GEOENGINEERING

effective climate protection or megalomania?

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effective climate protection or megalomania?

Methods – statutory framework – environment policy demands

01

INTRODUCTION

Climate protection strategies today basically pursue two approaches: Firstly, measures should be taken to reduce anthropogenic greenhouse gas emissions. Secondly, measures should be implemented that enable humans and the environment to adapt to unavoidable climate change.

For some time, proposals for counteracting climate change through large-scale intervention in global ecological processes have also been the subject of increased debate in literature and the media. Such measures are grouped together under the term geoengineering.

What is geoengineering?

Geoengineering comprises conscious and deliberate intervention in the climate system – mostly on a large scale – for the purpose of attenuating anthropogenic global warming (Royal Society 2009). According to the Intergovernmental Panel on Climate Change (IPCC), geoengineering is understood to mean technological measures that aim at stabilizing the climate system by means of direct intervention in the Earth's energy balance. The objective is to decrease global warming (IPCC 2007, WG III). The ideas are numerous and varied. In the main, two categories of geoengineering measures can be distinguished:

(1) Measures that are aimed at management of solar radiation (solar radiation management, SRM): These are intended to reduce the incidence and absorption of incoming short-wave solar radiation and to cool the atmosphere at ground level. These measures do not therefore counteract the causes of global warming, since they do not reduce increased concentrations of greenhouse gases (cf. Section 3.1).

(2) The second category covers technologies that are aimed at removing carbon dioxide from the atmospheric carbon cycle (carbon dioxide removal: CDR). These technologies are intended to influence concentrations of CO_2 in the atmosphere, but the quantity of anthropogenic greenhouse gases is not affected (cf. Section 3.2).

All geoengineering measures have one thing in common: they are based on the assumption that global warming can be reversed or reduced by means of large-scale technical measures. Geoengineering is therefore not applied at the causes of the anthropogenic greenhouse gas effect; it is merely intended to influence and alleviate the consequences.

In contrast to classic climate protection, greenhouse gas emissions are not reduced by geoengineering. Since most of the proposed measures represent large-scale technical intervention in the Earth's highly complex climate system, the consequences are difficult to assess. Nevertheless, in a number of countries – for example, in the USA and Great Britain – serious efforts are being undertaken towards practical implementation of such ideas. In Germany, the Federal Ministry of Education and Research (BMBF) has supported research in the area of marine geoengineering (inter alia EisenEx 2000, LOHAFEX 2009). However, the BMBF and the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) share the view that no meaningful climate protection is to be seen in large-scale iron fertilization of oceans.

The basic attitude towards geoengineering is also determined by prevailing traditional perceptions of different societies. It depends, in particular, on the relationship between man and nature, as well as on the degree of technology orientation and faith in technology. While in many European countries man's attempt to control the global environment is regarded as pretentious and arrogant, in societies that are more strongly orientated towards technology discussion of geoengineering proposals is less sceptical. There, the debate focuses mainly on whether and how such concepts can be realized technically and financially.

In order to decide, to what extent geoengineering should be considered as an effective measure to counteract global warming, a number of questions have to be addressed that at present can largely not be answered. These questions concern, among other things, the efficacy and development status of individual measures, risks and the weighing up of costs and benefits, as well as societal acceptance and statutory control. Discussion of these questions is essential, however, in order to decide, on the basis of scientific substantiation, whether and to what extent such proposals are in fact likely to make an effective contribution towards climate protection within the framework of sustainable development, and whether, in particular, the risks of such measures can be justified.

As a scientific environment authority, the German Federal Environment Agency has the duty to advise policymakers on appropriate concepts for sustainable climate policy. New concepts for climate protection measures are therefore examined by the Federal Environment Agency for the purpose of deciding whether they satisfy the demands of sustainable climate policy.

This 1966 photo shows the crew and personnel of Project Stormfury, which aimed to weaken tropical cyclones by seeding them with silver iodide. The project did not achieve its objective.

HISTORIC EXAMPLES OF GEOENGINEERING

The idea of geoengineering is not new. Geoengineering measures were already proposed in a variety of contexts in the previous century.

Scientists discussed how, with the aid of geoengineering measures, regions of the Earth could be reclaimed that had previously not been used by humans. In Russia, for example, whole rivers were to be redirected to irrigate the steppe of central Asia. The Siberian tundra was to be thawed with the aid of a dam across the Bering Strait or the application of soot particles.

In the 1950s and into the 1970s, at the peak of the Cold War, geoengineering was even envisaged for military purposes. Military research considered new methods of warfare. In 1966, for example, the mathematician John von Neumann published an article in the magazine „Fortune", in which he expounded methods of „climatic warfare". The weather ought to be influenced for military purposes and, among other things, sheets of ice melted.

All these proposals thankfully remained theoretical. In those days, too, it was primarily the effect of the respective measures and their technical feasibility that were discussed. Possible reservations concerning realizability and unintended side effects for humans and the environment, however, were hardly discussed.

Geoengineering cannot ignore the precautionary principle

The precautionary principle is one of the keystones of environment policy. Its purpose is to ensure that precautionary action is taken where there is incomplete knowledge of the type, extent and probability of occurrence of adverse effects on the environment, in order to preclude adverse effects and disturbances from the very beginning. Geoengineering projects must also be judged on the basis of the precautionary principle.

Natural systems – to which the climate system belongs – are extremely complex and characterized by the nonlinear dynamics of their processes. The impact of man on this system and the interaction of the climate system with other processes of the Earth system are not sufficiently understood. We have neither complete and far-reaching historical data on the state of the environment nor models that describe all the facets of nonlinear dynamics. Due to extensive lack of knowledge and uncertainties, the effects of measures that are aimed at geo-processes at one particular place can hardly be assessed. In view of the momentousness of geoengineering projects and the great uncertainties involved in assessing their consequences in the complex Earth system, the Federal Environment Agency recommends, on the grounds of precaution, that greater restraint be exercised and a moratorium imposed on the employment of such measures until there is a substantial improvement in knowledge of the interdependencies of geo-processes.

Overview

With this background paper the Federal Environment Agency provides an overview of the most important geoengineering proposals that are presently being discussed. Chapter 2 brings this conceptional approach into line with climate policy. In Chapter 3, individual geoengineering methods are then presented in detail. We provide information on the realizability and efficacy of these methods as well as assessments of risks for humans and the environment. Current scientific knowledge regarding individual proposals is highly varied. Geoengineering proposals, for which differentiated knowledge already exists, are analysed and assessed on the basis of current knowledge. Following this, applicable statutory regulations are reviewed in Chapter 4. In Chapter 5, we describe the criteria that policymakers should consider, should they intend to implement geoengineering measures. Finally, Chapter 6 looks at the outlook for the future and puts forward initial recommendations for dealing with the contentious and, regarding many issues, still unresolved topic of geoengineering.

FURTHER READING

The description of geoengineering proposals in this background paper is based, in the main, on the following publications:

- Geoengineering the Climate (Royal Society 2009)
- Iron fertilization of oceans to counteract climate change – position paper (Umweltbundesamt 2010a)
- CCS – Environmental Protection Framework for an Emerging Technology (Umweltbundesamt 2009a)

Important basic information on the topic of climate change is to be found in summarized form in:

- Climate change – Important insights from the Fourth Assessment Report (AR4) of the IPCC (Umweltbundesamt 2009b)

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HOW IMPORTANT IS GEOENGINEERING FOR CLIMATE PROTECTION?

The objective of climate protection policy is to stabilize greenhouse gas concentrations in the atmosphere at a level that prevents a dangerous anthropogenic disturbance of the climate system. Even with an increase in global average temperature of up to 2°C, compared to pre-industrial times, adverse effects on natural, biological and societal systems have to be expected. With an increase in excess of 2°C grave and irreversible damage is to be expected (UBA, 2009c). It has therefore to be avoided at all costs that global average temperature increases by more than 2°C.

CARBON DIOXIDE: ANTHROPOGENIC EMISSIONS AND ATMOSPHERIC CONCENTRATION

Anthropogenic generation of energy gave rise in 2008 to worldwide emission of 30 Gt CO_2 (equivalent to 8.2 Gt C) (IEA, 2010).
In the same year, energy-related emissions in Germany amounted to around 0.8 Gt CO_2 (IEA, 2010).

CO_2 concentration in the Earth's atmosphere has risen since 1750 by around 36%. The present CO_2 concentration was not reached in the past 650,000 years (180-300 ppm) and probably also not in the past 20 million years. The present annual rate of increase is the highest of the past 20,000 years. Around 65% of anthropogenic emissions since 1750 have been attributable to the burning of fossil fuel.

The rise in concentration during the decade 1996 – 2005 was considerably higher than that in previous decades. While average growth in the period 1960 – 2005 amounted to 1.4 ppm/ year, in the above-mentioned decade it reached 1.9 ppm/ year.

This trend has been documented since 1958 by regular measurements at Mauna Loa Observatory in Hawaii.

ARE THERE WAYS TO PREVENT GLOBAL WARMING IN EXCESS OF 2°C?

In order to meet the 2°C target with a probability of 75%, cumulative CO_2 emissions from 2000 to 2049 may not exceed a global total of 1,000 Gt CO_2 (Meinshausen et al., 2009). 234 Gt CO_2 were emitted merely between 2000 and 2006. If the human race manages to stop the annual increase in global greenhouse gas emissions at the latest in the period 2015 to 2020, and subsequently manages to reduce emissions by the middle of the 21st century to half the level of the year 1990, the global target can be achieved. According to the principle of joint and shared responsibility, industrialized countries are committed to reducing their emissions by 80-95% by the year 2050, compared to 1990.

In numerous studies, national, international and global scenarios have been developed that show how climate protection objectives can be met at all levels through the interaction / synergy of reduction measures (inter alia IPCC 2007b, IEA2009: Blue Map Scenario in WEO 2009, GP EREC 2010: Energy (R)Evolution, 2010, ECF 2010: Roadmap 2050, WWF 2009: Model Deutschland).

The Federal Environment Agency has described in its climate policy concept for Germany (Umweltbundesamt, 2009c) how further steps of an ambitious energy, climate protection and climate adaptation policy should be devised. In addition, in a recent study (Umweltbundesamt, 2010) the Federal Environment Agency described how power supply in Germany could be wholly produced from renewable energy sources by 2050, and thereby a precondition accomplished for radical emission reductions that are necessary in the long term, right up to a greenhouse-gas-neutral Germany.

In order to meet the 2°C objective, active and effective climate protection is essential. Above all, considerable efforts are necessary towards a drastic reduction in greenhouse gas emissions (see the box on page 6: Are there ways to prevent global warming in excess of 2°C?). Despite agreement on the 2°C target, reduction commitments do not suffice, and reduction measures have up to now not been implemented to a sufficient extent. It has to be considered at this point that successful climate protection has to consist of a large number of individual measures for reduction of greenhouse gas emissions. What is further required is reorganization of our economy and joint action at a global level.

Proponents of geoengineering, on the other hand, strive to offer policymakers a method that ought to enable global warming to be limited, without having to take measures for the reduction of greenhouse gas emissions, which often involve changes in the behaviour of the population and are therefore controversial. Advocates of geoengineering hope that this way the combating of global warming will be easier, cheaper and quicker to achieve.

It is further argued that geoengineering should be deployed as an additional and, at the same time, final rescue system in the battle against global warming. Such a case would exist, if efforts to reduce global greenhouse gas emissions to the required extent failed. With increasing warming of the global climate the risk grows that a climate ‚tipping point‘ will be reached, which is associated with strong or abrupt climate changes. Geoengineering is discussed as a quickly-effective measure to avoid reaching such a ‚tipping point‘.

Geoengineering offers, however, no guarantee of success. Were we to retain our emission-intensive industrial structure, and to attempt at the same time to combat global warming on a large scale with geoengineering measures for solar radiation management or carbon dioxide removal, greenhouse gas emission would continue to drive climate change. Should geoengineering not have the desired effect, or if it cannot be continuously maintained, further emissions of greenhouse gases would unabatedly change the climate.

A further problem arises, in particular, with geoengineering measures for solar radiation management. The proposed measures offer no solution to further damage to the environment caused by greenhouse gas concentrations. Such environmental damage includes, for example, acidification of the oceans.

Furthermore, the positive synergy effects of classic climate protection measures would be lost, which serve the purpose not only of greenhouse gas reductions but also conservation of resources, and thereby support sustainable development and have a positive effect on the economy as a whole.

Finally, the combating of causes would be delayed, were geoengineering to be pursued as an alternative to the necessary reduction of greenhouse gases. As a result, future generations would be burdened with still-unknown consequences.

With geoengineering a paradigm shift threatens

Geoengineering does not necessarily increase the probability of preventing dangerous climate change by offering a further – emergency – option to combat global warming. On the contrary, with geoengineering a paradigm shift threatens in climate protection policy, which puts into question the previous consensus that reduction measures on a large scale are required. For there is the danger that the combating of causes – that is greenhouse gas emission reduction – will be neglected, simply because supposed ‚rescue systems‘ are available.

The geoengineering idea appears to be in the ascendant because negotiations under the aegis of the United Nations Framework Convention on Climate Change (UNFCCC) on a new worldwide climate protection convention from 2013 are not yet concluded. Geoengineering measures could also be carried out unilaterally by individual states. Such measures could, however, give rise to considerable conflict potential within the community of states, since geoengineering can entail highly varied risks at a regional level for humans and the environment. Further discussion of geoengineering must therefore take care not to thwart classic climate protection endeavours towards international agreements or the motivation of every individual to avoid greenhouse gas emissions.

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GEOENGINEERING: WHICH PROPOSALS ARE BEING DISCUSSED?

The most important geoengineering proposals that are presently the subject of contributions to literature are displayed in Figure 1 together with their assignment to particular categories. Individual methods are examined in detail in the following Sections 3.1 and 3.2. The current state of knowledge concerning individual methods, as described in publications, is highly varied. Some methods can only be described as initial ideas, for which the theoretical relations of cause and effect are insufficiently thought-out and hardly or not at all researched. With other methods, knowledge from publications and research findings is more detailed, so that initial analysis and evaluation could be carried out. The described dissimilar state of knowledge concerning different proposals is therefore also reflected in the following sections of this background paper.

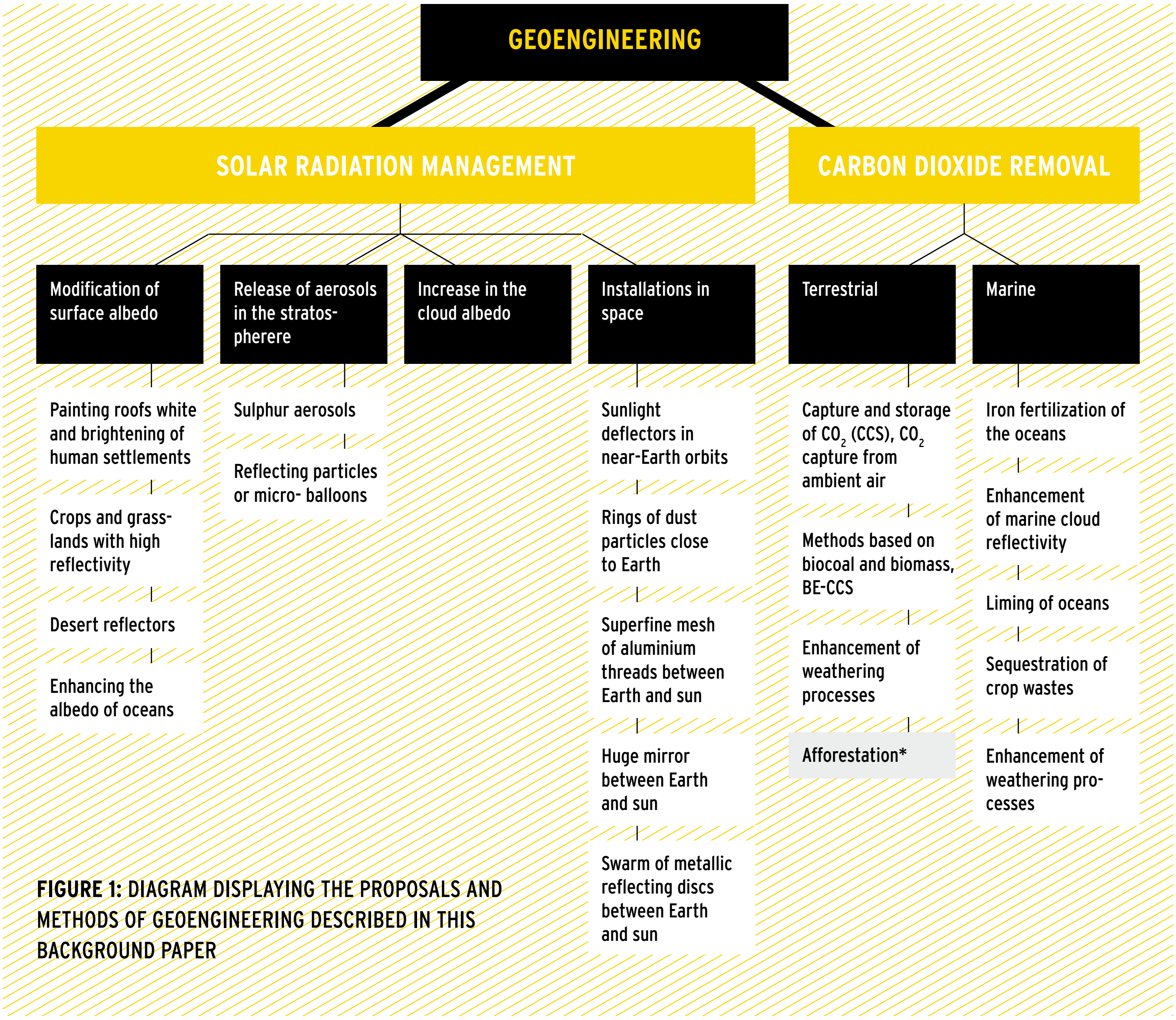


FIGURE 1: DIAGRAM DISPLAYING THE PROPOSALS AND METHODS OF GEOENGINEERING DESCRIBED IN THIS BACKGROUND PAPER

* Afforestation is not regarded by the Federal Environment Agency as a geoengineering measure. The Agency will prepare a specific paper on possible adverse effects of afforestation.

3.1 Proposals for solar radiation management (SRM)

Geoengineering measures would work by manipulating the energy balance of the Earth, the balance between incoming radiation from the sun, which acts to heat the Earth, and outgoing thermal radiation which acts to cool it. This so-called energy balance controls the Earth‘s temperature and drives and maintains the climate system. If the energy balance is disturbed the climate changes.

Part of incoming solar radiation is reflected by clouds as well as ice caps and bright areas on the Earth‘s surface. Part of outgoing thermal radiation is absorbed by greenhouse gases in the atmosphere and by clouds, thereby warming the atmosphere and the Earth‘s surface. Only around 60% of outgoing thermal radiation finally leaves the atmosphere after repeated absorption and re-emission within the atmosphere.

Outgoing thermal radiation increases strongly as surface temperature increases, while incoming solar radiation does not. This creates a strong negative feedback, because the temperatures of the surface and atmosphere increase until outgoing and incoming radiation are in balance and a new state of equilibrium arises.

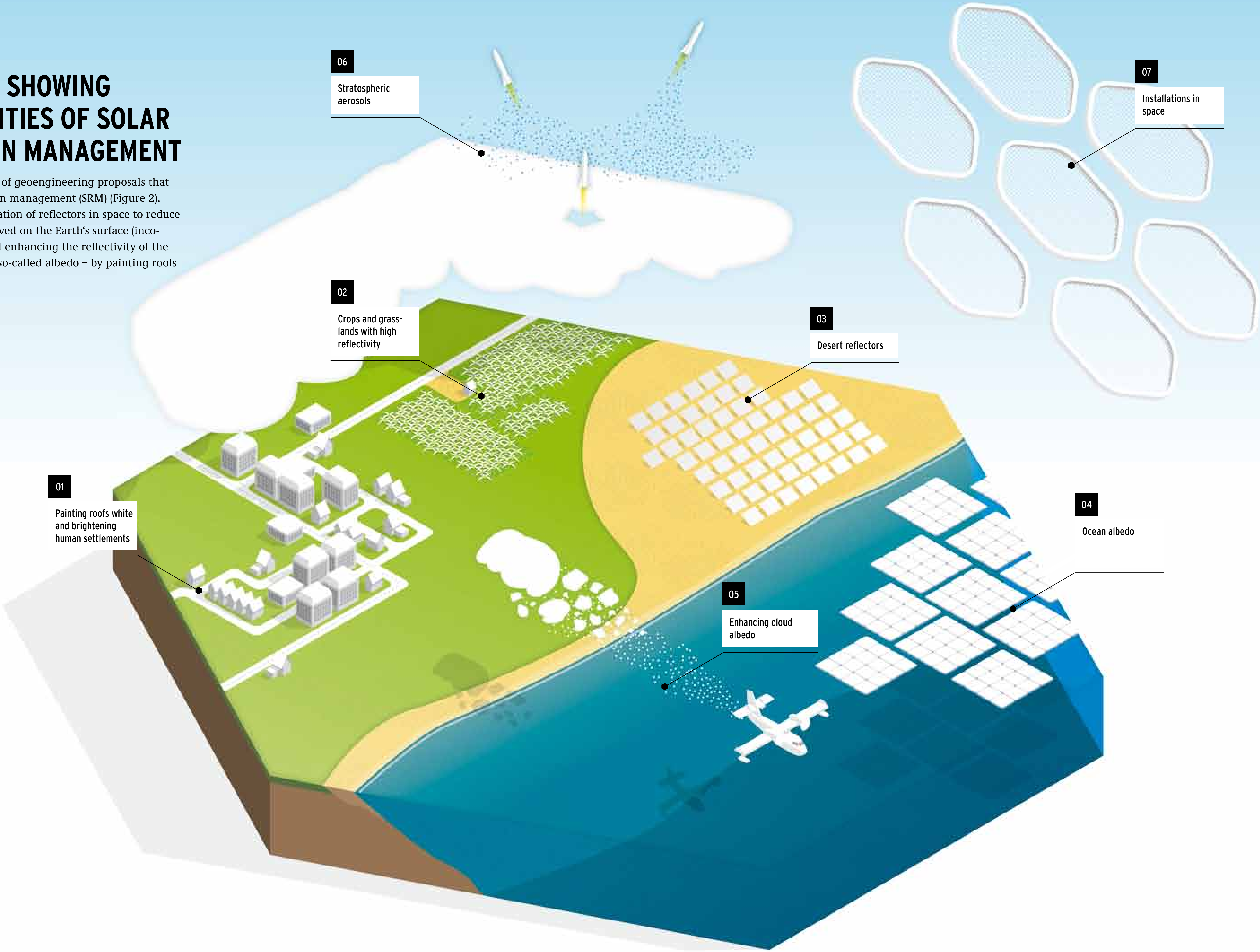
The basic principle is that if the described energy balance changes the Earth‘s global climate also changes. The following processes chiefly influence the energy balance:

- Changes in incoming radiation through changes in the Earth‘s orbit around the sun or through changes in the sun‘s activity.
- Changes in outgoing radiation; for example, as a result of changes in the Earth‘s snow- and ice-covered areas.
- Changes in radiation reflected to space; for example, through a change in the atmospheric concentration of greenhouse gases and aerosols[1].

FIGURE 2:

DIAGRAM SHOWING POSSIBILITIES OF SOLAR RADIATION MANAGEMENT

There are a number of geoengineering proposals that aim at solar radiation management (SRM) (Figure 2). They include installation of reflectors in space to reduce solar radiation received on the Earth's surface (incoming radiation), and enhancing the reflectivity of the Earth's surface – its so-called albedo – by painting roofs white, for example.



RADIATIVE FORCING

The term radiative forcing is used for quantitative description of disturbance of the energy balance of the Earth's surface and its atmosphere. It is a measure of the influence that a process – for example, an increase in greenhouse gases in the atmosphere – has on the change in the balance between incoming and outgoing energy. The importance of a process as potential actuator of climate change is derived by climatologists from the magnitude of radiative forcing, which is measured in watt per square metre (W/m2). A positive actuator tends to lead to warming, a negative actuator to cooling of the Earth's surface.

3.1.1 Proposals for modification of surface albedo

Incoming solar radiation is reflected to a varied extent by surfaces and objects on the Earth, depending in each case on colour and property. Snow- and ice-covered surfaces have a higher reflectivity than dark surfaces such as oceans. The measure of reflectivity is termed albedo, and is the ratio of radiation reflected from an object or surface to the radiation received by an object or surface. White surfaces have a high albedo. They subsequently become less warm than dark surfaces.

Various geoengineering proposals exploit this characteristic with the intention of increasing albedo. If albedo increases, reflected outgoing radiation also increases and air at ground level tends to cool.

01 Painting roofs white and brightening human settlements

The proposal envisages painting roofs, streets and pavements white in order to increase the albedo of human settlements (Akbari et al. 2009). This would be particularly effective in sunny regions and in the summer, since more solar radiation would then be reflected than in regions with shorter sunshine duration. This would also enable energy savings to be achieved in the operation of air conditioning systems.

Implementation of the proposal is clear and unambiguous. It does not represent greater manipulation of the natural environment than that of roads, human settlements and cities. In this respect, the measure could be immediately implemented.

The disadvantage is that because of dirt and pollution surfaces have to be repeatedly repainted. With initial painting additional resources could be consumed if the existing surface did not need to be painted. Should the white paint contain noxious substances, this would be another negative aspect.

Moreover, large settlements would have to be involved in order to achieve a global effect, however small it might be. Practical implementation of the measure could take several decades. A study estimates that for the available urban area the effect of the measure is a possible change in radiative forcing of merely -0.01 to -0.2 W/m^2 (Lenton & Vaughan 2009). This would be merely a negligible contribution to anthropogenic radiative forcing, which in 2005 amounted to 1.5 W/m2 (IPCC 2007a). The measure is estimated to be one of the least effective and most expensive proposals (Royal Society 2009). If one applies the measure to just 1% of dryland areas, material and labour costs would be very high at around 300 billion US dollars per year.

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Crops and grasslands with high reflectivity

The proposal to utilize the high reflectivity of vegetation is comparable to that of painting human settlements white. The idea is to plant types of agricultural crops that reflect more radiation to space than is the case with the crops currently cultivated. An example of this is maize. There are subspecies of maize whose albedo differs by up to 8%. Worldwide farmland and overgrown landscape partially used, or unused by humans covers around one-third of the land surface. Were reflective species to be cultivated on this area, estimates point to a reduction in radiative forcing of a maximum of 0.59 W/m^2 (Hamway 2007).

Consistent implementation of this proposal could fail, however, simply on the magnitude of the land involved. The cost of replacement of crops on this scale would bear no relation to the attained effect. Even if one succeeded in finding species that guaranteed the same yield in different climate zones, the overall intervention in the natural environment would be unparalleled, and the associated loss of complete ecosystems absolutely unacceptable. In the case of generation of large monocultures, besides biodiversity the economic independence of farmers would also be threatened.

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Desert reflectors

The idea of covering desert areas with a reflective surface also applies the principle of increasing albedo. In order to achieve a distinct effect, this measure, too, would require an immense surface area. The Royal Society (2009) estimates that 10% of all desert areas would have to be covered with reflective materials to offset anthropogenic global warming. Realization of the idea would require enormous sums of money for materials, execution, maintenance and disposal.

Desert areas appear to be particularly appropriate for increasing albedo, due to their very high levels of incident solar radiation and low human utilization, but such an approach would have grave consequences for the environment. The exclusion of sunlight through covering of the desert floor would destroy the basis of life in one of the most sensitive habitats on Earth. The fertilization function of deserts for oceans would also be curtailed. With desert sand, which is transported in the atmosphere over large distances, iron gets into the oceans, where it plays an important role in the supply of nutrients for marine algae. A further problem is that such a change in albedo could affect local and regional weather and precipitation patterns, such as monsoon circulation.

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Ocean albedo

Other proposals envisage increasing reflectivity of solar radiation through bright, reflecting objects (for example, floating cushions) on ocean surfaces. Were the idea to be realized on the required scale, a gigantic proportion of the largest ecosystem on Earth would be cut off from the supply of light. Sunlight is, however, a prerequisite for processes that enable life in oceans and on land in the first place.

Oceans play an essential role in the carbon/oxygen cycle, since they absorb and store carbon dioxide from the atmosphere. With application of this measure multifarious ocean functions would be substantially impaired. In addition, environmental effects from the generated waste as well as the required cost of placement, maintenance and disposal would have to be expected. Plastic waste in the ocean is one of the obvious problems. Pollutants accumulate on plastic products and particles, which are mistaken for food and thus enter the food chain (Umweltbundesamt 2010a). The idea of placing objects on ocean surfaces would stand in stark contrast to the objective of reducing wastes in the world‘s oceans.

A further, purely practical problem is that in order to guarantee the effect on albedo the reflecting surfaces would have to be free of dirt and growth. The cleaning operation that this would entail would give rise to additional costs as well as chemical discharges, and demand, moreover, great technical input.

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3.1.2 Enhancing cloud albedo

Clouds consist of millions of tiny droplets. Besides temperature and atmospheric humidity, tiny particles – such as grains of sand, salt crystals and dust, on which water condenses and droplets can form (so-called condensation nuclei) – play a major role in their formation. The concentration of water droplets determines the reflective properties of clouds and thus their albedo.

Increasing the albedo of clouds is another geoengineering proposal for solar radiation management. This measure would be applicable on low marine clouds that cover around 25% of the total ocean area. The marine atmosphere tends to be relatively clean, with little dust. Artificial enrichment of the marine atmosphere with cloud-condensation nuclei (CCN) could noticeably increase cloud albedo, since considerably more small droplets would be formed, which would scatter and so reflect more of the incident light. Moreover, smaller droplets could also increase the longevity of clouds, since it takes longer for large droplets to form that lead to rain. Latham et al estimate that a doubling of cloud-droplet concentration in marine clouds would sufficiently increase cloud albedo to compensate for a doubling of atmospheric CO_2 concentration, compared to the pre-industrial level (Latham et al. 2008). Previous consideration of artificial cloud-condensation nuclei has focused on tiny salt crystals, which are obtained from

sea water and sprayed into the atmosphere.
Suitable regions for enhancement of cloud albedo are areas off the west coast of North and South America as well as the west coast of Africa. Suitable particles, which have the effect of condensation nuclei, could be sprayed from ships or aircraft. Since clouds are irregularly distributed and their longevity is limited, the spraying of particles would have to be repeatedly carried out in large quantities and with sufficient spatial distribution. Particularly in the case of spraying by ship, only a small proportion of these particles would reach the areas in which cloud formation takes place and clouds exist.

The proposal is basically realizable in technical terms, but application is limited to particular marine regions. Furthermore, the required particles could be sprayed by aircraft or ship only in limited quantities. The method has one advantage: once carried out, the cooling effect can quickly occur, the place of application changed as required and the process halted at short notice.

Employment of the measure in large areas represents, however, an intervention in local and regional weather and current patterns. At the same time, effects on wind systems, ocean currents and precipitation – and thus also on marine organisms – would be conceivable.
One thing is already clear. Before application of such a measure the effects on the climate and environment must be investigated in depth. The environmental compatibility and the energy costs of this measure depend on the one hand on the particles used and their manufacture, and on the other hand on how the particles are released into the atmosphere.

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3.1.3 Stratospheric aerosols

The Earth's atmosphere is divided vertically into several layers. The lowest is the troposphere, above which, at an altitude of around 7 to 17 kilometres (depending on latitude – over the tropics higher than over the poles), the stratosphere follows, which extends to an altitude of around 50 kilometres. In the stratosphere, air mass exchange processes are considerably weaker than in the troposphere. Substances that enter the stratosphere have a longer lifetime than in the troposphere, and are therefore more effective. This becomes clear with the example of volcanic eruptions. With the eruption of large volcanoes particles and sulphur compounds are often expelled into altitudes of 10 to 20 kilometres. There, sulphur and ash particles reside for periods of from a few months to a number of years, and have the effect that less sunlight reaches the Earth's surface. Volcanic eruptions therefore tend to have a cooling effect, which in the case of large volcanoes can last for up to several years. Following eruption of Mount Pinatubo in 1991, a decline in global mean temperature of 0.1 to 0.2 °C at ground level was observed over the following two years (Robock & Mao 1995).
There are a number of geoengineering proposals based on the above-described effects. These range from the release of aluminium snippings or reflective micro-balloons into the stratosphere to the release of chemicals, above all sulphur compounds. Micro-balloons and other reflective objects have to be manufactured in large numbers, however, with corresponding costs for energy. Moreover, these objects would sink after a certain period of time from the stratosphere into the troposphere and, under certain circumstances, interfere with air traffic or have other adverse effects. The application of this proposal is therefore unrealistic.

The idea of releasing hydrogen sulphide or sulphur dioxide into the stratosphere is more frequently discussed. In the stratosphere these substances would oxidize to sulphate particles of appropriate size, which would scatter sunlight with the effect of a lower incidence of solar radiation on the Earth's surface. Rasch et al estimate that between 1.5 and 5 teragrams[2] of sulphur per year would have to be discharged into the stratosphere to offset the warming effect of anthropogenic emissions of greenhouse gases (Rasch et al. 2008). The cooling effect would substantially depend on particle size distribution of the formed aerosol particles, and would not be known at the outset. Furthermore, these aerosols only reside for a certain time in the stratosphere, so that sulphur compounds would have to be released at regular intervals in order to guarantee a long-term effect. Generally speaking, the effect of this measure is difficult to control. The question of the quantity of sulphur compounds that would have to be discharged into the stratosphere to achieve the desired effect on ground-level air temperature, and when, has not been scientifically resolved to a satisfactory extent. We cannot assume that the same processes will occur as with volcanic eruptions.

From the financial point of view – measured in terms of the cost of materials and operation – the discharge of sulphur compounds into the stratosphere appears to be a comparatively inexpensive proposal. We nevertheless regard this method as particularly problematic, since it can have considerable, unintended side effects. For instance, cloud formation in the troposphere would probably be affected as a result of the reduced incidence of solar radiation on the ground. Observations following the eruption of Pinatubo also showed a decline in rainfall over land (Trenberth & Dai 2007). Model simulations produced disturbances of the summer monsoons in Africa and Asia, as well as a reduction in rainfall, which is the precondition for food production for billions of people (Robock et al. 2008). Not only would agricultural yields probably decrease, forests and other natural carbon sinks could also be affected. Besides the influencing of global weather phe-

nomena, the eruption of Pinatubo also caused a distinct reduction of 2% worldwide in stratospheric ozone (Harris et al. 1997). The possible degradation of stratospheric ozone through chemical reactions on the surface of sulphur droplets is a further, highly-critical side effect of the method. Another possible side effect is the development of acid rain. Whether and to what extent this could occur, must still be investigated.

Summing up: The permanent creation of an artificial sulphur aerosol layer in the stratosphere could have considerable, unintended effects. It is presently not possible to determine these effects to a satisfactory extent or to carry out reliable risk assessment. On the grounds of precaution this method may under no circumstances be employed before adequate clarification of possible risks.

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3.1.4 Solar radiation management through installations in outer space

The Earth's temperature is highly dependent on the incidence of solar radiation. Ideas are therefore being discussed for the reduction of incident solar radiation on Earth through installations in outer space. Near-Earth orbits, the moon or a position between Earth and sun have been mentioned as possible locations.

Proposals for installations in outer space in near-Earth orbits range from sunlight deflectors to Saturn-like rings composed of dust particles. 2 billion tonnes of dust particles would be required to reduce incoming solar radiation by 2% (Royal Society 2009). Thin discs and dust would, however, probably sink to Earth after a certain period of time (Keith & Dowlatabadi 1992).

Alternatively, a location for reflective material between Earth and sun is proposed, at which, for example, a single huge mirror, a superfine mesh of aluminium threads or trillions of reflecting discs could be deployed. A sun-shield of about 3 million square kilometres would be required for a reduction in incoming radiation of around 2% (Royal Society 2009).

The deployment of sunlight deflectors in outer space would lead to a change in the incidence of solar radiation on the Earth's surface, which, however, would not be evenly distributed. This would imply a grave manipulation that would affect atmospheric and oceanic circulation, since atmospheric circulation is mainly controlled by varied irradiation conditions at the equator and at the Poles. A change in radiation variables would have sweeping effects on circulation, and thus

on temperatures, evaporation, clouds and rainfall in many regions of the world. This would in turn result in consequences for the living conditions of people, for food production and for the stability of ecosystems.

Substantial misgivings exist concerning the level of costs involved. It is also questionable whether these geoengineering measures would be reversible, or could be quickly halted. The controllability of large quantities of artificial objects positioned far from Earth is difficult, and a safety risk is involved.

3.1.5 Summary and assessment of methods of solar radiation management

Geoengineering methods of solar radiation management do not address the cause of global warming. They do not alter the fact that greenhouse gases are emitted into the atmosphere and their concentrations are further increasing. The huge problems that result, such as ocean acidification, therefore remain, and they can lead to dramatic consequences for marine flora and fauna. With solar radiation management the greenhouse-warmed climate would merely be regulated.

With continued emission of greenhouse gases such manipulation would have to take place continually to limit the rise in temperature. Due to the growth in greenhouse gas concentrations, the ending of such measures would lead to rapid warming. These measures could therefore not be ended even if they give rise to considerable or severe problems.

With many of these measures it is by no means clear whether they will function at all in practice. They are theoretical proposals that are hardly supported by research findings. The efficacy of many methods cannot be satisfactorily estimated. Considerable unforeseen effects could occur, whose risks are neither known nor calculable. The practical testing of some methods, such as the discharge of sulphur into the stratosphere, would represent a huge global experiment with unprecedented outcome.

Global mean radiative forcing for anthropogenic greenhouse gas emissions amounted in 2008 to 2.74 W/m^2, of which 1.74 W/m^2 was attributable solely to carbon dioxide (NOAA 2009). With a glance at this radiative forcing, the simple magnitude of the manipulation that would be necessary to achieve a noticeable effect on the global climate represents an extraordinary complexity and challenge. Generally speaking, the setting up, operation, infrastructure maintenance and required continual application of almost all these geoengineering measures require an enormous expenditure of energy and materials. With most measures for solar radiation management it is to be expected that the costs will be disproportionate to the attained effect.

Even if cooling of the global climate would be attainable with geoengineering measures, the climatic changes that would be caused and their scale at a regional level are uncertain. Temperatures and precipitation can change, and changes in circulation likewise occur. Such changes can have a highly varied and adverse effect on humans and the environment in different regions of the world.

Installations in space that change the incidence of solar radiation on the Earth's surface could affect the whole atmospheric and thus also ocean circulation. What is more, the intended effect of proposals, which aim at a change in the reflectivity of clouds or parts of the Earth's surface, are significantly dependent on influences such as cloudiness and precipitation, and require areas of an enormous size.

For the majority of measures assumptions on costs to be incurred are very unreliable. Due merely to great uncertainties about side effects, the follow-up costs cannot be estimated.

Not only with regard to costs, but also concerning a large number of incalculable risks, methods of solar radiation management do not represent a reasonable alternative to climate protection measures that apply at the roots, namely anthropogenic greenhouse gas emissions.

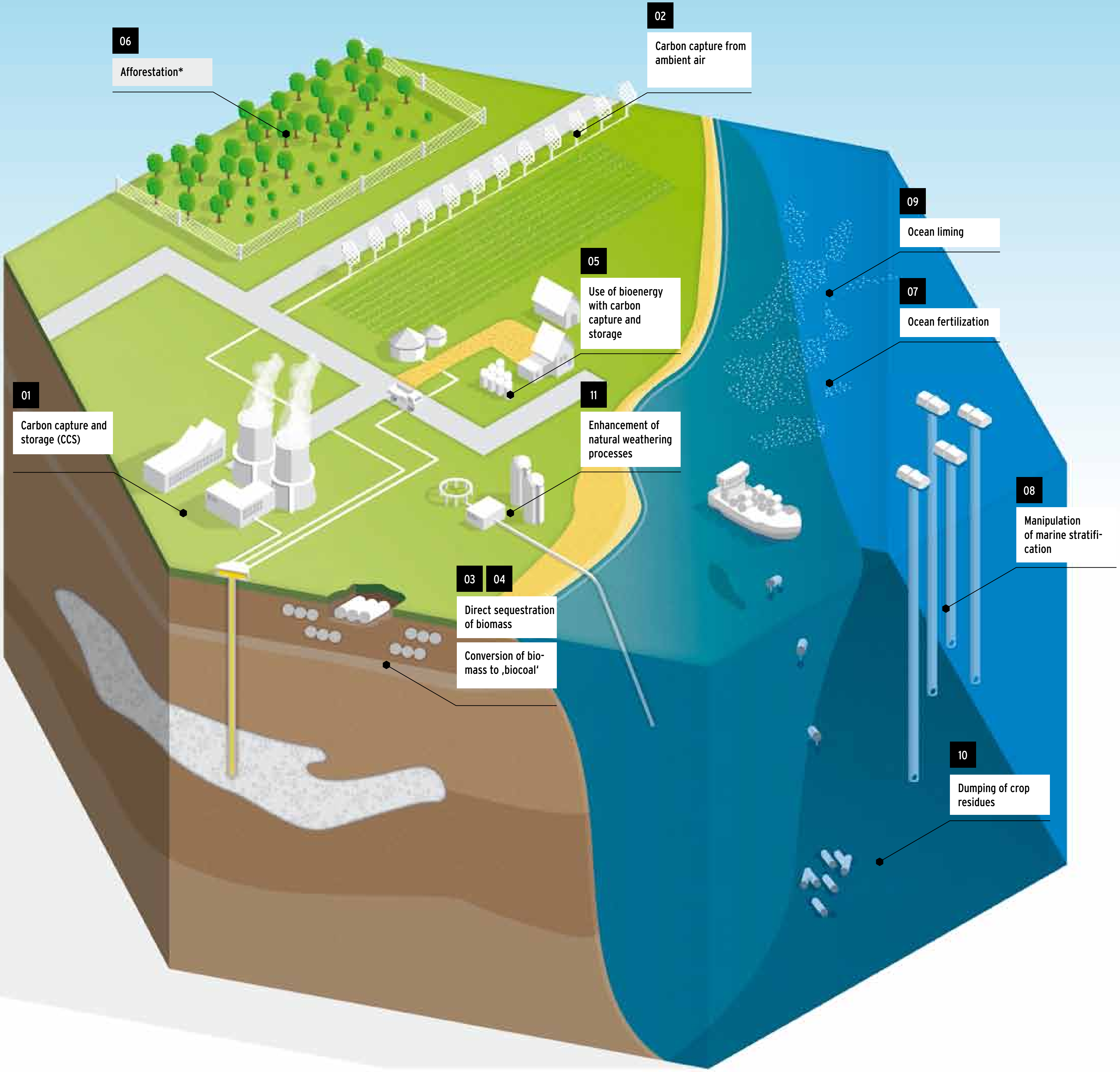
FIGURE 3:

DIAGRAM SHOWING POSSIBILITIES OF CARBON DIOXIDE REMOVAL

3.2 Proposals for carbon dioxide removal (CDR)

A second group of geoengineering measures pursues the objective of reducing the concentration of the greenhouse gas CO_2 in the atmosphere. This objective should be achieved by removing CO_2, permanently if possible, from the carbon cycle (see Figure 3).

This group of geoengineering measures can, on the one hand, be differentiated, depending on place of application, between terrestrial and marine measures. On the other hand, the group can be divided into three subgroups according to the method of carbon dioxide removal. Firstly, CO_2 could be permanently stored in subterranean formations (3.2.1, 3.2.2 and 3.2.4). The second subgroup relates to proposals with which carbon fixed in biomass is removed from the carbon cycle (3.2.3 - 3.2.6). Thirdly, CO_2 can be fixed as mineral carbonates (3.2.7).



* Afforestation is not regarded by the Federal Environment Agency as a geoengineering measure. The Agency will prepare a specific paper on possible adverse effects of afforestation.

NOTE ON APPLIED UNITS

1 gigatonne of carbon (Gt C) corresponds to 10^9 tonnes of carbon (t C).
1 tonne of carbon is equivalent to 3.67 tonnes of carbon dioxide.
The unit petagram (Pg) is also often found, whereby 1 Pg = 10^{15} grams = 1 Gt.

Since in the carbon cycle not only gaseous carbon dioxide is observed, but also all compounds in which carbon occurs, this data always relates to Gt of carbon.

01

3.2.1 Carbon capture and storage (CCS)

CO_2 emissions from large, stationary point sources (above all, power plants) could be permanently prevented from entering the atmosphere through the capture of CO_2 from flue gas and its subsequent permanent storage (carbon capture and storage). The captured CO_2 would have to be injected into deep geological formations that are able to guarantee permanent storage. Transport infrastructure has to be provided that corresponds with the distance from the point source to the storage site (Umweltbundesamt, 2009a).

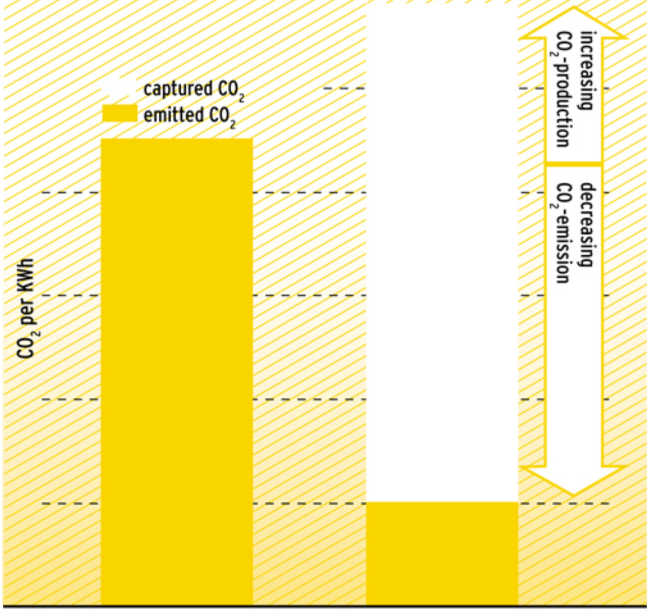
The potential of CCS depends primarily on the actually-available capacities of suitable storage sites. The suitability of a storage site should be mainly judged on permanent containment of the stored gas. With CCS, the size, location and temporal availability of the storage site must be matched to the respective emission sources. Specific geological exploration is not yet sufficiently advanced to allow reliable statements on the safety, receptivity and capacity of geological storage formations.

Most pilot projects test integration of CO_2 capture in the conversion of coal into electricity. There is worldwide no reference example for the large-scale application of the overall process from capture to storage, and no experience with the capture of the complete CO_2 flue-gas stream at a power plant. Commercial availability is to be expected at the earliest from the year 2025 (UBA, 2009a; WI 2010).

CCS is usually not counted among geoengineering methods, but is frequently described as a CO_2 mitigation option, although as an end-of-pipe technology it does not avoid the production of CO_2. Moreover, energy has to be consumed in its capture and transport, with the effect that in the process of converting coal into electricity about 30% more coal per produced kilowatt hour has to be burned, and accordingly more CO_2 and adverse environmental effects arise (Figure 4).

The potential of CCS and other methods with CO_2 storage is restricted by competition for use of subterranean geological formations, such as energy storage for

FIGURE 4: COMPARISON OF SPECIFIC CO_2 PRODUCTION BETWEEN CONVENTIONAL POWER PLANTS AND POWER PLANTS WITH FULLY-INTEGRATED CCS



natural or biogas and hydrogen, raw material production and geothermics. The Federal Environment Agency advises that care be taken that sustainable uses, such as geothermal production of heat and power, are not restricted through application of CCS (UBA, 2009a).

The environmental effects that CO_2 storage might have at a local level – for instance, salinization through the permeation of saline water into aquifers and acidification of drinking water – must be investigated in each individual case. It has finally to be borne in mind that with CO_2 storage there is the potential risk of CO_2 leakages and thus the migration of gas from the storage site.
The Federal Environment Agency is basically in favour of further research into this technology, but calls for a statutory framework that sets safety standards at such a high level that responsibility can be taken for CCS. For this purpose, the Agency has formulated necessary principles for environmental demands on CCS technology for the planned German law on CO_2 transport and

storage (UBA, 2009a).

02

3.2.2 Carbon capture from ambient air

Carbon dioxide can also be directly captured from ambient air. Three filtering techniques are being discussed: filtering, control of which is dependent on air moisture, and adsorption of CO_2 on solids, absorption into highly alkaline solutions and absorption into moderately alkaline solutions using enzymes as a catalyst.

The idea of such techniques is the erection of installations – so-called „artificial trees" – along streets over large areas, which would capture CO_2 from ambient air with the possibility of storage underground or in the deep sea. There is no doubt that this method is technically possible, but since CO_2 concentration in the flue gas of a power plant is 300 times greater than that in the atmosphere (0.4%), capture efficiency is from the outset more limited than in the case of CCS.

The operation of installations would require an enormous amount of additional energy, in particular for the separation of CO_2 from filter materials. Assuming that the consumed energy stems from a similar energy mix to that found today, at least half as much additional CO_2 would be emitted as is captured from the atmosphere (Dessler, 2009).

The advantage of carbon capture from ambient air is that the method can be employed just about everywhere. Transport costs can be minimized through proximity to a storage site. A further advantage compared to CCS is that ambient air, in contrast to flue gas flow, is relatively unaffected by pollutants that could cause additional problems with filtering or adsorption.

Nevertheless, the probable costs of a few hundred euros per tonne of CO_2 are considerably higher than the costs of conventional CO_2 mitigation measures (Keith et al. 2009). Since there is not a single project that demonstrates this measure, the costs are difficult to estimate. The method assumes a large number of installations, since an individual installation would capture a negligible amount of CO_2. The logistics cost is therefore enormous. Similar to CCS, this approach is limited by the capacities of available CO_2 storage sites. With application on a scale of relevance for the climate, the use and disposal of chemicals for CO_2 filtering would have an adverse effect on the environment. The risks of CO_2 storage are described above in Section 3.2.1.

3.2.3 Methods based on biocoal and biomass

In vegetation growth processes carbon dioxide is converted during photosynthesis into organic compounds. This way, land ecosystems remove more than 3 Gt of carbon (about 11 Gt of CO_2) every year from the atmosphere (Canadell & Raupach 2008). Vegetation stores carbon particularly during its growth phase.
When vegetation dies and decomposes, or is burnt, the carbon it stored is returned as CO_2 to the atmosphere. In the tropics, around 1.5 Gt of carbon are released every year through slash-and-burn and deforestation. Vegetation therefore provides only provisional storage of carbon. The same applies for products derived from vegetation, such as timber (for example, for furniture) or biofuel.

The following proposals for geoengineering measures have the aim of deliberate carbon storage in vegetation or in products derived from vegetation, such as constructional timber.

These methods have in common that their potential is limited by the availability of biomass. The cultivation of biomass for this purpose requires intensification of agriculture. The risk of aggravation of existing local environmental problems, such as water shortages, soil degradation, erosion, use of fertilizers and pesticides as well as biodiversity depletion, has to be examined on a case-by-case basis, as does possible competition concerning the demand for land for food production.

03

Direct sequestration of biomass

Deliberate sequestration of biomass is intended to prevent the release of CO_2 into the atmosphere during natural processes of decomposition of dead vegetation. All kinds of vegetative materials are suitable as a base. For this purpose, vegetative materials could be hermetically sealed and buried underground or in the deep ocean (see Section 3.2.6). Energy consumption for implementation of the proposal would be very high. Direct sequestration of biomass on a scale that would make a relevant contribution towards emission reduction is hardly realizable. Neither the energetic nor the economic aspects of direct biomass sequestration appear to have been adequately researched (Royal Society 2009). Finally, not only carbon but almost important nutrients contained in biomass would be withdrawn from the natural cycle.

04

Conversion of biomass to ‚biocoal'

Biomass could be converted to so-called biocoal. It could then be mixed with natural soils or used for energy generation. Two conversion processes are being discussed. In biomass pyrolysis, organic material with low oxygen content is heated and this way partially decomposed. In the process, oils and gases arise as by-products for use as biofuel. Alternatively, the application of hydrothermal carbonization (HTC) is being investigated. Here, biomass could be heated under high pressure in water and thus carbonized. Depending on the base material, it could be possible to convert through pyrolysis up to 50% and through HTC between 70% and 80% of the carbon fixed in biomass into biocoal. Biocoal, mixed with natural, low-yield soils could gradually decompose over several decades or centuries, in the course of which soil quality, with respect to yield, should improve (Lehmann 2006). Proponents of the technique quote the example of Terra preta soils[3], which are probably derived from charcoal and are about 2,000 years old.

Besides cultivated biomass, biomass residues could also be used, which accrue in industry, as urban waste and in forestry and agriculture (for example, from waste-paper, as cuttings or as residue from food production). According to a rough estimate, 0.16 GtC per year could theoretically be fixed in biocoal worldwide through pyrolisation of such residues.

No reliable information is available regarding the use of biocoal as an energy source. Moreover, direct energetic utilization of the base material biomass is arguably more effective than the use of biocoal.

It is questionable whether enough biomass is and will continue to be available for conversion into biocoal, since biomass residues are nowadays widely used and, among other things, naturally counter soil impoverishment and erosion. The technical resources – above all, in less-developed regions – that would be required have also to be clarified, as well as whether these are already available. It is also uncertain whether the properties deduced from Terra preta soils in the Amazon Basin equally apply to biocoal and in other climates. Neither long-term stability nor water and nutrient availability have been adequately investigated. Up to now, leaching and, degradation behaviour, nutrient retention capacity, interaction in soil and – in particular, with waste biomass as feedstock – pollutant concentrations and their impact in soil are all insufficiently researched.

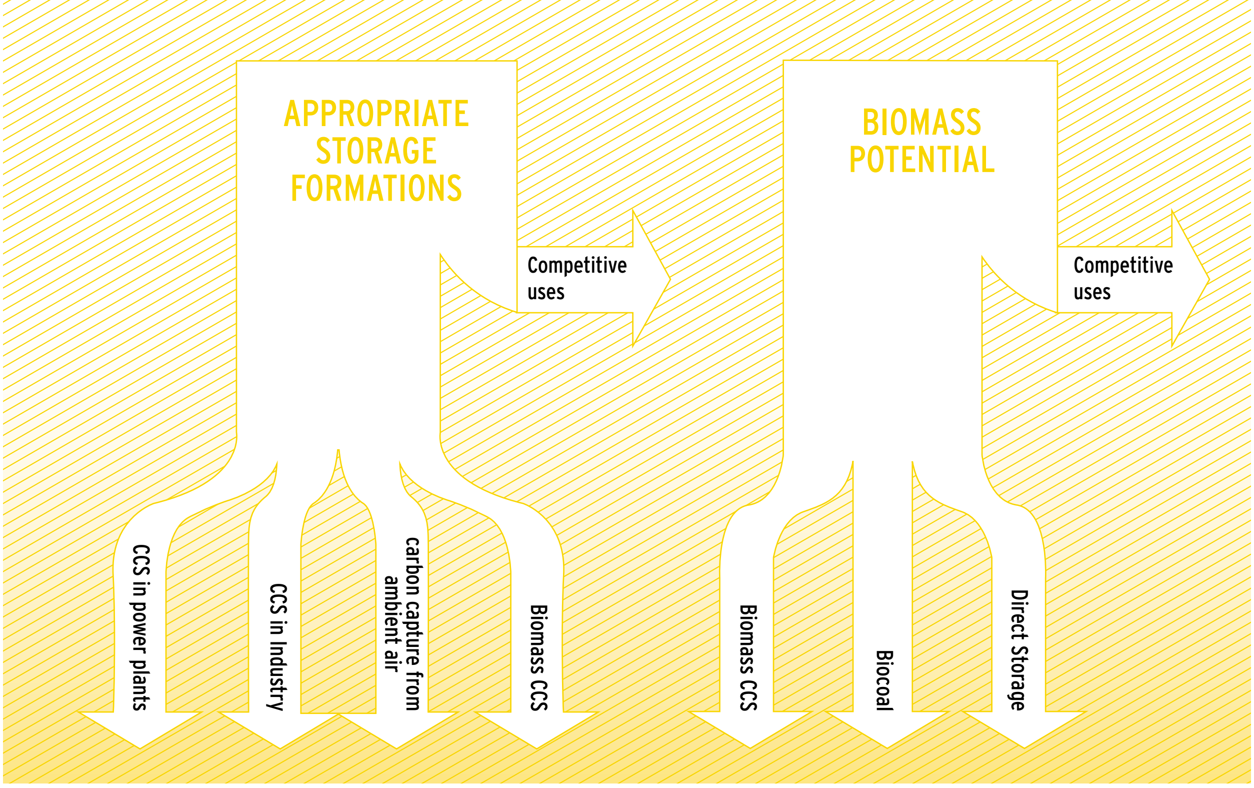
05

3.2.4 Use of bioenergy with carbon capture and storage

As an alternative to direct storage of carbon in biomass through partial prevention or delayed decomposition (cf. 3.2.3) there is the proposal to use biomass as a source of energy and to capture CO_2 released in energy generation and permanently store it underground. The process is known as bio-energy with carbon capture and storage, or BE-CCS, and, as the name suggests, BE-CCS combines established processes for use of bioenergy with CCS, which is still being tested (3.2.1).

BE-CCS is currently not deployed. While worldwide use of biomass is largely decentralized and on a small scale, CCS requires large CO_2 flows on economic grounds. BE-CCS is presumably only to be considered for relatively

FIGURE 5: MULTIPLE DEMANDS ON LIMITED POTENTIALS BY DIFFERENT CDR METHODS



large plants, such as large biomass power plants, paper mills and bioethanol refineries (Aznar et al. 2006), which require a large concentration of biomass flows.

BE-CCS appears to be attractive, above all because a negative CO_2 balance[4] might even be possible. However, this assumption requires substantiation of the whole process in respect of different options for energy-related use of biomass by means of substance and energy balances. Critical for energy balances is the energy consumption for capture, transport and storage as well as for transport and, where applicable, cultivation of biomass.

Use on a large scale would involve the same risks and restrictions as in the case of CCS (3.2.1) and other processes for biomass use (3.2.3). The potential contribution of BE-CCS to carbon dioxide removal (CDR) is determined on the one hand by existing storage capacities for CO_2, and by biomass potential on the other (Figure 5).

06

3.2.5 Afforestation

Additional carbon dioxide can be removed from the atmosphere through afforestation. The Kyoto Protocol laid down incentives for industrial countries in this respect. During climate negotiations in Cancùn in 2010 decisions were taken that clear the way for incentives for improved land use management in developing countries.

Many of these measures should be classified under convention land use. When, in the course of reafforestation, tree species are selected that are suited to local conditions and sustainable forms of forestry management are employed, a contribution is made not only to climate protection but also to biodiversity. The Federal Environment Agency does not consider afforestation to be a geoengineering measure. In literature, however, geoengineering methods are also described in connection with afforestation, including the planting of cloned or genetically engineered plants and monoculture plantation forests with tree species that are not suited to local conditions. While afforestation in harmony with nature and sustainable forestry management should be judged positively, such geoengineering methods harbour a number of problems. The Federal Environment Agency will prepare a special paper on these issues.

3.2.6 Marine geoengineering methods

Oceans are the largest and most important carbon sink on our planet. They absorb fifty times as much carbon as the atmosphere. At present, around 40,000 Gt C are stored in oceans, compared to just 750 Gt in the atmosphere (Johnston et al.1999; Raven and Falkowski 1999). The greatest proportion of carbon is stored in the deep sea (38,100 Gt) (Trumper et al. 2009). It is therefore no surprise that many geoengineering proposals want to utilize this important carbon sink.

The exchange of carbon dioxide between the atmosphere and oceans takes place above surface water. The dissolved CO_2 in the light-suffused water layer is fixed through photosynthesis of the smallest algae (phytoplankton) in biomass. Part of biomass formed in this way (gross primary production) is in turn metabolized by the phytoplankton to CO_2 and water; the rest is at the disposal of consumers (zooplankton - floating microscopic fauna) as food. When phytoplankton and zooplankton die, they sink into greater depths, if they have not already served as food. This downward transport of dead organic material (detritus) is termed the biological pump (Figure 6). While part of downward transported organic carbon is made available for other organisms by means of bacterial degradation, another part sinks into greater depths and is removed for a period of up to 1,000 years from the carbon cycle (Lampitt et al. 2008). This net carbon absorption is described as sequestration. Oceans are for this reason an important sink for CO_2.

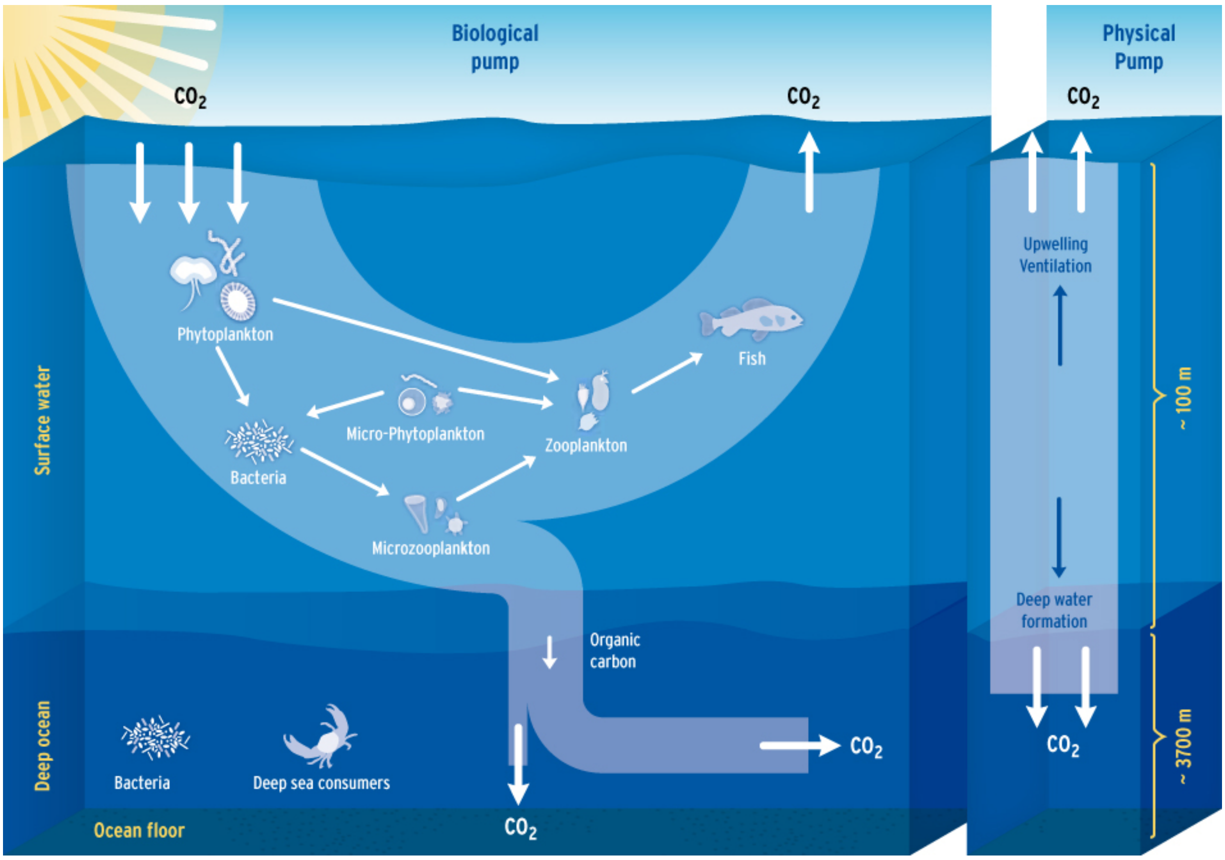
The biological pump functions all the more effectively the more nutrients are available to the phytoplankton for its growth. One marine geoengineering approach is therefore directed at increasing the efficiency of the biological pump through the influx of artificial nutrients (CBD 2009). This can be triggered either through the supply of external nutrients – that is, through iron fertilization – or by increasing upwelling processes affecting nutrient-rich deep water (Lampitt et al. 2008; Chisholm 2000; Royal Society 2009; Keith 2001).

Besides the biological pump, a second mechanism – the physical pump – transports CO_2 into the depths of the ocean (Figure 6). This pump is driven by the sinking of cold water masses of high density (caused by their high salinity) in the North Atlantic and the region of the Antarctic Circumpolar Current (ACC). The sinking water masses rise again at another place in the ocean (time scale: 500 to 1,000 year), as a result of which global ocean currents are set in motion. This second pump is also known as the ‚solubility pump', since it is based on the dependence of CO_2 solubility on temperature. One marine geoengineering approach is therefore directed at manipulation of this pump.

07 Ocean fertilization

The potential of ocean fertilization for removal of CO_2 from the atmosphere was initially judged to be encouraging on the basis of theoretical calculations. These showed that a 10% increase in the efficiency of the biological pump could additionally remove up to 1 Gt of carbon per year from the atmosphere. By comparison, in 2008, anthropogenic CO_2 emission was equivalent to 8.2 GtC. Were it possible to convert all idle nutrients of the Southern Ocean into phytoplankton biomass in the next 100 years (an extreme assumption), 15% of anthropogenic CO_2 emission could be compensated (Chisholm et al. 2001). On account of this theoretically high potential, ocean fertilization is one geoengineering measure that has been the subject of research for a long time. For ocean fertilization, not only can macronutrients such as phosphorous and nitrogen be dumped in large quantities into the ocean, but also, in smaller quantities, micronutrients such as iron. The choice depends on which nutrients are required by phytoplankton for growth in a particular region. The effects of ocean fertilization have been investigated since 1993 in 13 field trials that, however, were all very limited spatially (less than 300 km2), and were conducted only over short periods of time (up to 40 days). In the main, iron was used as fertilizer (Nellemann et al. 2009; Royal Society 2009). The enthusiasm derived from theoretical studies quickly foundered, since the precondition for fixing of CO_2, namely the sinking of phytoplankton, occurred, if at all, only to a limited extent. Initially, algae bloom formed over a wide area. This phase quickly abated, however, since other scarce nutrients and factors such as respiration and light deficiency had a limiting effect on algae growth. A large proportion of phytoplankton was rapidly eaten by zooplankton. Iron was swiftly removed from surface water by complex chemical processes. An appreciable net export of CO_2 into deep waters could be substantiated in none of the studies, since, among other things, this export of CO_2 is very difficult to measure with presently available methods, and biogeochemical cycles as well as ocean circulation have not been sufficiently researched (CBD 2009; Royal Society 2009). Model studies have also shown, however, that the efficiency of ocean fertilization is low, and that the greater proportion of carbon (up to 80%) is re-released (CBD 2009; Lampitt et al. 2008). Few scientific findings are presently available on fertilization with macronutrients such as phosphorous and nitrogen (CBD 2009). Evidence of the efficacy of ocean fertilization has therefore up to now not been produced.

FIGURE 6: THE PRINCIPLE OF BIOLOGICAL AND PHYSICAL PUMPS (ACCORDING TO CHISHOLM 2000)



It has to be borne in mind that a huge area would have to be fertilized. Furthermore, ocean fertilization would take effect only very slowly, since phytoplanktons sink very slowly into deep water, and there is also a delay between modified CO_2 concentration in the atmosphere and a change in global mean temperature. Fertilization would also have to be maintained over very long periods of time to have a sustained influenced on atmospheric CO_2 concentration (Lenton & Vaughan 2009). The quantity of CO_2 that arises during fertilizer production, transport and dumping would also have to be deducted from the potentially sequestered quantity of CO_2. This upstream CO_2 could possibly exceed that of fixed CO_2 (Lampitt et al. 2008). While certain researchers (Strong et al. 2009) are of the opinion that after 17 years of experiments evidence of the inefficiency of ocean fertilization has been provided, others call for large-scale field trials (100X100km) coupled with high-resolution, three-dimensional computer simulation (Güssow et al. 2010; Lampitt et al. 2008).

Besides the questionable efficacy of the measure, adverse effects on the marine environment are also very probable, since ocean fertilization intervenes in the highly complex structure of ocean food chains. The costs of the ecological consequences of ocean fertilization, such as eutrophication (excessive nutrient enrichment) and modified food chains, are presently incalculable. Increased nutrient supply changes the composition of phytoplanktons and has an effect on the entire food chain. Toxic algae blooms can also represent a hazard for humans and marine fauna. In a recently published study it was shown that iron fertilization in the subarctic Pacific leads to diatom blooms that produce a strong neurotoxin (Trickt et al. 2010). These algae species emerged in most fertilizer trials, but production of the toxin had previously not been measured. The toxin accumulates in the food chain and leads in humans to poisoning following the consumption of shellfish. Further adverse effects arise during the sinking of large quantities of dead phyto- and zooplankton, which in the long term can lead, in the case of accumulation on the ocean floor, to oxygen deficiency in the respective compartments, and also to the death of organisms on the ocean floor and in the water column. Oxygen-free sediments produce, in turn, greenhouse gases such as methane, which negates the effect of CO_2 reduction.

Finally, possible adverse effects in regions „downstream“ from the area of fertilization have also to be considered. They are supplied by ocean currents with water masses from which nutrients essential for phytoplankton growth (that are not contained in fertilizers) would have already been removed. The consequence of nutrient removal could be that merely a local shifting of algal biomass production is achieved. It is therefore necessary to take account of the carbon cycle in a much larger region in investigations (CBD 2009; MacCracken 2009).

The large number of unresolved side effects is the reason that at the 2008 IMO London Convention a resolution was passed that prohibits commercial fertilization (see Section 4.6). In the end, the eutrophication produced by ocean fertilization contravenes global, European and regional marine protection policy, which pursues the objective of reducing eutrophication and achieving a „good status“ of marine waters (Leujak et al. 2010).

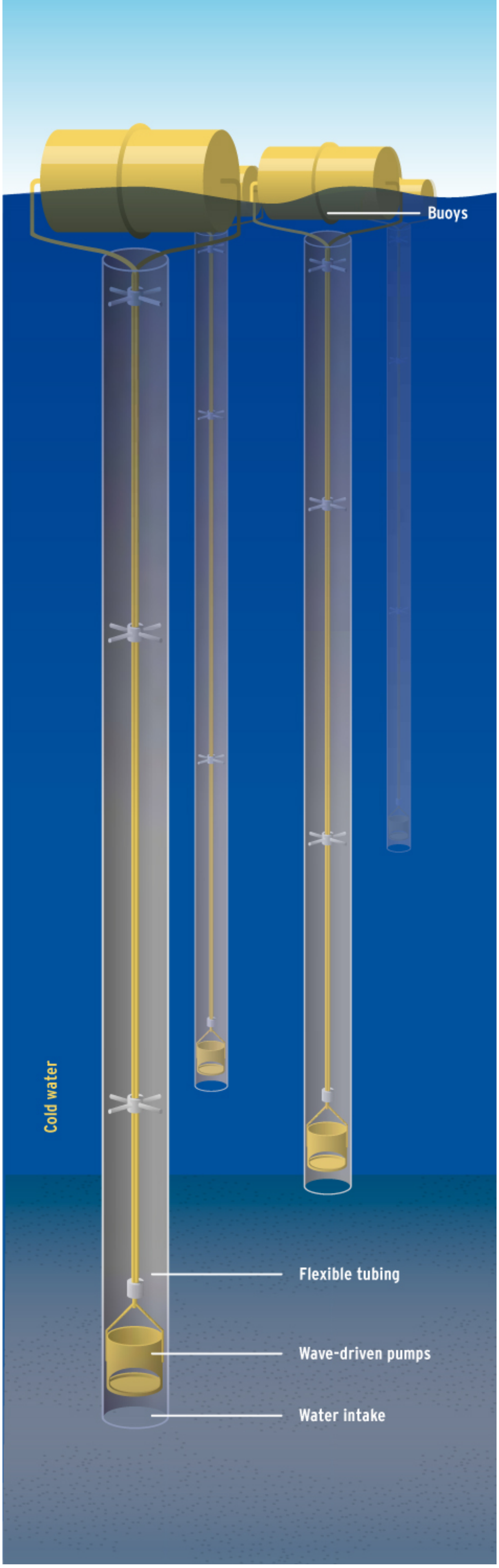
08 Manipulation of marine stratification

In oceans, layers of warm water overlie layers of cold water. The deliberate manipulation of marine stratification could lead to the rising of nutrient-rich deep water to the surface and, as a consequence, to an increase in the biological pump or, through the intensified sinking of water masses, to an increase in the physical pump. Lovelock & Rapley propose that upwelling of nutrient-rich deep water be enhanced with vertical pumps (Lovelock & Rapley (2007). These 100 to 200 metre long vertical tubes with a diameter of 10 metres could use wave energy to pump deep water to the surface. 21 prototypes have already been tested by the American company Atmocean Inc. (www.atmocean.com) (Figure.7). Deep water that is pumped to the surface has, however, already been enriched with CO_2 and can therefore absorb little CO_2, and in certain ocean regions even releases it to the atmosphere (Shepperd et al. 2007). Since upwelled nutrient-rich deep water would add no additional nutrients to the system, the efficiency to be expected from this method is distinctly lower than that of other methods of ocean fertilization that dump artificial nutrients. To increase ocean absorption of CO_2 by just 1 Gt of carbon per year, 200 to 800 million pumps would be required, depending on efficiency, which would cover an area of up to 1,000 square kilometres (by comparison: the city of Berlin covers an area of about 900 square kilometres) (Yool et al. 2009, Lampitt et al. 2008). Since the method is directed at increasing algal growth, the same side effects are to be expected in principle as with other methods of ocean fertilization. The installation and operation of pumps in the ocean could moreover affect marine organisms through noise and obstacles. In addition, the method is in competition with fishing, shipping, tourism and other uses of the oceans, and would also represent a safety risk for many such uses (for instance, shipping, fishing and military uses).

Besides proposals that focus on increasing algae growth, there are also others that envisage manipulation of the physical pump to convey CO_2 to great ocean depths on a permanent basis. At the same time, the attempt could be made either to increase artificially the CO_2 concentration of water masses, or to increase the volume of the sinking water. Zhou & Flynn evaluated seven methods, and it turned out that increasing the CO_2 concentration of water masses is not practicable, since surface water is already saturated with CO_2 (Zhou & Flynn 2005).

Only one method proved to be practicable and affordable, namely the artificial formation of ocean ice through the spraying of water onto existing ocean ice shields. These thickened ice shields can then provide greater cooling of the underlying water masses. Cooler water masses are heavier, with the effect that more

FIGURE 7: WAVE-DRIVEN PUMPS FROM ATMOCEAN INC



water sinks to the deeper ocean. It has to be considered, however, that the sinking of water masses in one region can result in the upwelling of water in another, so that it is difficult to estimate the method's CO_2 balance. In addition, the 10% decrease in the physical pump, which occurs as a result of global warming through a decline in the solubility of CO_2 in relatively warmer surface water (Körtzinger 2010), has first to be compensated. It has also to be assumed that such an intervention could have substantial adverse effects on marine organisms and complex marine food chains through a change in temperature conditions and hydrodynamics.

Zhou & Flynn come to the conclusion that this geoengineering method is probably much more expensive than other methods (cost: 177 US dollars per t CO_2), and therefore also regard it as impracticable (Zhou & Flynn 2005). The method is nonetheless still being discussed, since with its help one could possibly strengthen the North Atlantic current (part of Gulf Stream circulation), which is possibly weakening as a result of climate change. Adverse effects have not been discussed up to now, but they cannot be neglected, since intervention in highly complex ocean circulation process is concerned that decisively influence the Earth's climate.

09 Ocean liming

Ocean liming, too, has the objective of strengthening the physical or solubility pump by increasing the pH value of ocean water through the addition of calcium oxide. Marine water with higher alkalinity could then fix more CO_2 from the atmosphere. For this, calcium oxide must first be produced through thermal decomposition (heating to 850ºC) of limestone on land; a process that requires a lot of energy and water, which also releases carbon dioxide. Proponents of ocean liming argue that the quantity of released CO_2 is just half as much as the quantity that will be later fixed in the limed ocean (Kruger 2010). The method was first proposed by Kheshgi (1995), and is now mainly promoted by the British researcher Tim Kruger, who is looking for further development with public participation by means of a Website (www.cquestrate.com). Research into the feasibility of the approach, which also considers the consequences for marine ecosystems, is financed by Shell (Borel 2008). Rough estimates show that 1.5 cubic metres of limestone could fix 1Gt of CO_2 in the ocean. It would, however, take 750 years until the present concentration of CO_2 in the atmosphere was reduced to natural concentration; provided, of course, that each year 1 cubic kilometre of limestone could be mined (Borel 2008). Logistically, ocean liming represents an enormous endeavour, since great quantities of limestone would have to be mined and transported. Kruger argues that his method would also be capable of alleviating ocean acidification caused by climate change. This is questionable, however, since local liming only enables the pH value to rise within a limited area. Furthermore, the bringing into play of marine water with extremely high alkalinity could even harm marine organisms.

Critics regard the approach as implausible, since localized discharge of calcium oxide would make ocean water so alkaline that precipitation of calcium carbonate would be the immediate outcome. Even should this not be the case, scientists argue that the fixed quantity of CO_2 in the ocean would not significantly exceed the quantity released by decomposition of the limestone, and that the entire process would thus more likely produce additional CO_2. Lime would therefore have to be discharged into the ocean in substantial quantities to achieve a noticeable increase in lime content in ocean water. Since, however, the surface water of oceans is oversaturated with lime, this would not lead to accelerated dissolution of CO_2 in ocean water. Undersaturation with lime is found first at depths of several thousand metres. Little anthropogenic CO_2 finds its way to such depths; it is rather largely found in the upper ocean, and only in 1,000 to 2,000 years will it be spread over the entire water column. In the long term (in 10,000 years or more), it is precisely this reaction that will fix the greater part of anthropogenic CO_2. For this purpose, the natural lime content in oceans is sufficient (unless global CO_2 production, expressed in tonnes of carbon, would exceed 5.000 Gt C). Furthermore, the adverse effects of liming on the marine ecosystem have to be considered. The ocean light climate would change as a result of huge turbidity zones, in which photosynthesizing flora could no longer grow. This would have an impact on food chains and fishery yields.

10

Dumping of crop residues

Apart from proposals for direct storage of CO_2 in marine geological formation (CCS, see Section 3.2.1), a proposal for dumping crop residues in the ocean is also in circulation. This proposal (Strand and Benford 2009, see also Section 3.2.3) is known as CROPS: crop residue permanent sequestration. Strand and Benford assume that around 30% of crop residues (for example, straw) could be removed from fields without soil quality being diminished and soil erosion being intensified. Crop residues would be baled and transported with existing infrastructure (harvesting machines, lorries etc.) to the nearest port, loaded onto ships and, at places where the ocean is more than 1,000 to 1,500 metres deep, weighted with stones and sunk. The authors of the proposal assume that at this depth, due to the cold, oxygen deficiency and the lack of enzymes for cellulose degradation, decomposition of the organic material through marine bacteria would occur only very slowly, and that CO_2 would thus be fixed for up to thousands of years. They estimate that through the sinking of crop residues 92% of the CO_2 they contain would be fixed, whereas this proportion would be just 32% with the production of ethanol from the wastes and merely 14% with their burying in the ground. Initial cost-benefit assessments show that the fixing of one tonne of carbon would cost 340 US dollars, and that on a global scale about 15% of the annual global increase in CO_2 emission (0.6 to 0.9 Gt CO_2) could be removed from the atmosphere with this method. It would have to be guaranteed, however, that through the transport of crop wastes not more CO_2 was produced than was finally fixed in the ocean.

The ecological impact of this method can only be the subject of speculation, since deep-sea processes are largely unresearched. Strand und Benford (2009) recommend that crop residues be dumped only where terrestrial biomass has already been deposited by natural processes at greater ocean depths. The affected ocean area could be limited through the layering of bales (annual depositing of an up to 4 metres thick layer). Adverse effects of this method on complex marine ecosystems are highly likely. Fragile deep sea ecosystems would be destroyed, at least at deposition sites. The issue of whether decomposition processes lead to the release of hazardous substances (fermentation gases, greenhouse gases etc.) and can significantly harm marine organisms in a larger area, with unpredictable consequences also for humans, is unresolved. Should the bales break loose from their anchor and rise to the surface, the result would be the release of fixed CO_2 through decomposition processes. On land, soils would be deprived of important nutrients and trace substances through the removal of crop wastes from fields.

11

3.2.7 Enhancement of natural weathering processes (terrestríal and marine measures)

Not only forests store carbon dioxide, CO_2 is also removed from the atmosphere by natural weathering processes, during which silicate rocks are dissolved under the effect of carbonic acid, which is formed by dissolution of CO_2 in rain or soil water to form carbonates. At the same time, soluble calcium carbonates are formed, thus fixing CO_2. Finally, calcium carbonates are transported via rivers into the sea. Weathering has a major influence on CO_2 concentration in both the atmosphere and oceans, but the reaction is very slow, CO_2 being absorbed at a rate of less than 0.1 Gt C per year (Royal Society 2009).

Proposals are being considered to imitate or accelerate these weathering processes. The required base materials would be available in large quantities. To begin with, suitable minerals from the mining industry would have to be processed in such a way that they have as large a surface as possible.

Different methods for acceleration of weathering are being discussed. One envisages the adding of silicate minerals (for example, the base mineral olivine) to agricultural soils. There, after absorption of CO_2, they would be immobilized partly as carbonate materials and partly as bicarbonate solution. Large quantities of silicate materials would be required. According to estimates, 7 cubic kilometres of silicate minerals per year would absorb annual anthropogenic CO_2 emissions (Royal Society 2009). This quantity of silicate minerals roughly corresponds to double the current annual worldwide production of coal.

There are also proposals to enhance the rate of CO_2 reaction with basic minerals such as basalts or olivine in situ in the Earth‘s crust (Royal Society 2009). Perodotite rock, for example, formations of which are found in Oman, is rich in olivine, decomposes very quickly and absorbs large quantities of CO_2 (Kelemen & Matter 2008). One could accelerate weathering by injecting hot CO_2 gas under high pressure through drilled holes into the rock. With this process, more than 1 Gt CO_2 (0.27 Gt C) could be stored each year in Oman alone, and this without the transport of large quantities of rock. In contrast to ex situ methods little energy would probably be required.

With the so-called ‚bicarbonate solution technique‘, carbonate rock could be ground and reacted in chemical engineering plants with concentrated CO_2 captured from power plants to bicarbonate solutions (Caldeira & Rau 1999, 2000). The resulting calcium ions and bicarbonate would be released into the sea, where CO_2 in this chemical form can hardly be emitted into the atmosphere (less than 15 % of the CO_2 would be returned via gas emission to the atmosphere).

It is technically not possible, however, to completely remove CO_2 from flue gases. According to estimates, 2.3 tonnes of limestone and 0.3 tonnes of water would be required to absorb 1 tonne of CO_2, in the course of which 2.8 tonnes of bicarbonate ions are produced (Rau et al. 2001). The water could come to a large extent from the cooling water cycle of coal-fired power plants. Release of bicarbonate into the sea would lead to acidification, which, however, would be just 16% of acidification resulting from climate change (Caldeira & Rau 2000). According to Caldeira & Rau, an enormous infrastructure would be required to mine, transport, grind and dissolve the limestone as well as to pump out the end product. The technique would be economically competitive at places where limestone deposits occur close to the sea. Initial estimates of costs, depending on transport costs, amount to 6 to 68 US dollars per tonne of absorbed carbon. The calculations are based on the assumption, however, that water is available free of charge (Rau et al. 2001; Caldeira & Rau 2000).

There is also the idea to release strong bases, such as calcium hydroxide, into oceans. These would react with CO_2 to form calcium ions and bicarbonate (Royal Society 2009). The problem with this approach is that strong bases do not occur in nature in a sufficient quantity, and would first have to be synthesised. With syntheses, however, strong acids develop, and it is not clear how these could be disposed of. Ocean liming, a further marine approach, has already been discussed in Section 3.2.6.

All the proposals mentioned are technically and chemically feasible, their application in the required order of magnitude, however, is limited on a number of grounds. In the most favourable reaction ratio, at least one tonne of silicate rock is necessary to absorb one tonne of CO_2 (Royal Society 2009). A gigantic quantity of source rock would therefore be required. Necessary expansion of mining together with processing and transport would, on the one hand, be cost- and energy intensive, and give rise on the other hand to considerable environmental damage at a local level (Royal Society 2009). The accumulation of relatively large quantities of alkaline-acting end products involves further risks. It is assumed that the release of these end products into the ocean would have little impact, since these substances already exist in very large quantities in oceans. Reference is even made to the fact that an increase in the pH value of oceans counteracts acidification resulting from climate change. It is ignored, however, that local, strongly-concentrated release would have substantial effects on the pH value of the affected regions. The accompanying effects on ocean chemistry are not assessable. The enormous demand for water of some methods limits application, and should be examined against the backdrop of expected worldwide water scarcity.

3.2.8 Summary and evaluation of measures for the removal of CO_2

In principle, the removal of carbon dioxide from the atmosphere is more applicable to the cause of global warming than to the methods of solar radiation management. The attempt is at least made to reduce the increase in CO_2 in the atmosphere. At the same time, continuing acidification of oceans – a serious problem in connection with anthropogenic CO_2 emissions – is counteracted. In the case of marine geoengineering this is partly not the case, since the acidification of oceans might even be aggravated. Moreover, the removal of carbon dioxide from the atmosphere reduces merely the concentration of this greenhouse gas. All other gases – for example, nitrous oxide – remain unaddressed.

One can generally say that measures for solar radiation management could have a faster effect with regard to climate change than measures for removal of CO_2. The storage of CO_2 requires, as a rule, substantial costs and technical input as well as a great deal of time.

In view of high annual anthropogenic emission of CO_2, enormous quantities of carbon dioxide would have to be removed from the atmosphere to achieve a noticeable effect on the climate. The efficacy of a number of measures for the storage of CO_2 is doubtful, bearing in mind the high consumption of energy for installation, operation and maintenance of the required infrastructure.

The efficacy of certain measures for CO_2 storage requires that captured CO_2 be verifiably stored for long periods. The integrity of the storage medium must be such that CO_2 cannot migrate into the atmosphere for a long period of time. Overall potential is therefore directly set by the number of suitable and actually available storage sites. It also has to be considered that sustainable approaches towards the use of subterranean areas, such as geothermics, may not be adversely affected, and that as a result the number of available storage sites is further limited.

The measures differ greatly concerning the risks that are associated with them. Marine geoengineering measures involve, in part, major intervention in natural ocean processes. This concerns, among other things, the complex structures of ocean food chains and ocean circulation systems. The consequences cannot presently be adequately predicted or assessed. Moreover, the efficacy of problematic measures is in most cases low, due to the costs involved.

It has generally to be said that most of the described marine measures, which are based on the release of substances or materials into oceans, clearly contradict global, national and regional marine policy of past decades. Agreements have been concluded that prohibit, or at least severely restrict the dumping of substances and materials. This way, account has been taken of the need to protect our sensitive marine ecosystems, in order to be able to benefit from their natural functions and to enable their sustained use. The described proposals imply a paradigm shift in ocean protection, which, in our view, brings about substantial damage that outweighs any benefits they might offer.

Measures for ocean fertilization assume an exceptional position, since they have already been tested in field trials. Research findings clearly show that the efficacy of such measures is low, and that adverse effects on the marine environment are to be expected.

Insufficient knowledge is available for conclusive assessment of the effects and consequences of proposals for fixing of carbon dioxide. Up to now, none of the proposals has been sufficiently developed, and there are almost no examples of practical implementation. With a number of these measures it must be expected that the cost of consumed energy and logistics is incommensurate to the effect.

Finally, particularly in the case of terrestrial measures, it would have to be ensured that the people affected – local residents, for example – are identified and informed about such measures, in order that public acceptance can be achieved.

FOOTNOTES:

1 Aerosols are a gaseous suspension of fine solid or liquid particles.
2 1 Terragram = 1 million tonnes.
3 Terra Preta (‚black earth' in Portuguese) is a type of very dark, fertile soil found in the Amazon Basin, which contains a large proportion of charcoal. It is assumed that the indigenous population added charcoal to the soil.
4 A negative energy balance implies that in the overall process more CO_2 is removed from the atmosphere than is emitted. This is possible because vegetation removes CO_2 from the atmosphere during its growth phase. During the burning of vegetation in biomass power plants CO_2 is again released, but there is the possibility, through capture and permanent storage, to remove this CO_2 from the atmosphere.

04

STATUTORY FRAMEWORK

4.1 Legal issues concerning geoengineering

The above presentation of different geoengineering proposals has shown that they imply, in part, considerable intervention in the Earth's systems and potential risks for the global environment. Against this background, it has to be investigated to what extent the investigation and application of geoengineering is subject to statutory or regulatory control.

Instruments of legal control can apply at different levels of regulation. Individual states can promote, authorize or prohibit certain geoengineering measures. The respective national regulations are the result of the policy strategies of individual states. These cannot be dealt with here due to their large number.
At the same time, legal requirements also ensue as a result of international law. In view of the global dimension of geoengineering, these regulations are important because they are binding on individual states.

International legal obligations derive mainly from international treaties and customary international law. Customary international law involves unwritten standards that arise through state practice that is based on the conviction of legal obligation. Depending on the participation of states in corresponding state practice, regulations under customary international law can be valid globally or merely regionally. Furthermore, there are a large number of international agreements that trigger obligations merely for the respective contracting parties.

Before the details are explained, it should be pointed out that geoengineering measures are based, at least in part, on evolving technologies. The result is that international regulations were often not drawn up with these technologies in view, simply because at that time such technologies did not exist. There is therefore, where necessary, the need for adaptation or amendment.

Geoengineering technologies are intended to combat anthropogenic climate change. It has therefore first to be examined whether relevant provisions are to be found in international climate protection law. Special treaties relating to different geoengineering measures are then examined. Finally, aspects relating to a future statutory framework are discussed.

4.2 International climate protection law

International climate protection law contains no specific provisions on geoengineering. The basis of international climate protection law, the 1992 United Nations Framework Convention on Climate Change (UNFCCC),[5] lays down as the objective of international climate protection, however, that the concentration of greenhouse gases in the atmosphere be stabilized, in order to prevent dangerous interference with the climate system. In measures for attainment of this objective the Contracting Parties have to observe the principles of precaution and sustainable development. The Contracting Parties are obliged – also in co-operation with each other – to develop technologies and processes for reduction of greenhouse gas emissions, and to promote the sustainable management as well as the maintenance and enhancement of greenhouse gas sinks and storage. The Kyoto Protocol,[6] moreover, obliges industrial countries to reduce their greenhouse gas emissions to a particular extent.

Legal obligations for the avoidance of climate change relate only to such measures that either reduce the emission of carbon dioxide or store carbon dioxide that has been emitted into the atmosphere in sinks. International climate protection law therefore applies for all geoengineering technologies that relate to the storage of carbon dioxide. It has not yet been resolved, whether geoengineering measures intended to bring about cooling at ground level through solar radiation management are covered by international climate protection law, since these will have no effect on greenhouse gas concentrations in the atmosphere (Reynolds 2011).[7]

Should measures for solar radiation management have an adverse effect on the regional climate, however, as is feared in the case of large-scale installation of reflectors in desert areas, they could even be contrary to the spirit of the Framework Convention on Climate Change, which is aimed at the prevention of harmful anthropogenic disturbances of the climate system.

International climate protection law contains no clear requirements concerning geoengineering. The significance of the principle of precaution, for instance, is the subject of debate. On the one hand, the principle of precaution is put forward as a reason for not carrying out measures that involve risks for the environment. On the other hand, it is also argued in political discourse that on the grounds of precaution every measure must be tested, at least as ultimo ratio, in order to be able to counteract anthropogenic climate change. What is more, the Framework Convention on Climate Change expressly demands the development of measures to counteract climate change.

Beyond international climate protection law, the principle of precaution[8] is also recognized as a general principle of international environmental law, from which various requirements can be derived regarding geoengineering measures. In any case, the principle of precaution requires that states avoid risks for humans and the environment, even when the presence of risk cannot be entirely substantiated scientifically.

4.3 International law on the protection of biological diversity

Geoengineering can doubtless have a harmful effect on biodiversity. Marine measures, for example, can intervene in ocean food chains. Agricultural and forestal measures also involve risks for biodiversity.
The Contracting States to the globally applicable Convention on Biological Diversity (CBD)[9] therefore addressed the question of ocean fertilization in 2008, and adopted in October 2010 a politically significant resolution on geoengineering, which provides for a broad moratorium on geoengineering. In view of the lack of a scientifically well-founded, global, transparent and effective control and regulation mechanism for geoengineering, and in accordance with the principle of precaution, no geoengineering measures should be implemented until such time as an appropriate scientific basis for justification of geoengineering exists, and the risks for the environment and biodiversity associated with geoengineering as well as its social, economic and cultural consequences can be properly considered and examined. Excluded from this moratorium are merely small-scale research studies that are conducted in controlled circumstances. Furthermore, such research projects must serve the purpose of acquisition of specific scientific data, and possible environmental effects have to be thoroughly examined.[10]

With this resolution, for the first time general requirements for geoengineering activities and, above all, research projects were formulated under the aegis of a globally valid convention. A possible future binding legal regime will reflect the provisions of the resolution (moratorium for geoengineering activities as well as control of corresponding research, particularly for the avoidance of adverse environmental effects).

4.4 Terrestrial geoengineering

For the legal assessment of geoengineering measures it is decisive, among other matters, where they will be carried out. Some geoengineering measures – for example, the cultivation of renewable raw materials, CCS measures and enhancement of the albedo of surfaces – will be generally carried out on the territory of one or more states. Other measures, such as ocean fertilization, take place in the main outside the sovereign territory of states, namely on the high seas. The discharge of aerosols into the stratosphere necessarily involves the territory of other states; and the installation of sunlight deflectors in outer space affects several, if not all states.

Insofar as measures are conducted solely in the sovereign territory of one state, the respective state is fully responsible. That basically applies for all terrestrial geoengineering technologies.

This freedom to act is not, however, limitless. In accordance with customary international law, states have to ensure that activities on its territory do not give rise to substantial adverse consequences for the environment beyond their own borders. Substantial adverse effects on the environment may be brought about neither in neighbouring states nor in other states and in areas outside the jurisdiction of states, such as the high seas, the Antarctic and outer space. Furthermore, states are obliged to undertake procedural measures; for example, should the risk of considerable transboundary effects of a project exist, environmental impact assessments have to be carried out in advance (ICJ, Pulp Mills Fall, judgement of 20 April 2010, paragraph 204) and potentially affected states have to be timely and substantially informed and consulted (Birnie et. al. 2009).[11]

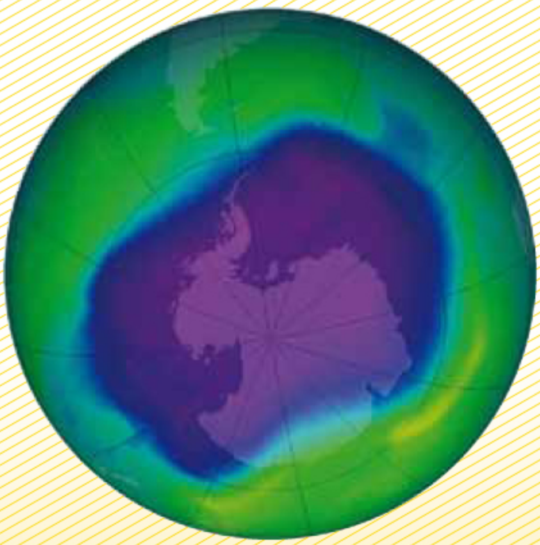
Customary international law thus demands that substantial adverse effects on the environment outside a state's own sovereign territory be avoided, and further obliges states to examine risks and to inform and consult affected states in advance.

4.5 Atmospheric geoengineering

Another proposal is the scattering of sunlight through the release of sulphur aerosols into the stratosphere to effect a cooling at ground level. With this measure, a large proportion of the global stratosphere has to be affected.

Sovereignty extends by way of the air column above a state's territory into outer space. There is disagreement over the precise position of the frontier between airspace and outer space. According to general agreement, airspace extends up to an altitude of 80 kilometres above the Earth's surface (Graf Vitzthum 2010a).

Within their airspace individual states bear responsibility due to their sovereignty. If an individual state wants to take action in the territory of another state, it requires the agreement of that state. It is therefore questionable, whether unilateral atmospheric geoengineering measures, which should be implemented in global airspace, would be permissible without the agreement of affected states.



The ozone hole over the South Pole, the largest on record on 24 September 2006

Total Ozone (Dobson Units)

110 220 330 440 550

The release of sulphur aerosols could, moreover, be contrary to the international legal regime for protection of the ozone layer, since as a consequence the ozone layer could be damaged or destroyed. Though sulphur is not among those substances that are regulated in accordance with the Montreal Protocol[12], the 1985 Vienna Convention on Protection of the Ozone Layer[13] requires Contracting Parties to avoid activities within their territory that as a consequence of the change in the ozone layer probably damage human health and the environment.

The release of sulphur aerosols would therefore be contrary to the provisions of the Vienna Convention, if it is to be assumed that as a result, due to the released quantities for example, the ozone layer will be damaged and harmful effects on health caused.

Of further importance is the 1979 Geneva Convention on Long-Range Transboundary Air Pollution, whose Contracting Parties are restricted – with the exception of the USA and Canada – to European states.[14] In the agreed protocols to the Convention the Contracting States have committed themselves to reducing emissions of sulphur. The deliberate release of sulphur aerosols is contrary to the spirit of these commitments (Bodansky 1996).

Apart from that, the general ban in international law on substantial adverse transboundary environmental effects applies. Besides the already-mentioned depletion of the ozone layer, the release of sulphur aerosols can result in a substantial decline in rainfall in the Asian and African summer monsoon; and this could affect the food supply of millions of people.

4.6 Marine geoengineering

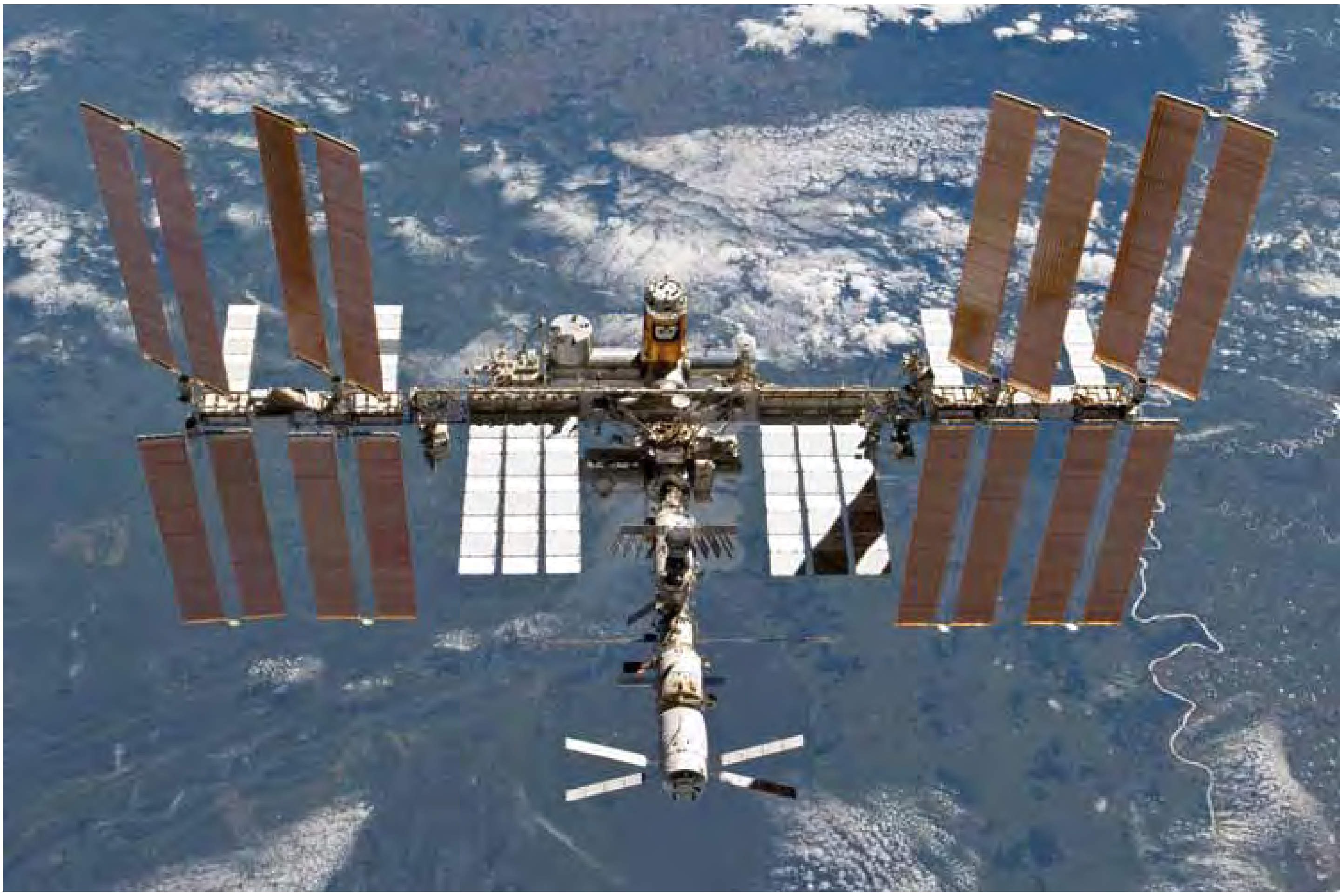
A further measure to influence the global climate is ocean fertilization. Of particular relevance for this is the 1982 United Nations Convention on the Law of the Sea, and the 1972 Convention on the Prevention of Marine Pollution through Dumping of Wastes and other Matter, and the corresponding London Protocol.

Since the provisions of these conventions are not unequivocal, the Contracting Parties adopted in 2008 a politically highly important resolution, which further allowed research activities in the area of ocean fertilization, but prohibited all other measures, in particular those of a commercial nature. It has to be examined beforehand whether the experiments are necessary, and whether they involve unjustifiable adverse effects on the environment. In October 2010, the Contracting States agreed on an assessment framework for the examination of research projects. It has to be assessed whether besides the scientific quality adverse environmental effects are also to be expected. According to the assessment framework, economic interests may not influence the direction of the research project. In the preliminary stage, other states and interested parties have to be consulted. The importance of the assessment framework is that for the first time assessment standards for research projects in the field of geoengineering have been agreed at an international level. The assessment criteria and standards are demanding, but also appropriate.

At the same time, the Contracting Parties are negotiating over how the 2008 resolution can be transformed into a legally binding version. The Contracting Parties to the 2008 Convention on Biological Diversity formulated a resolution whose content was virtually identical to that of the 2008 London Convention and London Protocol (LC/LP). The resolution was confirmed by the Conference of Contracting Parties to the CBD in 2010.

4.7 Geoengineering in outer space

Finally, there is the proposal to install sunlight deflectors in outer space. In contrast to national territory and the air column above it, outer space – as also the high sea – does not lie under the jurisdiction of any state. Legal relationships in outer space are governed by the 1967 Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies (hereafter: Outer Space Treaty)[15] and certain supplementary international treaties. The Outer Space Treaty firstly established that the exploration and use of outer space must be conducted to the advantage and in the interests of all states. All states may equally and peacefully use and explore space (free use of outer space) in accordance with international law, and in so doing co-operate with each other. The Treaty expressly prohibits only such harmful environmental effects as result from the extraterrestrial discharge of substances. It is questionable, however, whether the free use of outer space also covers activities in outer space that cause harmful environmental effects in another manner on Earth, such as changes in the water cycle, since they are not „to the advantage and in the interests of all states“ (Konstantinov 1990).



The International Space Station (ISS) – still without reflectors, but with solar collectors for a self-sufficient power supply in space

In any event, the ban on substantial transboundary environmental effects is also an obstacle to geoengineering in outer space if and when substantial damage would be caused to the environment.

4.8 Laws on the responsibility of states

Even when geoengineering measures can have a positive influence on the climate, they can at the same time have considerable adverse consequences for the climatic conditions of individual regions. It is feared, for instance, that the reduction in rainfall in India or Africa could result in substantial crop failure.

Can one state demand damages from another state, when this state has carried out geoengineering measures? There are no general provisions in international law governing liability between states. Regulation of state liability is recognized, however, under customary international law. In 2001, the International Law Commission of the United Nations drew up Draft Articles on the Responsibility of States for Internationally Wrongful Acts, which were later adopted by the United Nations General Assembly in the annex to a legally non-binding resolution. The regulations contained therein represent binding international law only insofar as they codify customary international law (Graf Vitzthum 2010b).

A prerequisite for state liability is infringement of an obligation under international law. However, as already mentioned, it is not always easy to determine the specific obligations that exist under international law with regard to the rights of other states in connection with the realization of geoengineering measures. There is, moreover, the difficulty of substantiating cause and effect relationships (Shaw 2009).

4.9 Consequences for a future statutory framework

As already mentioned, existing international regulations are incomplete. Up to now, no clear regulatory concepts have been put forward concerning how geoengineering measures should in future be treated. The most progress has been achieved with requirements on ocean fertilization under maritime law.

In relation to the future statutory framework, it has to be said that most geoengineering methods are merely theoretical reflections, whose efficacy has still to be tested. This situation must be addressed in international law. In this respect, the regulatory concept on ocean fertilization can serve as orientation. Research is basically allowed, but with research activities it must be ensured that hazards for humans and the environment do not result. It can be argued in favour of the necessity of preliminary state control of research into geoengineering that the technology can involve substantial risks and irreversible consequences (cf. Reynolds 2011).

It has to be clarified whether there should be a standardized, broad regulation on geoengineering, or whether the respective international conventions should be supplemented with provisions on geoengineering meas-ures. For a standardized, broad regulation on geoengineering the United Nations Framework Convention on Climate Change would be an option.

FOOTNOTES:

5 There are 192 Contracting Parties to the Convention (191 States and the European Union [EU]), http://unfccc.int/parties_and_observers/parties/items/2352.php (query: 02.02.2010).
6 The Kyoto Protocol is binding for 189 States and the EU, http://unfccc.int/files/kyoto_protocol/status_of_ratification/application/pdf/kp_ratification_20091203.pdf (query: 15.11.2010).
7 This is laid down in Article 3 (3) of the Framework Convention on Climate Change
8 The principle of precaution is classed, in part, as a general principle of international law (cf. Maurmann 2008). It is also frequently assigned validity under customary international law (see Sands 2003 and Birnie et al 2009). The ICJ has described the principle of precaution as a possible aid for interpretation of contractual regulations (ICJ, Pulp Mills Fall, judgement of 20 April 2010, paragraph 164)
9 The CBD is valid for 193 States, http://www.cbd.int/convention/parties/list/ (query: 15.11.2010).
10 Explicitly excluding carbon capture and storage from fossil fuels when it captures carbon dioxide before it is released to the atmosphere (cf. 3.2.1)
11 International Law Commission (ILC) of the United Nations: Draft articles on prevention of transboundary harm from hazardous activities, 2001.
12 The Montreal Protocol on substances that lead to depletion of the ozone layer introduces stabilization and reduction commitments as well as trading restrictions for certain substances. 160 states and the EU are Contracting Parties to the Protocol; http://www.unep.ch/ozone/Ratification_status/index.shtml (query: 12.02.2010).
13 195 states and the EU are Contracting Parties to the Convention; http://www.unep.ch/ozone/Ratification_status/index.shtml (query: 02.02.2010).
14 50 states and the EU are Contracting Parties to the Convention http://www.unece.org/env/lrtap/status/lrtap_st.htm (query: 12.02.2010).
15 The Treaty has been signed by 100 Contracting Parties http://www.oosa.unvienna.org/oosatdb/showTreatySignatures.do (query: 12.02.2010).

05

CRITERIA FOR ASSESSMENT OF GEOENGINEERING MEASURES

Geoengineering leads in most cases to large-scale technical intervention in the environment, with effects not only on the climate but also on other environmental assets and humans. The efficacy and impacts of geoengineering measures can hardly be predicted on the basis of currently available knowledge. In this background paper we look into the following fundamental questions:

- **On the basis of which criteria can geoengineering measures be meaningfully assessed?**
- **Under which conditions is large capital investment in geoengineering justified?**

The criteria defined below are intended to assist policy-makers in the assessment of geoengineering measures; they concern not only the investigation and testing but also the application of such measures.

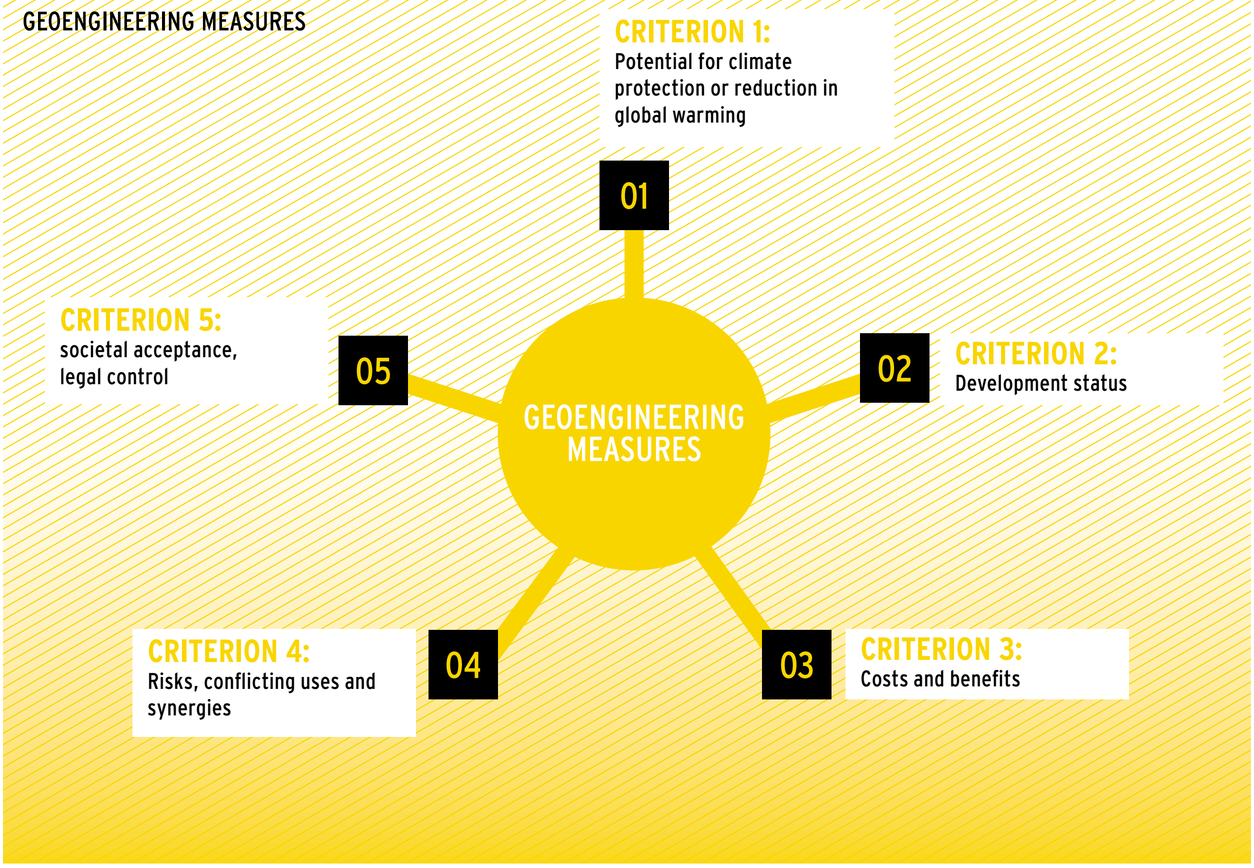
It is obvious that simple investment appraisal or cost-benefit analysis is insufficient for resolving complex issues. Not all impacts can at present be the subject of economic assessment. Moreover, great uncertainties exist in the assessment of possible impacts and risks for humans and the environment. Global effects and impacts that will occur only in the distant future are to some extent also involved. Assessment therefore strongly depends on how future costs are weighted compared to present-day costs. This is expressed in the applied discount rate (interest rate)[16]. A zero discount rate implies an even balance of damage today and in the future, and thus equal treatment of the interests of present-day and future generations, as implied by the concept of sustainability. The higher the discount rate the lower the significance of the cost of damage occurring in the future for current cost calculations.

Against the backdrop of these restrictions, comparison of known and ascertainable costs and benefits can in our view be only one criterion for the assessment of geoengineering measures. Beyond that, further criteria have to be considered.

Geoengineering measures have the aim of curtailing anthropogenic climate change. They therefore compete to a certain extent with measures for emission reduction and adaptation to climate change. Even when a strict alternative of ‚either emission reduction or geoengineering‘ is not involved, it has to be borne in mind that funds available for climate protection are limited, and that „more“ geoengineering measures entails „less“ emission reduction measures.

Important criteria for decisions on whether and to what extent geoengineering technology should be called for and financially supported are, in the view of the Federal Environment Agency, its potential for climate protection and reduction in global warming, the development status of the respective technology, economic costs and benefits, risks and synergies as well as societal acceptance and the legal framework.
On account of interdependencies, however, the criteria cannot be applied in such a selective manner as is described below.

FIGURE 8: FIVE CRITERIA APPLIED BY THE FEDERAL ENVIRONMENT AGENCY TO EVALUATE GEOENGINEERING MEASURES



Criterion 1: Potential for climate protection or reduction in global warming
In an initial step towards fulfilment of this criterion the following question has to be answered: What effect is to be expected from the measure to be assessed, and at what cost? Geoengineering measures should only be considered if a significant benefit for the environment can be expected.

Decisive questions are:
- Is the geoengineering technology able to effectively influence climate change or reduce global warming. If it can, to what extent?
- If the technology promises sufficient success only when applied over large areas, is the technology applicable extensively? To which emission reductions would this correspond? What cost would be associated with it?

High potential coupled with low costs or a modest degree of intervention should be assessed positively.

Criterion 2: Development status
In assessing the measure it is decisive whether the technology can be employed immediately, or whether realization and efficacy are uncertain and further research required.

Decisive questions are:
- What is the R & D status of this geoengineering technology? Do pilot projects already exist?
- In which countries has relevant experience already been gained?
- With what certainty can positive and negative effects be predicted generally and in relation to individual measures?

A high development status, available experiences – for example, with pilot projects – and the possibility of prompt application should be assessed positively.

Criterion 3: Costs and benefits

This criterion aims at revealing costs and benefits for economic assessment. In the overall assessment it has to be borne in mind that the presented costs represent only a part of relevant positive and negative impacts. The costs and benefits of the entire life-cycle should be included in estimates. Insofar as the costs and benefits accrue in different periods, the influence of the selected discount rate on the results should be shown (for example, through sensitivity analysis).

Possible cost and benefit categories are:

- R & D costs and the costs of pilot applications,
- capital cost and costs of operation,
- up- and downstream costs (for example, costs of disposal) and follow-up costs (for example, replacement costs dependent on life-cycle),
- costs resulting from harmful effects on the environment or human health (if quantifiable in financial terms),
- scarcity costs of resource consumption,
- follow-up costs for the national economy, if predictable (for example, due to long-term state financing of the measure),
- effects on the national economy (for example, on GDP and employment),
- benefits for climate protection / climate impact (illustrated by means of appropriate non-qualitative or quantitative indicators) and
- other benefits (for example, for industry, employment and other environmental areas).

Compilation of costs and benefits (also under other criteria) should be supplemented by such effects as can only be measured qualitatively. This avoids overemphasis in decision-making of effects that can only be assessed in monetary terms.

In balancing costs and benefits it has to be ensured for the purpose of comparability that they relate to a defined measure and unit. Generally speaking, the higher the cost-benefit ratio the more positive the assessment. The question of whether costs arise on a sustained basis is also relevant for the assessment. Whereas, for example, with energy efficiency measures costs arise at the beginning of measures, geoengineering measures can be characterized by the fact that a positive influence on the climate can be attained only with repeated, long-term intervention.

Geoengineering represents an intervention in nature whose risks cannot be comprehensibly assessed in monetary terms. One can therefore assume that the actual costs of geoengineering measures are higher than calculated costs, which accordingly represent merely a minimum level.

On the other hand, emission reduction measures offer an additional benefit, since they often serve not only climate protection but also conservation of resources.

Geoengineering measures, which from the outset are economically inferior to emission reduction measures, should be assessed negatively.

Criterion 4: Risks, conflicting uses and synergies

A decisive criterion for the assessment of geoengineering measures is the risk that is directly associated with the degree of intervention in the natural environment. Of particular relevance is whether an irreversible intervention is involved. A useful assessment aid is provided by the categories of global environmental risk that have been drawn up by the German Advisory Council on Global Change (WBGU 1999).

In the view of the Federal Environment Agency, key questions for the assessment of risks, conflicting uses and synergies are:

Risks:

- Impact on ecosystems
  What effects (qualitative and quantitative) do geoengineering interventions have on ecosystems and the environment? Are the objectives of pertinent statutory regulations endangered? What is the extent of such interventions in space and time? How fundamental is the change in the natural environment? Are particularly protected or sensitive areas and / or species of flora or fauna targeted or endangered?
- Extent of the intervention
  How large is the spatial extent of adverse effects (large-, medium- or small-scale; for example: CO_2 storage merely local, sulphur aerosols inevitably worldwide)? Can regions be variably affected by adverse effects (for example, the impact of the albedo effect in Africa, or effects of iron fertilization of oceans on different regions)?
- Risk management
  What risks arise for humans and the environment? Does effective risk management exist for the development and testing of geoengineering technology? Can the inducement of possible adverse effects be halted once application of geoengineering technology has begun? Are adverse effects reversible in the medium term?

Conflicting uses and synergies:

- Which conflicting uses can arise (CO_2 storage versus geothermics, for instance, or renewable raw materials versus food production)?
- Which synergies can emerge? Is there comparable win-win potential, such as with strategies for energy savings, increased energy efficiency and expansion of renewable energy (cost savings, technology promotion, reduced dependence on imports, increased domestic value added and employment as well as improved competitiveness)?

Criterion 5: Societal acceptance, legal control

Societal acceptance and legal feasibility evolve in societal discourse and are dependent on the socio-political environment. Generally speaking, geoengineering measures could encounter greater scepticism in Germany, for example, than in the USA.

Geoengineering measures have aspects that elude objective scientific assessment yet are highly important for societal acceptance. The question of how individual societies deal with uncertainties concerning both opportunities and risks is an important criterion in this context.

In our view, the key questions are:

- Is there societal discourse on the application of this geoengineering technology; and if there is, what is the trend of opinion? Is the development and / or application of the geoengineering technology accepted by society and politically communicable?
- Which ethical, moral, religious or aesthetic principles are touched on by application of this technology?
- How should existing uncertainties concerning opportunities and risks be dealt with?
- To what extent will risks be passed on to the next generation?
- Is an appropriate international legal regime available to control decisions relating to the development and application of geoengineering technology (for example, the prevention of unilateral decisions)? Could all the above-mentioned aspects be the subject of comprehensive consideration by a legal control regime?

FOOTNOTES:

16 This rate „discounts" costs and benefits incurred in different time periods, towards a single point in time and a single value, the present value in most cases. The present value is the amount one would today have to invest at the respective interest rate in order to pay the cost of future damage. For example, one would have to invest 95.24 euros at an interest rate of 5% in order to be able to cover costs of damage one year later amounting to 100 euros.

06

OUTLOOK AND RECOMMENDATIONS

The idea of applying geoengineering technology for climate protection is relatively new, and it is presently attracting considerable attention. A number of states, such as the USA, are already seriously considering geoengineering measures for the purpose of climate protection.

The attraction of geoengineering is obvious: Firstly, little or no behavioural change has to be demanded from society for the reduction of CO_2 emissions. Secondly, a technical solution to the problem is promised. And thirdly, in the case of certain geoengineering measures, protracted international negotiations are avoided; states can effectively take unilateral action. The geoengineering idea was given a strong impetus by unsuccessful efforts towards a new global climate protection convention under the aegis of the United Nations Framework Convention on Climate Change. The climate protection compromise that will ultimately be achieved by the international community of states is still unclear in the run-up to the next Conference of the Parties (COP 17) in Durban, South Africa at the end of 2011. What is certain, however, is that academics, policymakers and society in general will continue to be occupied with the topic of geoengineering.

In the view of the Federal Environment Agency, the possible paradigm shift in climate policy, which could be associated with application of geoengineering technology, is problematical. Three aspects are particularly critical:

The first aspect concerns the assumption that man is actually capable of shaping and controlling environmental processes on a global scale. Human beings have indeed always used and fashioned nature and the environment for their own purposes (for instance, in agriculture and forestry). Geoengineering measures aim, however, at global manipulation of environmental processes, and that, not only in its dimension but also in its complexity, is a completely different matter. Many geoengineering proposals are based on the assumption that man understands the short- and long-term consequences of influencing global environmental processes, and can control them.

Secondly, there is the danger that geoengineering measures will be regarded as a substitution for reduction and adaptation measures. This would represent a basic shift in the direction of climate protection policy, away from the reduction of greenhouse gases and adaptation to climate change towards geoengineering. We view this with concern, for the promotion of geoengineering would weaken the basically sustainable and precautionary climate policy of avoidance and adaptation.

The third critical aspect concerns the fact that fundamental principles of international environment policy as well as various international climate protection treaties (combating of greenhouse gas emissions at source, reduction of pollutant discharges and equal protection of the media air, water and soil) should no longer apply. Some geoengineering proposals threaten to annul all painstakingly-achieved successes of past decades in reducing substance discharges into water, air and soil, and are in conflict with previous environment policy. In marine geoengineering, for instance, substances should in future be deliberately discharged into the marine environment, whereas up to now the minimization of substance discharge has been the declared objective of international endeavours.

Most geoengineering measures are still in their infancy, at the stage of theoretical consideration. As a rule, neither can unambiguous statements on the efficacy and timing of expected application be made, nor can the risks and side effects be soundly assessed. Even with concepts that have been well investigated – such as iron fertilization of oceans – effect mechanisms that form the theoretical basis of such investigations are still insufficiently understood, and substantial risks and side effects have to be expected, whose consequences are neither controllable nor reversible.

There is still a considerable need for clarification concerning the criteria that policymakers should apply in examining geoengineering measures. The Federal Environment Agency has therefore drawn up a catalogue of assessment criteria, which sets out minimum demands (See Chapter 5).

It has finally to be stated that geoengineering measures differ considerably as far as their dimensions of risk, controllability and reversibility are concerned. While with all geoengineering measures effects on the global climate are intended, they differ, above all, with regard to the spatial extent of other effects on humans and the environment. Measures, whose effects on humans and the environment are for the most part spatially limited, are not comparable with measures such as the discharge of sulphur aerosols into the atmosphere, which have a global impact beyond their climatic effect. Global effects are more difficult to control than local effects. Measures that have merely a local effect can also, however, involve considerable risks; for example, due to the particular sensitivity of the region concerned. Geoengineering measures can therefore not be thrown into one pot, but rather require individual, differentiated assessment. Conclusive appraisal of different geoengineering measures has up to now not been possible on the basis of available data.

Against this backdrop, a large number of research projects on geoengineering measures are to be expected. Research will range from modelling to initial field tests and presumably also to experiments on a larger scale. It is essential that besides the risks and side effects of geoengineering, researchers also concern themselves with ethical, moral and social implications. With large-scale experiments the borderline to commercial application can become blurred. Here, regulations are necessary to preclude that commercial interests influence the direction and conduct of such experiments.

Having examined the current status of research, the Federal Environment Agency comes to the following conclusions and recommendations on climate-related geoengineering.

- Geoengineering measures are for the foreseeable future no alternative to emission reduction and adaptation to climate change. Climate protection must primarily tackle the cause of the problem, namely the emission of greenhouse gases, and reduce it. At the same time, the human race must adapt to the no longer avertable consequences of climate change. The decisive advantage of reduction and adaptation measures, compared to geoengineering, is that not only are climatic effects combated but also other effects of CO_2 emissions, such as acidification of the oceans. Moreover, climate protection often has further benefits; for example, fossil resources are conserved and air loaded with fewer pollutants. Geoenginnering, on the other hand, and in particular measures for solar radiation management, do not reduce the adverse effects of greenhouse gas emission. Conclusion: The emphases of climate research, including state promotion, may not be shifted to research into geoengineering measures.

- Industrial countries bear a particular responsibility with regard to climate change. Measures must therefore satisfy the demand that developing countries should not again have to bear heavy burdens. Geoengineering measures do not meet this demand, since they result, in part, in specific risks for developing countries. Measures for solar radiation management, for example, can lead to temperature changes in developing countries that give rise to droughts and endanger food security.

- The investigation, development and testing of theoretical considerations concerning geoengineering will generally extend over long periods of time. Early deployment of the technology is therefore not in sight. Progressing global warming requires, however, rapid action. Climate protection strategies with corresponding reduction targets for greenhouse gases already exist that, firstly have positive effects, for industry for example, and secondly have no serious side effects for humans and the environment.

- Geoengineering measures should be envisaged at most as an emergency option, in order to be prepared for a situation in which, despite substantial efforts in the area of reduction and adaptation, climate change accelerates and additional measures become necessary. Research into certain promising geoengineering measures could be useful in such an emergency.

- A fundamental disadvantage of geoengineering measures, compared to emission reduction measures, is that economic incentives cannot be set for producers of climate gas emissions. With appropriately-designed incentives, emitters themselves – industry, energy sector, agriculture and consumers – have a vested interest in reducing greenhouse gas emissions, since they reduce costs by saving energy. They therefore have an interest in cutting costs at all levels through innovation. Geoengineering measures – whether research projects or actual application – on the other hand, are generally financed by the state, and this over a number of years. This amounts to taxpayer-financed treatment of symptoms, for which market mechanisms cannot be applied.

- In the basic assessment of individual, climate-related geoengineering concepts the following aspects should be considered:
  - Potentials for climate protection or reduction of global warming
  - Development status of the respective technology
  - Costs and benefits
  - Risks, above all for humans and the environment, conflicting uses and potential synergies with climate and other environment policy objectives
  - Societal acceptance and legal control regime

- The authorization and realization of geoengineering measures has to be tied to evidence that the measure is at least effective; that is, a positive contribution to climate protection will be made. In this connection, a comprehensive energy balance has to be drawn up, which covers the energy-related cost of preparation and realization of the measure as well as possibly necessary withdrawal. It has also to be proven that considerable adverse effects on humans and the environment are ruled out. In accordance with the principle of precaution, adverse effects have also to be avoided when risks, as a result of uncertain knowledge, cannot be conclusively assessed. Finally, in decisions on specific geoengineering measures possible highly-varied regional effects have to be taken into account.

- In the case of geoengineering measures for solar radiation management there is a further relevant risk. Such measures do not reduce the concentration of greenhouse gases in the atmosphere. CO_2 concentration in the atmosphere would therefore further increase. If, however, as a result of application of these measures, grave effects such as droughts or degradation of stratospheric ozone occur, these measures would nevertheless have to be pursued; otherwise, due to high greenhouse gas concentrations in the atmosphere, the consequence would be accelerated global warming. Depending on the level of CO_2 concentrations, catastrophic effects could occur. For geoengineering measures for solar radiation management the maxim is: withdrawal implies acceptance of continued global warming at an increased rate, with all its consequences for humans and the environment.

- Even the investigation and testing of geoengineering measures must be subject to state control, since geoengineering measures involve substantial risks. In some cases, irreversible environmental change or damage is to be feared, and the risks are hardly controllable. The risks of research activities have to be determined and assessed at a preliminary stage. The prerequisite for authorization of research or testing is that considerable risks for humans and the environment are ruled out. As a rule, accompanying research on potential risks should be obligatory.

- Statutory provisions at an international level presently control the research, testing and execution of geoengineering measures to only an inadequate extent. This results from the fact that the idea of geoengineering was unknown at the time when standards were laid down. The development of an appropriate statutory framework is therefore required. It should be examined whether specific regulations should be developed within the scope of a new regime created for this purpose, or under the aegis of the UN Framework Convention on Climate Change. In order to curtail the cost and complexity of the issues, it appears to be expedient to strive for solutions within the scope of specific environmental agreements.

- In any event, new regulations have to ensure that before realization of geoengineering measures states that might be affected are informed and consulted. Unagreed unilateral measures should be prohibited by international standards.

07

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