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Reverse emissions or influence solar radiation:

Is “geoengineering” worthwhile, feasible and if so, at what price?

The aim of the Paris Agreement is to limit global warming to well below 2 degrees Celsius, if possible even 1.5 degrees Celsius. Various scenarios show that very great efforts are necessary to achieve these goals through emission reduction measures alone. This motivates the search for additional solutions. Technical interventions in the climate system, often referred to by collective terms such as “geoengineering” or “climate intervention”, are therefore discussed. However, most of these measures are associated with costs, risks and undesirable side effects that have so far been very difficult to assess. While some measures only exist in theory, others have been tested in small format, but nevertheless there is a lack of knowledge about the effects of an application on the required large scale. Since the measures would not have the same effects in different parts of the world, ethical questions of global and regional justice are also particularly important and should be covered by international regulations.

Introduction

With the Paris Agreement, the international community has set itself the goal of limiting global warming to less than 2 degrees Celsius, if possible even to 1.5 degrees Celsius, compared to pre-industrial times. The currently declared national emission reduction targets still disagree with this intent. Provided they are really achieved, this would lead to global warming in the range of 2 to 4 degrees Celsius, which is far from sufficient. Even the latest economic and political developments do not suggest that efforts to reduce emissions will be sufficient to achieve the intended limitation targets with reduction measures alone.

This is also reflected in virtually all available scenarios for meeting the 1.5 degree target used by the scientific community – and also in many scenarios for meeting the 2 degree target – which contain “negative” CO_2 emissions, i.e. measures to remove CO_2 from the atmosphere. Some scenarios also include technical activities to influence solar radiation. Table 1 shows the importance of CO_2 removal in the scenarios reviewed by the IPCC and in the scientific literature. These figures show that with current annual emissions the existing emission budget for meeting the 1.5 degree target would be exhausted in four to a maximum of twenty years.

Technical measures to remove CO_2 from the atmosphere that has already been emitted or to at least dampen warming can therefore no longer be excluded from the discussions on limiting climate change. This should also be seen in the light of the fact that some of these technical “corrective measures” may be cheaper to implement than certain emission reduction measures.

Two different approaches

In the case of measures that are sometimes summarized under the terms "geoengineering" or "climate intervention", two fundamentally different approaches must be distinguished and therefore need to be considered separately.

The **removal of CO_2 from the atmosphere** (the most common technical terms for this are "carbon dioxide removal", **CDR** or "negative emission technologies") is an attempt to reverse some of the man-made CO_2 emissions and slow down the increase in CO_2 concentration. This will address the main cause of climate change. Examples of CDR are the energetic use of biomass in combination with capture and geological storage of the resulting CO_2 ("BioEnergy with Carbon Capture and Storage", BECCS); the technical capture of CO_2 from the atmosphere followed by geological storage ("Direct Air Capture and Storage", DACS); the fixation of CO_2 from the atmosphere in forests through large-scale afforestation; the storage of additional carbon in the soil through appropriate soil management or biochar; the fertilisation of oceans to enhance algae growth with associated CO_2 fixation; or the artificial acceleration of rock weathering, whereby carbon is incorporated into the material. It should be noted that, due to the inertia of the climate system, CDRs only have a delayed effect, i.e. the effects become apparent after a few years to decades at the earliest.

What is the difference between CDR and "normal" emission reduction measures under current climate policy? In both cases it is a matter of influencing the CO_2 concentration in the atmosphere. The aim of emission reduction measures is to prevent CO_2 from entering the atmosphere in the first place, while with CDR CO_2 that already has been emitted is removed from the atmosphere. For this reason, CO_2 capture at source, e.g. in power plants, and subsequent underground storage ("Carbon Capture and Storage", CCS) is usually included in emission reduction measures, but not in CDR.

Table 1: Estimates of the role Carbon Dioxide Removal (CDR) in achieving the objectives of the Paris Agreement (Source: EASAC 2018)

	Gt CO_2
Range of the estimated remaining total amount of CO_2 emissions in order to achieve the Paris target of 1.5 °C	130 to 700
Current global CO_2 emissions per year	36
Post-2050 annual removal of CO_2 assumed in IPCC models by applying CDR	−12
Range of assumptions for annual CO_2 removal in other literature	−7 to −70

Solar Radiation Management (SRM), on the other hand, tries to address one symptom of climate change, namely warming. This is done by artificially increasing the reflection of solar radiation in the atmosphere or at the earth's surface, thereby counteracting the warming of the earth's surface[1]. This can be achieved, for example, by introducing aerosols into higher atmospheric layers. Furthermore, the artificial brightening of clouds by the addition of condensation nuclei or of ground surfaces by changing the ground cover or even the placement of "parasols" or "mirrors" in space is being considered. SRM measures could, for example, be used to save time for emission reductions or to prevent a temporary "overshooting" of temperature targets until the increase in CO_2 concentration in the atmosphere can be sufficiently slowed down. SRM measures could also appear attractive because they work much faster than CDRs and could therefore provide short-term relief in the event of progressive global warming and related drastic impacts. It should be noted, however, that this does not address the rising greenhouse gas concentrations that cause climate change, nor does it address the non-temperature-related consequences of climate change, such as ocean acidification.

Figure 1 and Table 2 summarize the two types of measures and their main characteristics. They are also compared with emission reduction measures of current climate policy. Tables 3 (CDR) and 4 (SRM) provide an in-depth overview of the various measures and their characteristics; the data are an integration of various studies and assessment reports (see literature references).

State of the art

With regard to SRM and many CDR measures, technical knowledge regarding feasibility is often (still) lacking, especially in such large dimensions that a measurable effect could be achieved. In the field of CDR, afforestation has long been practised and the challenges are well known. The biggest problems here are space requirements, which compete with other uses, and governance, which must be negotiated locally. Direct CO_2 capture from the air (DACS) is (energy) expensive because the highly diluted CO_2 in the air has to be separated and then pressed into suitable and safe geological repositories. There are only a few pilot plants for DACS and a commercial plant for bioenergy production with CO_2 separation (BECCS). In addition to the development of technologies, the availability of low-CO_2 energy or sustainably produced biomass, the reliability of geological storage and high installation and operating costs are potential obstacles. Other technologies such as enhanced weathering or ocean fertilisation have only been tested on a small scale, if at all, and their effectiveness and possible side effects are still very uncertain.

Even further away from an application are all the approaches described in connection with SRM. Although the injection of aerosols into the atmosphere already seems possible with today's technical means, test experiments have so far only

1 In the case of the thinning out of high ice-water clouds (so-called cirrus clouds; see Table 4), which is also attributed to this type, it is not a matter of reflection of solar radiation, but of change in heat radiation.

been announced, but not yet carried out. Possible side effects are largely unexplored, such as the danger of a change in the regional precipitation patterns. Indications of possible side effects of SRM can be seen in connection with larger volcanic eruptions such as Pinatubo 1992 or Tambora 1815, which, at least on the time scale of a few years, triggered significant changes in precipitation patterns with sometimes serious regional effects.

High risks and unknown side effects

The high risks, which are often difficult to assess, and the many possible undesirable side effects are a major obstacle to the use of CDR and even more so of SRM. Climate model calculations are often not meaningful enough for important topics such as regional precipitation distributions or ecosystem effects. The effects of small test projects cannot simply be transferred to corresponding large scale application.

In the case of CDR, the risks lie primarily in the possible local or regional side effects of the measures, e. g. the effects of changes in vegetation or land and water consumption (for further effects, see Table 2). The risks and possible side effects of SRM are even greater. SRM does not mitigate the entire man-made influence on the climate, but rather creates a new human intervention that, for example, leads to new and hardly predictable changes in precipitation patterns. A further important problem with SRM is that, once it has been started, the measures must be continued infinitely or at least until greenhouse gas concentrations have fallen back to the level prior to the use of SRM, e. g. as a result of CDR or natural degradation. If SRM was to be stopped abruptly, the climate would very quickly transform into the much warmer state it would have reached without SRM due to the higher atmospheric CO_2 concentration. It would therefore be difficult to adapt to such a rapid warming.

The crux with energy use

A fundamental problem with most CDR measures is the consumption of resources: in addition to land area, water and fertiliser (in the case of biomass-based measures), almost all CDR approaches often consume considerable amounts of energy, particularly for technical CO_2 removal from the air, CO_2 capture in bioenergy plants and crushing of rock for enhanced weathering, but also for afforestation, fertiliser production or the acquisition and processing of biological material. If the required energy is not obtained with low CO_2 emissions, the effect of the respective measure is drastically reduced in some cases, since part of the removed CO_2 is replaced by the operation of the CDR measure. As long as most of the world's energy is still obtained from fossil sources, it is usually more efficient to use low-CO_2 energy primarily for the substitution of fossil energy sources and not for CDR.

Governance challenges and ethical problems

How should the application of CDR and SRM be regulated internationally? Not all countries can benefit from a "more favourable" climate achieved by reducing global temperature through SRM. Who determines the "right" temperature that should not be exceeded? How to compensate countries that are affected by the negative side effects of a measure, such as unfavourable changes in precipitation? Who pays for the measures? How and by whom is the required technology made available to poor countries? Where and how should CO_2 extracted from the atmosphere be stored in the long term and under what conditions are these storage facilities acceptable to the population? Climate negotiations to date and national emission reduction plans demonstrate how difficult it is to find global solutions to such questions. The large-scale application of technical CO_2 extraction would entail costs at an unprecedented scale for global distribution issues. The governance of CDR and SRM therefore poses challenges to the international community, similar to those posed by mitigation measures.

In addition to governance issues, ethical and justice issues also arise. In the case of biological CDR, such as afforestation or BECCS, competition with food production can become a central ethical and justice problem.

Measures with CO_2 capture – from the atmosphere or at the power plant – compete with each other in terms of available storage volumes. This competition also leads to ethical and legal challenges.

In the case of SRM, also generational question arises: future generations must continuously maintain the "symptom control" by reducing solar radiation, otherwise a much faster rise in temperature compared with the current warming threatens to create major adaptation problems for society and ecosystems. Such a "burden" for future generations would have to be taken into account when assessing SRM net benefits. In addition, the geographically uneven distribution of risks in the application of CDR and SRM is an ethical problem that should not be underestimated, with far-reaching implications for equity.

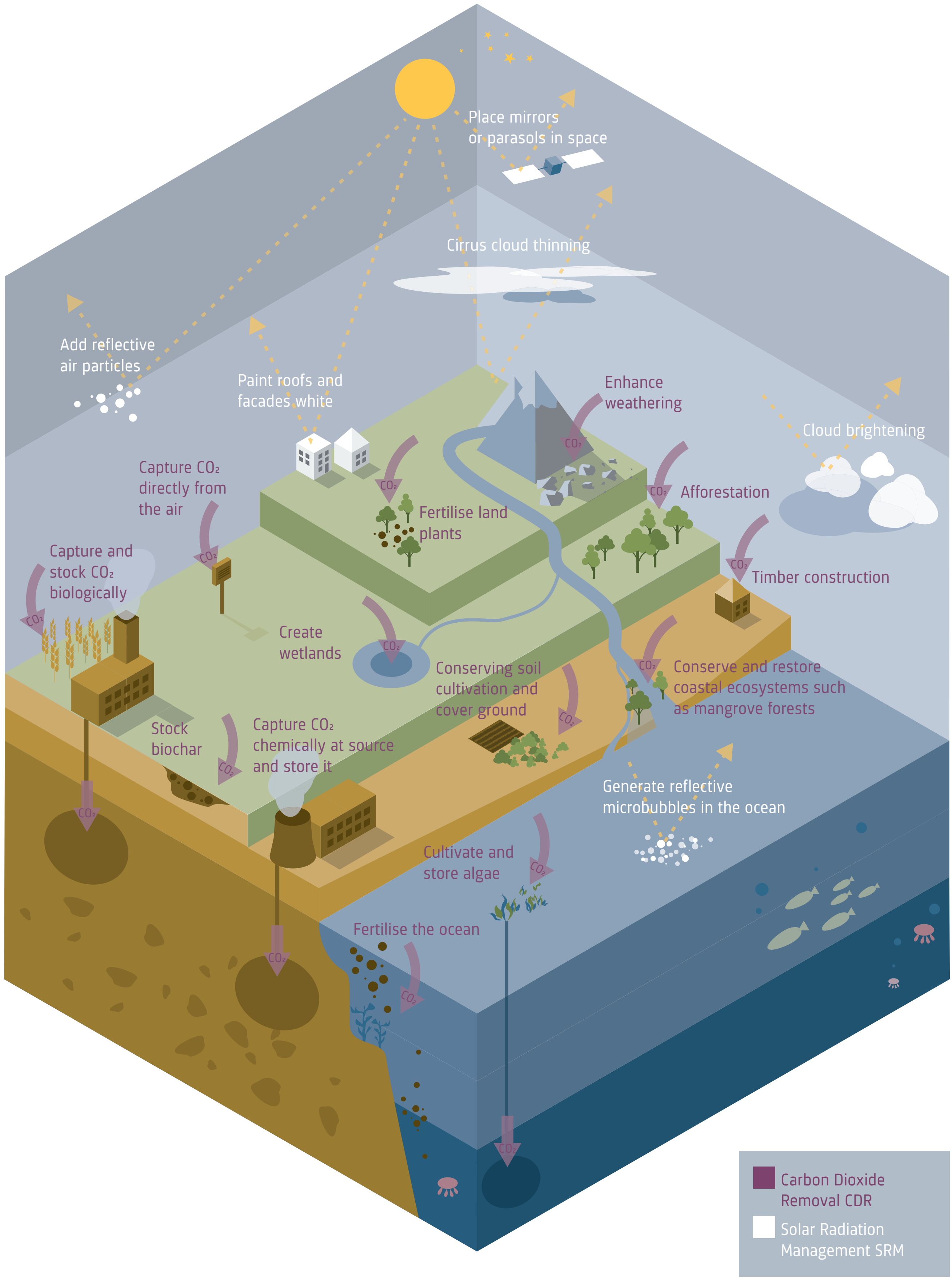
Do we need more research?

Fears are widespread that more attention to CDR and SRM may lead to neglect of adaptation and emission reduction efforts or encourage large-scale testing for CDR or SRM without sufficient knowledge or consideration of the risks involved. They are cited as arguments against research concerning such measures. Nevertheless, there will be no getting around the discussion of CDR/SRM in the future. This will be discussed and dealt with at the international level. More research on CDR and SRM is therefore indispensable so that the corresponding costs, risks and side effects are known in the case of specific application projects. However, this should not only involve research in the technical sense, i. e. research that investigates the ecological and climate-related effects and other side effects of CDR and SRM. It is also important that such research is accompanied by political, social and ethical reflection on the social, societal and legal risks of such measures at national and international level. It should also be kept in mind that current developments in international climate policy raise the question of whether the risks and consequences of global warming of 3, 4 or 5 degrees Celsius could not be greater than the risks of, for example, CDR measures.

Table 2: Characteristics of different types of measures

	Mitigation	Carbon Dioxide Removal (CDR)	Solar Radiation Management (SRM)
Counteracting causes and symptoms	Reduces the emission of CO_2 (directly addresses the cause of climate change)	Reduces the CO_2 concentration in the atmosphere (addresses the cause of climate change)	Enhances the reflection of solar radiation (addresses only the warming as a symptom of climate change)
Effect	Reduces the increase of the greenhouse effect	Reduces the increase of the greenhouse effect	Has a quasi-instant cooling effect
Risks	Avoids new global climate risks	Avoids new global climate risks. Can cause positive or negative changes in regional climates	Possibly causes new and additional global climate risks
Costs	Large range of costs	Large range of costs, but mostly significantly more expensive than emission reduction	Large range of costs, but generally cheaper than CDR
Obstacles	Cost issues are important, often there are co-benefits	High costs as main obstacle, co-benefits are possible	Risk and feasibility are main issues
Governance	Often feasible locally. Global governance issues relating to commitments and financing	Primarily local governance issues, possibly global commitment and financing issues	Difficult global governance issues concerning responsibility, financing and liability
Cooperation	Noticeable effect only with far-reaching international cooperation	Noticeable effect only with far-reaching international cooperation	Could possibly also be carried out unilaterally, but this would be conflictual
Lasting effect	Measures have a lasting effect if they are not reversed	Measures have a lasting effect if they are not reversed	Most measures must be constantly renewed, otherwise climate will "jump" into the state that had occurred without these measures, with serious consequences
Main problems	Political feasibility and acceptance as main problems	High investment and space required, saturation and competition to other uses as main problems	Governance, equity issues and high risks as major problems
Ressource consumption	Resource consumption through measures is low	Often high demand for low-CO_2 energy, often high demand for land, water or geological storage volume	Energy and resource consumption is rather low

Figure 1: Overview of the various methods of Carbon Dioxide Removal (CDR) and Solar Radiation Management (SRM).



Conclusion

It should be noted that CDR and SRM cannot be a substitute for efforts to reduce emissions as quickly and sustainably as possible. The latter are still in the foreground. Both CDR and, even more so, SRM can only serve as additional measures that supplement efforts to reduce emissions to achieve socially desirable goals.

Due to the major risks and uncertainties as well as global ethical and governance issues, the use of SRM beyond local applications seems irresponsible for combating global climate change for the moment. The use of CDR on a small scale seems rather possible. The large-scale use of certain CDR included in most model scenarios to achieve the objectives of the Paris Agreement, on the other hand, is hardly feasible or desirable given the very limited state of knowledge and the many unanswered questions. A scientific basis on how to use CDR, its effectiveness, risks and costs is necessary, even if it would be for a robust justification as to why certain options should not be used.

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SDGs: The International Sustainable Development Goals of the UN

In this publication, the Swiss Academies of Arts and Sciences provide information on measures that remove CO_2 from the atmosphere or attempt to limit the warming of the climate system through technical measures to reduce solar radiation (known as "Geoengineering") and the associated risks. It thus makes a contribution to the SDG 13: **"Take urgent action to combat climate change and its impacts".**

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Table 3: Characteristics of Carbon Dioxide Removal measures (CDR).

CDR Approach	Method / measure (C = Carbon)	Process / Stability (C = Carbon)	Timescale Storage (years)	Theoret. Potential[1]	Positive or negative side effects and risks	Cost per tonnes of CO_2	Technical development status	Issues of ethics and equity; governance
Biological capture and storage in biomass	**Afforestation / Reforestation, improved Land Management**	CO_2 absorption by increasing biomass production; reversible (through forest fire, parasites, deforestation), requires permanent management	~ 50–500	0,5–10	Possible increase in soil quality and water retention capacity; local warming (esp. in high latitudes) or cooling (dry locations); impacts on water cycle and biodiversity; probably higher N_2O emissions through fertilisation; competition with food production	1–100 $; 0,1 ha land	Technologies are known and used (also on a larger scale)	Possible competition with food production; compensations
	Storage of biochar in the soil	C storage by storing biochar in soil; stable for decades to centuries; limited by soil uptake capacity	~ 50–500	0,5–5	Reduces N_2O and methane emissions; reduces fertiliser and possibly water requirements; increases soil fertility and agricultural production; possibly more heat absorption through darker soils; worse CO_2 balance than biomass for energy production	10–135 $; 0,02–0,1 ha land	Production capacity is very limited	
	C storage in the soil (e.g. conserving soil cultivation; intercrops)	Increased C content in soil through favourable cultivation methods; reversible; limited by soil uptake capacity	~ 50–500	1,5–10	Increases soil fertility and agricultural production; improves water and air quality; change of local energy balance and evaporation at the earth's surface, needs fertiliser	0–80 $	Widely known techniques	
	C storage in timber construction	C storage in pools with long residence cycles; reversible	~ 50–500	?		?	Timber is known as a construction material	
	Fertilisation of land plants	CO_2 absorption by increasing biomass production; reversible	~ 50–500	?	Change of local energy balance and evaporation; probably higher N_2O and CO_2 emissions (fertiliser production)	?	Widely known techniques	
	Creation of wetlands	Storage of CO_2 in carbon pools with long residence cycles	~ 500–5000	?	Requires little space for much carbon storage; changes local energy balance and evaporation; probably higher methane emissions	?	known technologies (water logging)	Compensations
	Management of coastal ecosystems ("blue carbon")	Increase of CO_2 content in coastal ecosystems (esp. mangrove forests) by favourable management	~ 50–500	0,15–0,3		?	Not tested	
Chemical or biological capture with permanent geological storage	**Bioenergy carbon capture and storage (BECCS)**	Energy production from biomass (if possible from waste) and capture of the resulting CO_2 with subsequent storage; high stability in adequate reservoirs; limited by available biomass	permanent resp. > 10000	0,5–5	Business opportunities; economic diversification; energy independence; changing local warming and evaporation; biodiversity and food production decrease when growing energy crops on agricultural land; air pollution during combustion; N_2O emissions increase; high energy consumption	50–250 $; 0,03–0,1 ha + 60 m^3 water for energy plants	1 demonstration plant worldwide; large-scale feasibility is uncertain	Possible competition with food production; compensations; long-term reservoir management
	Direct air capture and sequestration (DACS)	Chemical capture of CO_2 from the air and geological storage; high stability in adequate reservoirs	permanent resp. > 10000	0,5–10	Business opportunities; high costs and energy consumption (possibly low CO_2 effect depending on energy source) and water consumption	40–1000 $; 3500 kWh; 1–25 m^3 water	Prototypes are being tested; technically not well-developed	Long-term reservoir management
Enhanced CO_2 absorption in the ocean	**Ocean fertilisation with iron, phosphate and nitrogen**	Increase in plankton growth, increased sinking and deposition of plankton on the ocean floor; uncertain stability, variable saturation of ocean waters	~ 500–5000	1–4	Possibly increased fishing; increased production of biomass; increased production of non-CO_2 greenhouse gases; possible disturbance of marine ecosystems and decline in biomass production in downstream areas; acidification/oxygen deficiency in the deep ocean; possibly toxic algae; possibly negative regional side effects for oceanic food.	50–500 $	Some small-scale experiments; no consensus on long-term effects	International supervision, responsibility; existing agreements[2]
	Ocean fertilisation by artificial buoyancy of deep water	Increase in plankton growth, increased sinking and deposition of plankton on the ocean floor; uncertain stability, variable saturation of ocean waters	~ 500–5000	?	Probably change of the regional carbon cycle which counteracts the CO_2 storage; compensating decline in other regions; possibly negative regional side effects for oceanic food	?	Not tested	International supervision, responsibility; existing agreements[2]
	Algae cultivation and storage	Increase of biomass production and storage	~ 500–5000	?	?	?	Not tested	International supervision, responsibility
Enhanced weathering	**Addition of silicates to soils or oceans**	Enhancement of the weathering of silicate and carbonate rocks (binds CO_2) by rock crushing and distribution on the ground or in the ocean; stable	~ 500–5000 for carbonates, permanent for silicates	0,5–4	Decrease in acidity of soils and rivers or in the ocean; impacts on terrestrial, freshwater and marine ecosystems; release of heavy metals and plant nutrients in the soil; high energy input for provision; possibly negative regional side effects	20– > 1000 $	Not tested	

[1] Theoretical technical potential in gigatonnes (= 1'000'000'000 tonnes) of CO_2 per year. Social and economic aspects (such as acceptance, ethics or governance) are not taken into account.

[2] Is affected by the London Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter; Iron fertilisation is affected by the Convention on Biological Diversity (only permitted if there is a sufficient scientific basis).

Table 4: Characteristics of Solar Radiation Mamagement measures (SRM).

SRM Method / measure	Process	Timescale of impact	Investment	Side-effects / risks	Cost per tonne of CO_2	State of the art	Issues of ethics and equity	Governance problems
Space mirrors	Reflection of solar radiation by mirrors or parasols in space, resulting in a reduction of solar radiation	Lifetime of the installations	No knowledge	Attenuation of the global hydrological cycle with regionally varying impacts; possible increase in carbon capture by land and ocean	High	Not tested; unlikely to be available in this century	No exit option; unequal regional (side) effects; transferring risks to future generations	Supervision, responsibility
Injection of aerosols in the stratosphere	Injection of air particles into a higher atmospheric layer (15–20 km altitude), thereby reducing solar radiation (similar effect to volcanoes); the effect depends on the type and size of the particles; there is saturation – not every cooling amount is possible	Has a very rapid effect (< 10 years), but must be constantly renewed (if stopped: will after a few years result in the same climatic conditions as if without measure)	2–8 million t sulphur per year for a global cooling of 1 °C	Depletion of the ozone layer in polar regions (resp. delay in the recovery of the ozone layer by 30-70 years); increase in photosynthesis activity; change in global precipitation patterns; regional increase in ocean acidification; implies a further anthropogenic component in the climate system with unknown consequences; rapid temperature rise to the level without SRM if the measure is stopped, with numerous adaptation problems	1–10 billion $ for a 1–2 W/m² cooling (depending on selected discount rate, application dynamics or side effect risks)	Not tested, but technologies exist in principle; volcanic eruptions can be used as analogues to some extent; large-scale experiments over years to decades would be necessary to estimate side effects	Multinational issues; no exit option; regionally unequal (side) effects; transferring risks to future generations; impacts of unilateral measures; Moral of taking over control over the global temperature	Supervision (Who supervises? Who defines the target temperature?); Responsibility (Who is responsible for use, costs, compensation?); International Conventions (e.g. Montreal Protocol)
Marine cloud brightening	Insertion of sea salt in clouds above the sea (especially in tropics and subtropics). The consequences are more and smaller water droplets, brighter clouds and stronger reflection of sunlight; saturation effect (brightness of clouds is limited)	Has a very rapid effect (< 10 years), but must be constantly renewed (if stopped: will after a few years result in the same climatic conditions as if without measure)	100–300 million t dry sea salt per year for a global cooling of 1 °C	Regional differences in effects; change of local energy balance and evaporation as well as possibly oceanic and atmospheric fluxes; implies another anthropogenic component in the climate system with unknown consequences	1–10 billion $ for a 1–2 W/m² cooling	Not tested; some findings from observations of ship routes; the effect of the measure is controversial, as only very few ships achieve the desired effect	No exit option; unequal regional (side) effects; transferring risks to future generations	Supervision, responsibility
Surface albedo alteration (in towns, deserts, agriculture)	Higher reflection of solar radiation through brighter surfaces; possible in towns, on grass and agricultural areas or in the ocean (e.g. through more microbubbles)	As long as the measure is maintained	Insignificant on a global scale, it mainly has a regional impact	Cooling mainly in the region of the measure; possibly influence on precipitation in monsoon regions	Not yet estimated	Not tested; model simulations confirm the mechanism	No exit option; unequal regional (side) effects; transferring risks to future generations	Supervision, responsibility
Enhancement of outgoing long-wave radiation	Thinning of high cirrus clouds by injection of ice cores and thus weakening of their greenhouse effect. The effect is controversial.	As long as the measure is maintained	Unknown	Changes in precipitation regimes; depletion of the ozone layer (more UV radiation)	Unknown	So far only in theory	No exit option; unequal regional (side) effects; transferring risks to future generations	Supervision, responsibility