a general change in attitude toward climate protection has not yet been clarified.

### How likely is it that commercial influence will be brought to bear on the development of certain CE technologies?

AC2
RESEARCH SIDE-EFFECTS

Public responses to climate engineering sometimes express the fear that advocates and promoters of climate engineering are largely motivated by self-interest. This fear is triggered especially by the co-authorship of papers and by financial backing originating in the energy sector. In this context, it is not surprising that concerns about commercial control are one of the most significant factors in the mobilization of opposition to climate engineering.

Market for the technologies

**There will only be an incentive for commercial influence on the development of a technology if a market for such technologies exists (or it can be assumed that such a market will exist some time in the future).** In the case of technologies for injecting aerosols into the stratosphere or modifying clouds, no such markets or regulatory frameworks exist as yet. Accordingly, the development of these technologies is not currently a profitable activity. With regard to various CDR technologies, regulation would also be required to create a market. For $CO_2$ certificates to be a viable proposition, carbon storage would have to be officially verified and certified for participation in the market.

Unregulated markets for $CO_2$ offsets

Unregulated $CO_2$ markets already exist. These are the so-called $CO_2$ offset markets in which $CO_2$ credits can be purchased, for example in order to make flights carbon-neutral. It follows that commercial incentives to develop CDR technologies such as iron fertilization of the ocean exist to a limited extent, as $CO_2$ offsets could be sold. However, participation in such markets is currently limited by the absence of a regulatory system allowing quantification and verification of the carbon storage achieved. Nor are the price signals strong enough to incentivize large-scale commercial development of CDR technologies. These markets are outside the political regulation of emission control, so they cannot function as substitutes for other avoidance measures. For this reason, it is currently unlikely that such privately organized markets for $CO_2$ offsets will develop to the point where an independent body dominated by private-sector interests will be the outcome.

"Legitimate scientific research" compatible with London regime

In the specific case of ocean fertilization, the parties to the London Convention and the London protocol have agreed (in a resolution which is not formally binding) that only "legitimate scientific research" is compatible with the London framework. Against the background of the recently adopted (equally non-binding, but politically important) Assessment Framework for Scientific Research Involving Ocean Fertilization, experiments with a purely commercial background would not constitute "legitimate scientific research". At their tenth conference, the parties to the Convention on Biological Diversity (CBD) resolved that "no climate-related geo-engineering [...] with the exception of small-scale scientific research studies" should take place (para. 8 [w]). It remains to be seen whether these non-binding resolutions will be effective enough to impose restrictions on commercial activities.

Markets for relatively pure $CO_2$

A market for relatively pure $CO_2$ does already exist, as $CO_2$ can for instance be used to manufacture dry ice or for fertilization in greenhouses (Lackner 2010). This explains why different air capture technologies have already been scrutinized by the private sector or in joint ventures with universities and research institutes. However, the quantities traded in such markets are much too small to exert any significant influence on the large-scale implementation of air capture.

Influence on public perception

Apart from the question of direct commercial interests, public perceptions of climate engineering reveal suspicions that enterprises or states profiting from trade in fossil fuels stand to benefit from exploiting the substitution effects associated with climate engineering. Fears exist that certain companies would profit from reduced emission control and might thus have an interest in playing down the risks involved in climate engineering or influencing the image of climate engineering in the media in such a way that too little significance is attributed to potential side-effects or uncertainties.

**On balance, it appears that, in the case of most CE technologies, research is not likely to lead directly to commercial exploitation of processes and results unless states create a regulatory framework that in its turn creates markets for them.** Where markets already exist (e.g., the market for pure $CO_2$), competition law and regulatory bodies must tackle negative or distorting effects. At the moment, there are no indications suggesting that commercial interests will exercise significant influence on the development of CE technologies. However, commercial interests might conceivably play an indirect role if commercial sponsorship for the dissemination of research placed a bias on the information released to the public. That could involve (i) a slackening in efforts to reduce emissions and (ii) an impact influence on the attitudes entertained by the general public toward climate engineering.

### Are large-scale field studies a necessary precondition for research on CE technologies?

**AC2**
RESEARCH SIDE-EFFECTS

What kind of knowledge are we after?

The answer to the question depends on the exact nature of the knowledge that research is expected to generate. Simulations with models and empirical laboratory research may be sufficient for carrying out basic research on particular CE technologies. But if research is geared to bringing the concrete deployment of a given CE technology to fruition, field research will be unavoidable in most cases. In some instances this results in serious conceptual problems.

Large-scale field studies

**Field studies relating to RM technology would need to be carried out on a large scale and over a period of at least a decade in order to be able to distinguish the effectiveness of the technology from climate noise.** Undertaking studies on this scale would practically imply the intended deployment of the RM technology in question with all its associated side-effects. As the complexity of the effects cannot be modeled precisely enough, there are no alternatives available drawing on models to evaluate the precise effects of RM technology on regional climates

Laboratory work and small-scale field studies

Laboratory work and small-scale field studies on CDR technologies can verify the efficacy of individual technologies. However, evaluation of the entire chain of events resulting from deployment, including possible side-effects, would require extensive research, and in some cases this research would have to be carried out over long timescales. Over and above this, the assessment of the effectiveness of some CDR technologies is problematic, as the $CO_2$ take-up cannot be measured directly for all technologies. This applies, for example, to iron fertilization in the ocean and to the spreading of lime. The effectiveness of these CDR technologies could only be assessed by gathering data over long periods and subjecting it to statistical analysis. It appears, then, that there are only a limited number of CE technologies for which large-scale field studies would not be required to test their efficacy and effectiveness.

**To what extent can research mitigate the uncertainty surrounding the effectiveness and side-effects of CE technologies?**

AC7
RISK ETHICS

Many of the answers to the preceding questions have shown that considerable uncertainties still exist in relation to the expected side-effects of CE research and CE deployment. Due to the complexity of the Earth system, future research drawing on mathematical models and fieldwork will not be able to ensure risk-free climate engineering, nor can uncertainty about the evolution and the consequences of anthropogenic climate change be eliminated completely.

**Are particular CE research approaches covered by international legal norms?**

No general prohibition in international law

On many points, the legal status of climate engineering is uncertain, especially in relation to the risks of environmental damage as a result of CE technologies that have not yet been subjected to comprehensive scientific evaluation. But especially against the background of the requirements of the UN Framework Convention on Climate Change, it is essential to note that no general and absolute prohibition of climate engineering exists in international law. In cases where no prohibition on individual CE technologies derives from detailed legislation, the legal assessment of CE research depends primarily on future approaches to the phenomenon of colliding environmental aims. Preliminary indications from state practice suggest that the precautionary principle could be operationalized as an instrument for reconciling interests, given that the approach to scientific uncertainty enshrined in this principle has been integrated into the majority of treaties that are potentially or actually relevant.

The catalogue of questions set out above assembles information relevant for the assessment of arguments put forward in the CE debate. It makes no claim to deal with the topic exhaustively. Conclusive answers to the empirical questions are still in abeyance, and the reader should not assume that all the relevant factual questions have been broached in this treatment of climate engineering.

## 8.2 Significance of results to date for the evaluation of individual CE technologies

The previous section was primarily based on the findings produced by an analysis of the relevant arguments. This section summarizes findings for each individual CE technology that can help to elaborate a preliminary evaluation. A sophisticated evaluation of the matter primarily at stake here—whether and in what form CE technologies should be scientifically investigated and deployed—needs to draw both on descriptive scientific findings and on normative assumptions. In principle, these normative assumptions (such as what conditions are desirable or what risks are acceptable and tolerable) cannot be established scientifically, so scientists should play no part in determining what they are.

Within the specific framework of this report, the implications of this are as follows: the analysis of the arguments advanced in the CE controversy has revealed the existence of numerous arguments for and against research on, and deployment of, climate engineering. Taking up a position in this debate means giving close consideration to complex normative arguments in order to find a balance that enables us to establish priorities. For example, the chance of using RM technologies to develop a fall-back option must be weighed up against the various potential (and possibly negative) consequences of RM research, in particular its capacity to exert a negative influence on emission control.

In the following, we summarize the key statements on each CE technology. This summary does not directly translate either into a hierarchy of technologies or into guidelines for political action.

### 8.2.1 RM technologies

**Reflectors in space:** There are theoretical plans indicating how this technology could work, but they have not yet reached the implementation stage. It can indeed be expected to take decades before this technology is technically ready for deployment. In addition, it appears that the deployment costs would be prohibitively high. It would probably also be difficult to secure acceptance for this technology among the broader public, as it is widely perceived as being both too expensive and, in particular, too risky. Moreover, such technologies would violate the Outer Space Treaty (OST) if they were to result in disadvantages for individual states (common interest clause), cause damage by contaminating space (space debris), or result in damaging changes on Earth (environmental protection clause).

**Aerosols in the stratosphere:** This technology could prove to be extremely effective as a means of temperature regulation. In comparison to other RM technologies, research here has already made considerable progress. The effects of natural volcanic activity demonstrate how the technology could work. The fundamental meteorological side-effects and limits of SRM apply to this technology. Estimates of its operating costs have recently been corrected upwards, but they still appear low in comparison to other CE technologies. This would enable the technology to be deployed unilaterally or minilaterally. However, this is one of the technologies with the greatest potential to trigger conflicts in society, especially if it were to be deployed unilaterally. As yet, the economic costs cannot be estimated. If a negative effect on the environment can be demonstrated, the Convention on Long-Range Transboundary Air Pollution would demand its parties to prohibit the injection of particles into the stratosphere. Upper limits for sulfur are established in the Protocol to Abate Acidification, Eutrophication and Ground-level Ozone.

**Modification of marine stratus clouds:** This technology could prove to be an effective and economical RM technology if its effectiveness were to be demonstrated, at least in principle. The general meteorological side-effects and limitations of SRM apply to this technology. Individual studies conclude that this technology would exert a relatively powerful influence on the hydrological cycle. The means of implementation currently under discussion in the literature (automated flettner ships) is not ready for deployment; aspects of the technology still remain to be developed. Even with the significant increases in estimated costs to be expected, the operating costs would be relatively low. Accordingly, the technology could be deployed unilaterally or minilaterally. It has the potential to trigger major conflicts in society, especially if deployed unilaterally. As yet, the economic costs cannot be estimated. Even if the effectiveness of the technology could be demonstrated, the imperative to exercise consideration for others in international waters would militate against any desire to proceed with the deployment of this technology unilaterally.

**Modification of cirrus clouds:** This technology has less potential for influencing global temperature than the modification of marine stratus clouds or the modification of the stratosphere. At present, the fundamental mechanisms behind it are poorly understood. As this technology would also have a major impact on shortwave radiation, the fundamental meteorological side-effects and limitations of SRM also apply to this technology. It can be expected to exert a strong influence on the hydrological cycle. The operating costs associated with this technology are expected to be relatively low, which would enable the technology to be deployed unilaterally or minilaterally. It does however have the potential to trigger major social conflict, especially if it were to be deployed unilaterally. As yet, the economic costs cannot be estimated. The legality of this technology also rests on international air quality standards. If negative side-effects cannot be ruled out, the probability of such effects occurring would be decisive. The

Convention on Long-Range Transboundary Air Pollution would demand its parties to refrain from injecting material into the stratosphere if concrete evidence for the negative environmental effect of doing so were available.

**Modification of the Earth's albedo:** The effectiveness of this technology is limited by the space available; it does not represent an effective technology on a global scale. It can, however, help optimize the climate in urban areas and also make a marginal contribution to emission control. The legitimacy of isolated deployments planned and executed on the territory of individual states is first and foremost a matter for domestic law. Limitations on the modification of deserts could result from the Convention on Biological Diversity, if the deployment is not intended to combat desertification in line with the aims defined in the United Nations Convention to Combat Desertification.

### 8.2.2 CDR technologies

**Physical methods for increasing oceanic carbon uptake:** No effective physical methods for storing carbon in the ocean exist at the present time.

**Chemical methods for increasing oceanic carbon uptake:** Spreading pulverized lime or silicates could bind large quantities of $CO_2$ and store them in the ocean. The secondary effect of this would be to counteract the acidification of the oceans. The investments required to bind large quantities of $CO_2$ would be very high. This factor plus the complex logistics involved would restrict the potential of these technologies. Spreading calcium oxide would be more effective than using lime but given the energy required for calcination would probably involve even higher costs. As raising the alkalinity of the ocean would counteract the acidification that is currently having a detrimental impact on marine ecosystems, it would not result in side-effects contravening international legal agreements. Consequently, if the spreading of pulverized rock does not have negative ecological consequences, these CE technologies would be unlikely to encounter international legal restrictions, as long as the interests of other states in exploiting the oceans were not seriously disrupted.

Spreading olivine in the catchment areas of large rivers to bind $CO_2$ does not currently appear to be an effective and cost-effective CDR technology, as the processing of the olivine would be complex and the target areas are inaccessible. The legality of spreading olivine on forest floors would primarily be a matter for domestic legislation. If dissolved silica were to enter the sea from rivers together with some of the absorbed carbon, the same legal considerations would apply to this technology as apply to ocean fertilization, given that this would also be a form of fertilization.

**Biological methods for increasing oceanic carbon uptake:** The carbon removal potential of iron fertilization in the Southern Ocean is the subject of controversy, and estimates of the operating costs vary widely. As the quantity of carbon taken up can hardly be measured with any degree of precision, no economic policy instruments could be used to engineer a decentralized implementation of iron fertilization effectively. It follows from this that implementation would need to be coordinated internationally and a mechanism for dividing up the costs would have to be developed. It is conceivable that side-effects might materialize after some time as a result of the transport of altered nutrient and dissolved oxygen inventories far beyond the areas initially fertilized. But the political conflict potential that this would engender seems likely to be limited. However, reactions by the public to the field study carried out in the framework of the LOHAFEX project suggest that the potential of this technology to create conflict in society is relatively strong in Germany. "Legitimate scientific research" on ocean fertilization is currently permitted by the London regime. The Assessment Framework for Scientific Research Involving Ocean Fertilisation lays down stringent requirements that have to be met with by research activities in order to be categorized as "legitimate scientific research". But it does allow some scope for weighing the environmental risks of ocean fertilization experiments against their potential advantages with regard to the minimization of the negative consequences of climate change.

The carbon removal potential of nitrate or phosphate fertilizers in the ocean is small taking into account the emissions involved in the production of the fertilizer. Increasing the availability of nutrients by mimicking natural upwelling has also a small potential. Additionally, the thermal inertia of the ocean, which is important for the future development of the Earth's temperature, would be undermined. Given the freedom of the high seas, the deployment of pumping systems on the high seas to increase upwelling would generally appear to be within the limits of international law, but only as long as the freedom of other states (freedom of navigation, etc.) were not significantly disrupted. In the exclusively economic zones, coastal states have the sole right to decide on the construction of installations that are permanently fixed on the seabed. Only these coastal states are entitled to grant planning permission and regulate the construction, use, and operation of such installations. This also applies to floating installations, but only when these installations are (also) engaged in scientific marine research.

**Chemical $CO_2$ scrubbing (air capture):** The direct air capture of $CO_2$ with chemicals in reactor towers is limited by the storage space available for captured $CO_2$, by the energy efficiency of the separation process, and by the cost of the technology. This technology can be implemented decentrally. Given the relative insignificance of the side-effects, the external costs are low. The effectiveness of air capture can easily be established by measuring the quantities of $CO_2$ collected. Another advantage of the technology is that it can be deployed in the vicinity of suitable storage locations. Apart from local protests against $CO_2$ storage locations, air capture is not expected to engender controversy. The towers will be installed on the territory of individual states and are thus subject to domestic legislation only; storage outside the area of the state would be governed by the regulations that also apply to CCS.

**Biological methods for enhancing terrestrial carbon uptake:** The potential of afforestation and of biochar production is limited, as not enough land is available for afforestation at a reasonable cost. Decentralized, small-scale deployment might possibly supplement conventional emission control. The potential of these CDR methods to generate conflict is comparatively low. Afforestation and forest management are subject to national regulation. The afforestation of deserts and semi-deserts is a contravention of the Convention on Biological Diversity except where the aim is to combat desertification, but aside from that, afforestation and forest management are subject to national regulation. These CDR methods would be relatively easy to integrate into the UNFCCC process, more specifically into the mechanisms of the Kyoto Protocol or a follow-up protocol.

## 8.3 Closing remarks

Research on climate engineering and debate concerning its deployment are still in early stages. Climate engineering is virtually unknown to the public at large, so the debate has been taking place mainly among a small circle of predominantly academic participants plus a few representatives from the private sector. Up to now, the debate has largely taken place in the UK and North America. The report prepared by the Royal Society (2009) and the Asilomar Conference are examples of activities that have attracted attention beyond academic circles.

Research on climate engineering began with very general considerations of how the Earth's radiation budget could be manipulated. The exploration of specific technical approaches has now led to research on a wide range of technologies for Radiation Management (RM) and Carbon Dioxide Removal (CDR). Various specific technologies have been proposed, but initial estimates of operating costs and investment costs are available only for a limited number of technologies for which specific engineering approaches have been elaborated.

Other aspects of the various CE technologies have attracted less interest or have been completely ignored by researchers. The social sciences, in particular, have scarcely begun to investigate the social issues involved in climate engineering. The majority of CE technologies either requires international coordination or would take place in international territory where state legislation does not apply. Accordingly, the political and legal aspects of the deployment of such technologies should also be subjected to much more comprehensive research. Research on economic aspects has not yet advanced beyond conceptual studies. This applies especially to the study of external effects. Empirical research on such effects is only gradually beginning to materialize.

Investigation so far has shown that CDR and RM have very different characteristics and need to be evaluated differently. CDR may become necessary if a global consensus on emission control necessary for the purpose to reach the target laid down in Art. 2 of the UN Framework Convention on Climate Change—the prevention of dangerous antropogenic interference with the climate system—cannot be achieved. The later such an agreement is reached, the more probable it is that negative emissions will need to be maintained for a specific period during this century. In other words, the uptake of $CO_2$ from the atmosphere would have to be greater than the quantity of $CO_2$ emitted in this period. RM, by contrast, is largely seen as an intervention resource to be mobilized if climate change were to speed up dramatically, or if the Earth system looked like moving toward a tipping point and the rise in the Earth's temperature needed to be halted abruptly. This has consequences for the research needed on CDR and RM technologies, for the timescales over which research should be carried out, and for the possible deployment of these technologies.

CDR technologies can largely be seen as a supplement to emission control, although economic analysis shows that CDR and emission control can also substitute for one another to some extent. In the light of the current evolution of greenhouse gas emissions and research on the scale of climate change to be expected, investigating how far this complementary function can extend is one of the major research issues that needs to be addressed.

From what we know at the moment, the likelihood cannot be ruled out entirely that the deployment of many RM technologies would be associated with considerable side-effects, the extent and impact of which are not yet known. Research priorities and the timing of research activities are of particularly acute significance here. While numerous publications on the efficacy of many technologies exist, research on their side-effects does not seem to be proceeding at the same pace. We have no findings as yet from studies on regional side-effects that draw on climate models and integrated impact assessment studies. These findings are essential for further research on the economic costs of RM, on the political dimensions of deployment, on the applicable legal framework, on the theory of justice, and on acceptance of RM in society.

As the various effects resulting from the exertion of significant influence on the global climate cannot be forecasted reliably, if at all, the actual deployment of CE technologies would involve risks deriving from the gaps in our knowledge of the side-effects to be expected. Extension of research on the effects of the dynamics of the Earth system on individual regions is of course indispensable. But we also need to investigate how precise the scientific forecasts on the effects of CE deployment could be. Methods for CE risk management should then be developed to counteract any residual uncertainty.

Irrespective of the role individual CE technologies will play in future climate protection, it is patently obvious that the debate on climate engineering technologies and research cannot be considered in isolation. The assessment of CE technologies, for example, is already affected by the extent to which other climate protection measures have been implemented. New research findings indicate with increasing clarity that greater attention must be paid to a variety of anthropogenic influences on the Earth's radiation budget and the interactions between them. Future political decisions on climate protection will have to take account of all anthropogenic influences on the climate. This means that an integrated climate policy must consider the different effects on the climate of anthropogenic aerosol emissions and surface changes, whether these are the results of CE deployment or the side-effects of economic development.

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## Imprint

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**Assessing the Climate Engineering Debate**

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