

Climate engineering and our climate targets – a long-overdue debate

CLIMATE ENGINEERING IDEAS

Radiation management (RM)

Stratospheric aerosol injection

Cloud seeding

Afforestation

Biochar

Coastal carbon enhancement

Enhanced weathering

Direct air capture

BECCS

Enhanced weathering

Iron fertilisation

CO₂ storage

Artificial upwelling

Direct injection

Carbon dioxide removal (CDR)



Risks, Challenges,
Opportunities?

Climate engineering and our climate targets – a long-overdue debate

Priority Programme 1689 of the
German Research Foundation (DFG)

DFG

ABBREVIATIONS

BECCS – Bioenergy with carbon capture and storage

CCS – Carbon capture and storage

CDR – Carbon dioxide removal

CE – Climate engineering

CO₂ – Carbon dioxide

IPCC – Intergovernmental Panel on Climate Change

NET – Negative emission technologies

RM – Radiation management

SDGs – United Nations Sustainable Development Goals

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“The purest form of madness is to leave everything as it is
and still hope that something will change.”
Albert Einstein

PREFACE

The Paris Climate Agreement of autumn 2015 was a major diplomatic breakthrough, with the Parties agreeing to significantly reduce their greenhouse gas emissions. Despite those commitments, however, the Agreement has yet to deliver noticeable results. In fact, the opposite has occurred. In 2018, global carbon dioxide emissions reached a new record high. This means that the emissions budget still available for Parties to achieve their climate targets is rapidly dwindling – and with it, the amount of time left to act.

Both awareness to, and perceptions of, climate change as a global social challenge have grown considerably in recent months, partly thanks to the Fridays for Future campaign. We have reached a point where action must be taken across the board and all available options explored. A number of those options are grouped under the term ‘climate engineering’.

Climate engineering (CE) refers to deliberate large-scale intervention in the climate system, that – alongside emission avoidance – aims at curbing human-caused climate change. The range of proposed CE methods and their potential effects – positive or negative – is broad. On the one hand, CE includes ideas for intervening in the Earth’s carbon cycle in order to remove carbon dioxide from the atmosphere and store it on land or in the ocean. On the other hand, the term also covers proposed ways of directly influencing the Earth’s radiation budget – such as by deflecting part of the solar radiation that hits the Earth’s surface so as to reduce warming. Proponents believe that even if further increases in carbon dioxide concentrations in the atmosphere are not stopped quickly enough, intervening in the radiation budget in this way might help to avoid most dangerous climate change after all.

Back in 2013, a group of concerned scientists launched the Priority Programme 1689, “Climate Engineering: Risks, Challenges, Opportunities?”, as a climate responsibility initiative funded for a period of six years by the German Research Foundation (DFG). Since that time, it has become increasingly clear that limiting global warming to well below 2 °C is unlikely to be achieved simply by reducing emissions. Already in its 5th Assessment Report published in 2013, the Intergovernmental Panel on Climate Change (IPCC) projected that limiting global warming to below 2 °C would for almost

all scenarios require vast quantities of carbon to be removed from the atmosphere. In its subsequent Special Report on Global Warming of 1.5 °C, the IPCC stated in 2018 that this was now the case for all scenarios that could still limit warming to 1.5 °C.

In the past, the debate on carbon dioxide removal has often been conducted alongside the debate on radiation management under the generic term ‘climate engineering’. However, the entirely different risk profile of the two approaches has frequently exposed the debate to ideological influence, making it difficult to argue based on facts. There is thus much to be said in favour of rethinking our use of ‘climate engineering’ (or geoengineering) as an academic catch-all term. Given the urgent need for action, a nuanced, targeted debate is required if we are to assess and politically steer the methods involved. Although this publication has the term climate engineering in its title, it would appear more appropriate and helpful to use more specific terms for the various measures involved – in order both to focus the debate itself and to speed up climate decision-making.

This publication was produced in 2019 as part of the public outreach work under the DFG Priority Programme, with only minor changes made for the English-language edition compared with the German edition. Its aim is to promote open social and political debate that is informed by the best available knowledge about the possibilities and risks of the various climate engineering ideas. It also makes it very clear that climate engineering cannot circumvent the need for timely and dramatic reductions in carbon dioxide emissions.

Rather than addressing the scientific community alone, this publication is designed to contribute to a transparent debate on strategies for achieving the climate targets that have been agreed upon and pledged. It is hoped that it will help inform judicious policy decisions to ensure that the impacts of human intervention in the climate system are kept within a realm that is socially and environmentally responsible and acceptable.

Andreas Oschlies

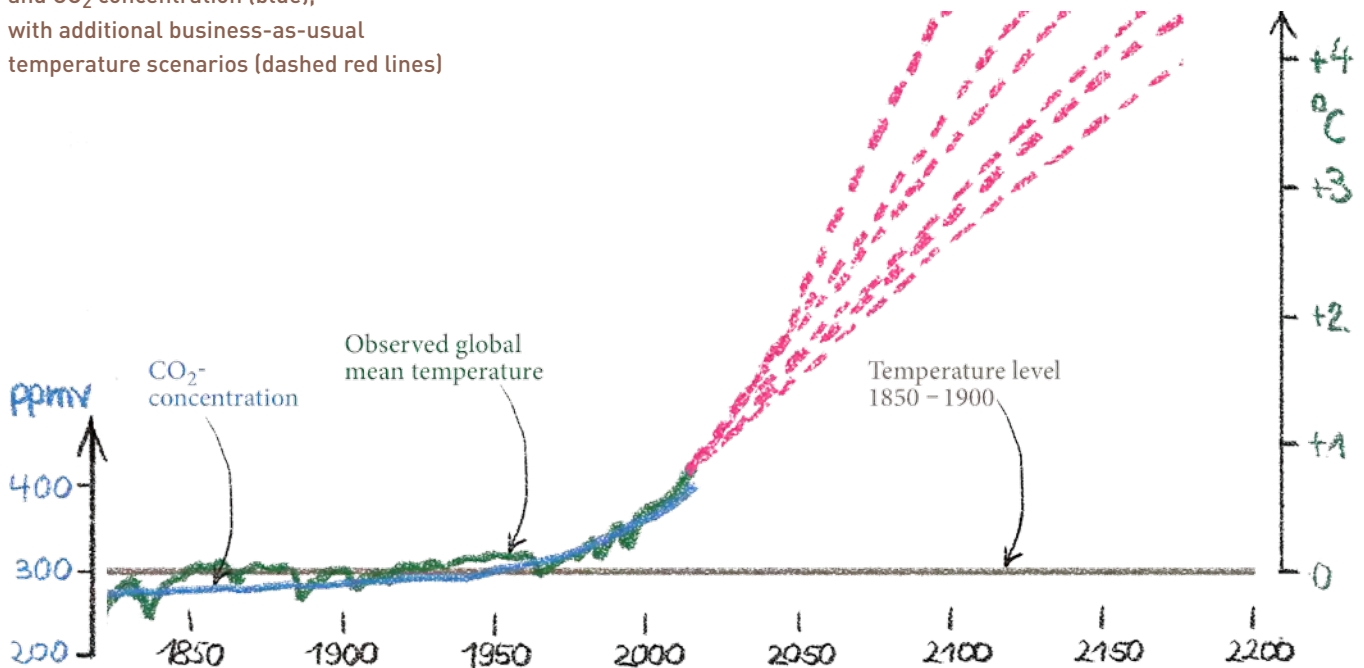
*Coordinator of the Priority Programme (SPP 1689)
on the Assessment of Climate Engineering*



Transport, electricity, food: Carbon dioxide is in everything that makes modern life easier. But the greenhouse gas is something we can neither see nor smell nor taste. Unnoticed by large parts of the population, it accumulates in the atmosphere and is heating up the Earth.



Change in temperature (green)
and CO₂ concentration (blue),
with additional business-as-usual
temperature scenarios (dashed red lines)



FACTS:

CARBON DIOXIDE – THE EXHAUST GAS THAT CHANGED THE WORLD

Humankind has released more than 2,200 billion tonnes of carbon dioxide (CO₂) into the atmosphere since the start of the industrial age some 270 years ago. That figure does little to raise people's awareness to the problems involved. The greenhouse gas can't be seen, tasted or smelled. That is why most people find the topic easy to ignore. Whether indoors at work or out in the open, no one notices how atmospheric CO₂ concentrations increase.

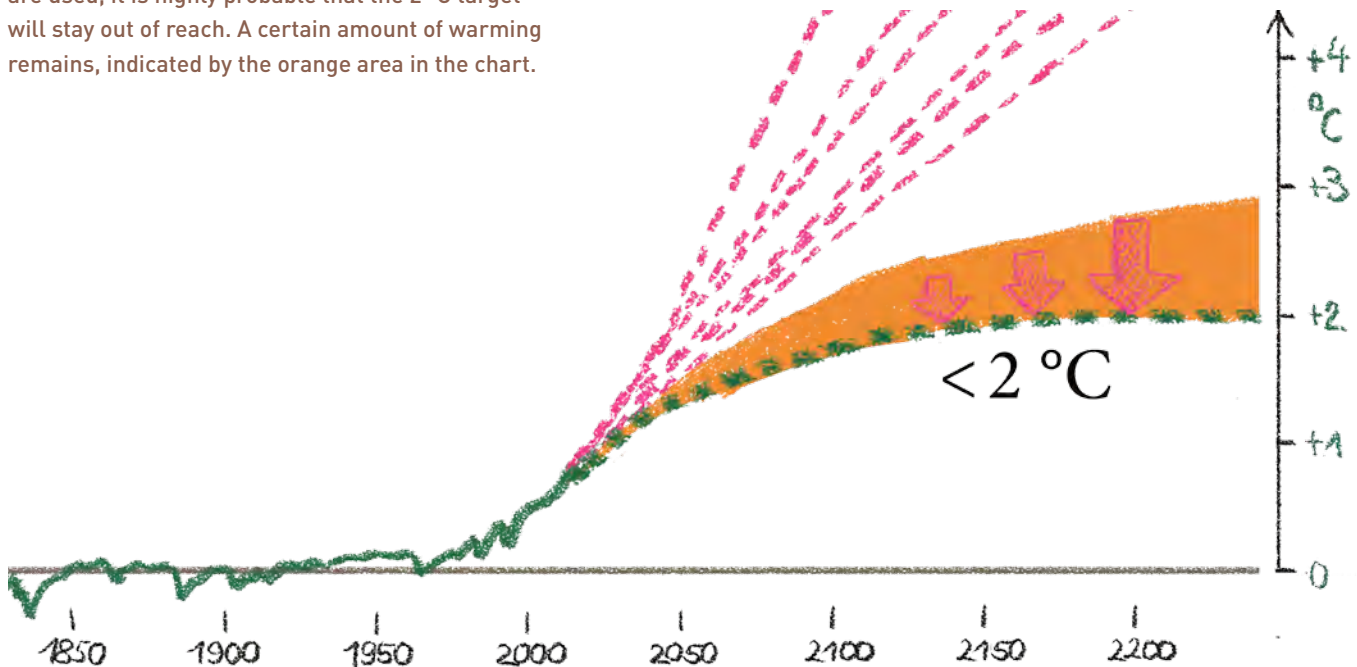
Even so, the impacts of ongoing CO₂ emissions are becoming increasingly evident. The gas accumulates in the atmosphere and slows down the Earth's cooling mechanisms. The Earth's surface can no longer as easily as it once could, radiate infrared energy back into space. Instead, the heat becomes captured in

the Earth system. The global mean surface temperature has consequently risen by 1 °C over the past 100 years. In Germany, warming was even stronger: In the period 1881 to 2014, annual average temperatures rose by 1.3 °C. Climate change has had visible impacts on Germany's North Sea and Baltic Sea coasts. In the past century, sea levels in both these areas have risen by between 10 and 20 centimetres because glaciers and ice sheets are melting, and the increasingly warmer waters expand.

Challenge on a global scale

The picture is similar all over the world. In Alaska, people on islands and in coastal villages like Shishmaref and Newtok plan to relocate their communities because the Arctic permafrost on which their homes are built is melting and being washed away by the sea. After a long drought in 2018, the Cape Town metropolitan area almost ran out of drinking water. The Gulf Stream is weakening, glaciers in polar regions and on the

Even if all possibilities for reducing CO₂ emissions are used, it is highly probable that the 2 °C target will stay out of reach. A certain amount of warming remains, indicated by the orange area in the chart.



highest mountain peaks are melting, and in Australia's Great Barrier Reef – the largest coral reef on Earth – almost half of the corals died due to heat stress following two consecutively warm summers in 2016 and 2017. Low-lying island states such as Kiribati and Tovalu are currently struggling with the effects of sea-level rise. In these regions mentioned or elsewhere, it is obvious: Climate change does not stop at borders. It is a global problem whose consequences affect different countries to different degrees, but its causes and impacts can only be addressed if countries join forces and work together.

For this reason, since the 1990s, the international community has sought to negotiate an international policy framework to limit greenhouse gas emissions. A key breakthrough was achieved in December 2015 at the 21st Climate Change Conference in Paris, when government representatives from 175 nations agreed to limit global warming to well below 2 °C and to pursue efforts to limit the temperature increase to 1.5 °C. In other words, the Parties agreed to drastically reduce greenhouse gas emissions. After the Paris summit, almost all countries defined national emission reduction targets.

Whether the international community will actually succeed in implementing this agreement in policy form depends on individual states translating their words into action and introducing effective measures to reduce their emissions.

Carbon-neutral lifestyles: The only solution

Carbon dioxide is a very long-lived greenhouse gas which is produced as an undesired waste product in almost everything that simplifies our lives – in air, road and rail transport, in burning coal, oil and gas, in agriculture, in building and construction, and in the production of most consumer goods. Once released, CO₂ can drive the Earth's temperature curve upwards for centuries to come. By way of example: 1,000 billion tonnes of CO₂ in the atmosphere have the potential to increase the Earth's temperature by as much as 0.7 °C. Climate researchers are thus trying to determine the quantities of greenhouse gases that have already been emitted to date, so they can then calculate how much CO₂ can still be emitted before a given temperature level is reached.

To achieve the 1.5 °C goal, the Intergovernmental Panel on Climate Change (IPCC) says that around 420 billion tonnes of CO₂ can be emitted after 2018. That figure would increase to 1,200 billion tonnes if the temperature is not supposed to rise by more than 2 °C. At present, some 40 billion tonnes of CO₂ are globally emitted every year. This means that at the current rate the budget available for the 1.5 °C goal would be exhausted before 2030, and the budget for the 2 °C goal by 2050. Some scientific studies give humanity slightly more time, others slight less, but their core message is the same: If global warming is to be halted, CO₂ emissions must be reduced to zero – even if science is not able to exactly quantify how much time remains before specific temperature targets are met.

Equitable burden sharing

One important question is how this can be done without endangering economic and social development worldwide.

The fact is, that the Earth is not warming up at the same rate everywhere and that climate change affects different countries to different degrees. For example, many emerging and developing economies near the equator are already feeling the effects of global warming to a far greater extent than many industrialised nations in the North. Long periods of drought, poor harvests and hunger are just three of many negative impacts of climate change. But there are regions that actually benefit when temperatures rise. For example, fishermen in Greenland profit from climate change. Many popular food fish are now caught in their nets after having migrated in the Atlantic Ocean from mid-latitudes to waters further north as a result of rising water temperatures. However, the losers will outnumber the winners.

As climate change continues, large regions of the world might become uninhabitable for humans. The changing climate threatens crop growing in many areas around the globe and

SPOTLIGHT

MODELLING

How much time is left?

Do we have five years, 30 years or perhaps much longer? There is no clear answer to the question of how much time humankind has left to halt global warming. On the one hand, this is due to the natural variability of the climate system and more importantly the uncertainties regarding trends in anthropogenic emissions. On the other, researchers have to simulate the Earth's future in order to predict climate trends. Those simulations may be carried out using numerical mathematical models, but they still contain uncertainties.

What is modelling?

A computer model can be thought of as a gigantic collection of mathematical equations. Those equations are linked in such a way that they simulate the interaction between different components of a system – be it the Earth's climate system or the world economy – on the basis of scientific laws and economic assumptions in space and time.

Simple climate research models describe the processes in a sub-area of the climate system, such as ocean currents. Coupled climate models, on the other hand, are able to resolve the processes and interactions between several subsystems. So-called Earth system models also contain modules to represent terrestrial vegetation, soils, marine ecosystems and biogeochemical cycles.

Economists work with models that describe the behaviour of individuals, households, companies and governments in various contexts. For example, they can investigate how certain actors would react if motor fuels were taxed much more heavily than they are today.

Computer models have meanwhile become an indispensable tool for many research groups, both in the natural sciences as well as in social and economic sciences. They give scientists the opportunity to conduct 'what if?' experiments in a virtual world, including some that would not be possible in the real world. In

this way, climate researchers can, for example, melt the entire glacial ice of the Earth to investigate how high and how fast the sea level would rise following a total glacial melt. The different model types are increasingly being coupled beyond disciplinary boundaries.

Simulations can hence be used to calculate idealised scenarios and, if necessary, present them as projections of a possible future, test hypotheses or represent complex relationships for which measurements, surveys and experiments are neither sufficient nor feasible. In many cases, modelling is in fact the only tool that can be used to investigate sub-processes of a complicated system – for example, in the simulation of a technical intervention in the Earth’s climate. A test run of this kind can only be safely carried out in a model.

What models does the IPCC use?

The scenarios used by the IPCC for future greenhouse gas emissions and atmospheric concentrations are based on integrated assessment models. These combine climate models with models that describe things like economic and population growth, energy consumption and land-use.

To understand the effects of greenhouse gas scenarios on the climate, the IPCC refers to Earth system models. These are driven either by the scenarios for emissions and land-use from the integrated assessment models or directly by their greenhouse gas concentrations. These models then project the outcome for the climate and Earth systems. They forecast, for example, how climate change will affect the Earth’s ice sheets, water cycle, oceans and vegetation.

How accurate are the model results?

Despite the progress made to date, many of the models are not able to represent the processes and interactions in a given system down to the last detail, and neither should they. There are three reasons for this:

→ First, levels of future anthropogenic greenhouse gas emissions are uncertain, because it is hard to predict how the global society will develop. While changing values, political developments and even leaps in technological advancement

cannot be predicted, they can significantly impact greenhouse gas emission levels. To take such different potential developments in global society into account a range of emission scenarios are being developed. This approach makes it possible to draw specific if-then conclusions, but not to predict the future.

→ Secondly, even processes and variables that are well known and understood in principle can only be represented in a simplified way in computer models, as they are too small-scale to be fully captured by a model’s spatial and temporal resolution (clouds dynamics for example). Their effects can therefore not be calculated by the model, but instead have to be estimated using approximation methods. This is what scientists call parameterisation and it is one of the main reasons why there are uncertainties in modelling.

→ Thirdly, a detailed understanding of important natural processes is lacking in many areas. In climate modelling, for example, short-term fluctuations in the climate and the underlying feedback between components such as the atmosphere and the ocean are not yet well understood.

This means that the simulated world is not a perfect reflection of reality. Modelling – not only in climate and Earth system research – always involves simplifications, potentially neglects important processes and relationships, and depends on unknown initial and boundary conditions. Thus, each model simulation is fraught with uncertainties which must be considered when interpreting the results. These uncertainties are also the reason why climate researchers cannot say exactly how much CO₂ we may still emit or how much time we have left before reaching the 1.5 °C goal.

Does such uncertainty also reduce the pressure to act? No way! For one thing, the indications of the great risks of climate change for humankind are overwhelmingly clear. For another, uncertainties cannot be used as an excuse for inaction. In everyday life, we approach uncertainties head on. In other words, we do not let them stop us, but instead weigh them up or take out insurance to deal with extreme events such as accidents, theft and fires. Uncertainties are part of life and are not negative as such – we just need to know how to deal with them if and when they occur. ♦

Business as usual is one of the worst options we have. What is needed is broad public, and above all honest, debate about whether the international community is prepared to take far-reaching decisions on climate action.

hence world peace. The international community thus does not only face the challenge of finding fast-track paths to a carbon-neutral future. It must also find ways to equitably distribute the burden and the costs of developing emission-free societies, as well as the costs for adapting to climate change. Otherwise, the UN Sustainable Development Goals (SDGs) will not be met. Those goals include combating poverty and securing access to sufficient supplies of food and water, as well as to sustainable, reliable energy for all people on the planet. Climate action and sustainable development are inextricably linked.

Can 0.5°C make a difference?

Given the political debate surrounding the Paris Agreement, the question arises as to what difference it will make if global warming is limited to 1.5°C rather than 2°C. Does it really make sense to pursue such an ambitious goal?

The IPCC set out the differences in impacts regarding the 1.5°C goal in its 2018 Special Report. In a world that warms by only 1.5°C by 2100, the ice sheets in the Arctic Ocean would less frequently completely melt in summer than in a 2°C world. Sea levels would rise to a much lesser extent at 1.5°C compared to 2°C. This would increase the chances for adaptation for both people and ecosystems in coastal areas and on small islands. Ocean acidification would increase at a lesser rate at 1.5°C and marine communities would be less severely affected. For example, in a 1.5°C warmer world, up to 30 percent of the world's coral reefs would survive, while at 2°C, there is a far greater chance of them disappearing altogether.

The difference of 0.5°C would also be relevant for conserving terrestrial habitats and the extent of species loss. Over land, daily maximum temperatures would rise less dramatically, the risk of weather extremes such as heavy rain and heat waves would be lower, and the world would be spared tremendous economic impacts. At the moment, however, we are even far from limiting global warming to 2°C, and unless concrete measures are taken that go beyond the existing pledges of individual states, we are heading for a world that is more than 3°C warmer. ◆

IN A NUTSHELL

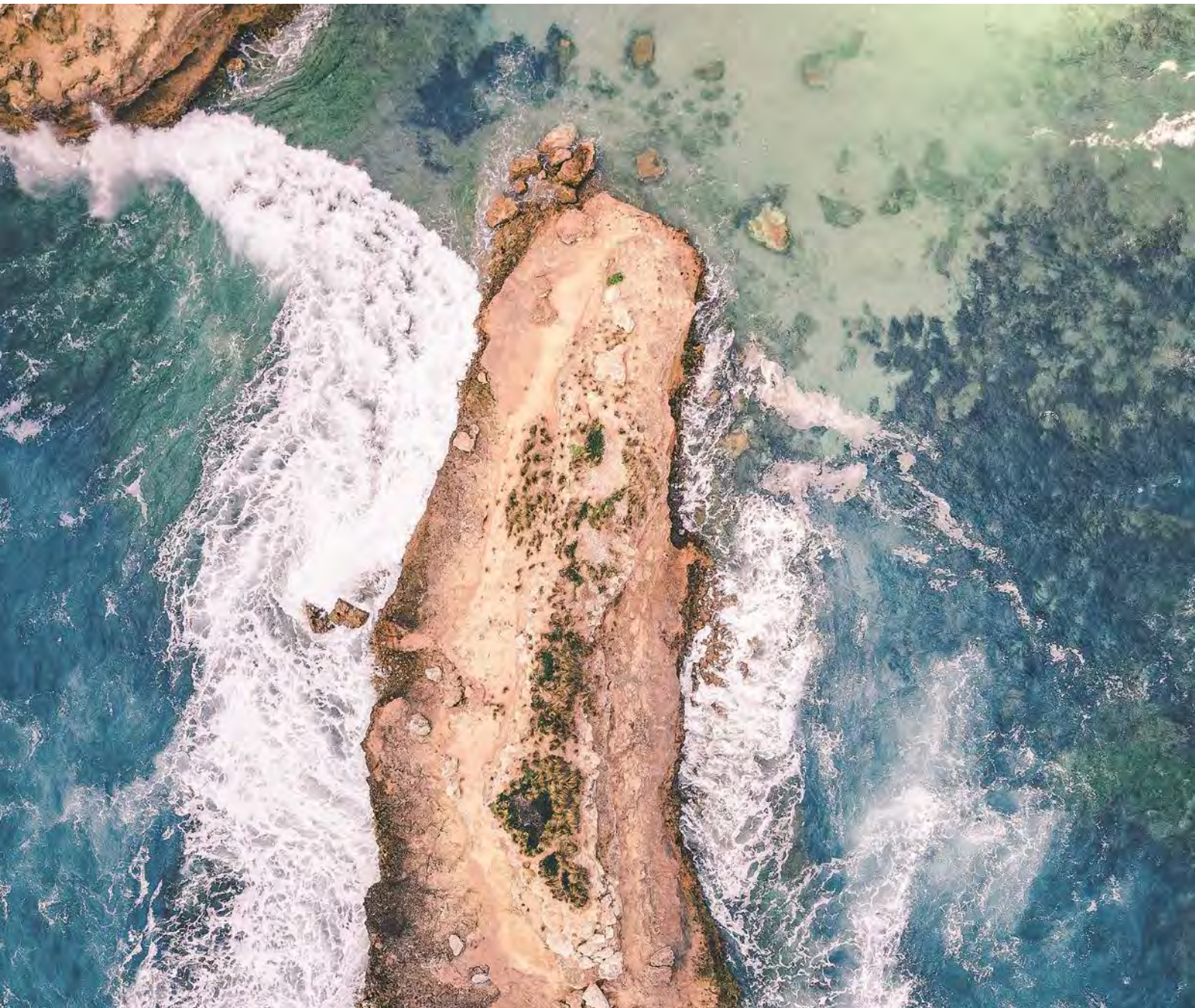
Since the beginning of industrialisation, levels of CO₂ in the Earth's atmosphere have been rising continuously and have intensified global warming. The global surface temperature rose by 1°C over the course of the 20th century, a trend that continues today.

→ The effects of global warming are now being felt in all parts of the world and are leading, among other things, to an increase in extreme weather events and sea-level rise. The impacts of global warming threaten millions of people worldwide.

→ At the Climate Change Conference in Paris, 175 countries agreed on the goal of limiting global warming to well below 2°C by 2100, and in the best case even to 1.5°C. To achieve this, by the second half of the century at the latest, global annual CO₂ emissions must be reduced from the current 40 billion tonnes to zero.

→ The effects and subsequent costs of climate change will be less drastic if global warming can be limited to 1.5°C rather than 2°C.

→ To promote sustainable development and social peace (for example avoiding major refugee flows), the costs and burdens of the needed adaptation and social change must be shared equitably.



Global energy demand will increase 30 percent by 2040. At the same time, human greenhouse gas emissions must be reduced to zero by mid-century if global warming is not to exceed 2°C. Far-reaching measures are needed if we are to achieve both these goals.

REALITY CHECK:

SERIOUS CLIMATE ACTION MEANS CHANGE

China, Australia and India have led the way. In 2017, these countries invested more in the expansion of renewable energy sources than in the construction of new coal-fired or gas-fired power plants. Electricity from renewable sources such as solar and wind power, biogas plants and smaller hydropower plants now accounts for 12.1 percent of electricity generated worldwide – and this percentage is rising, partly because prices for photovoltaic plants, wind turbines and lithium batteries are going down. Energy market experts predict that by 2030 in some parts of the world it will be cheaper to install solar systems than to burn coal in ageing power plants.

Nonetheless, these advances in the Earth's greenhouse gas balance amount to no more than the proverbial drop in the ocean. Some 81 percent of the electricity currently produced still comes from fossil fuels. To be added to this are the combined emissions from transport, industry and agriculture, the sum of which has been rising steadily for decades.

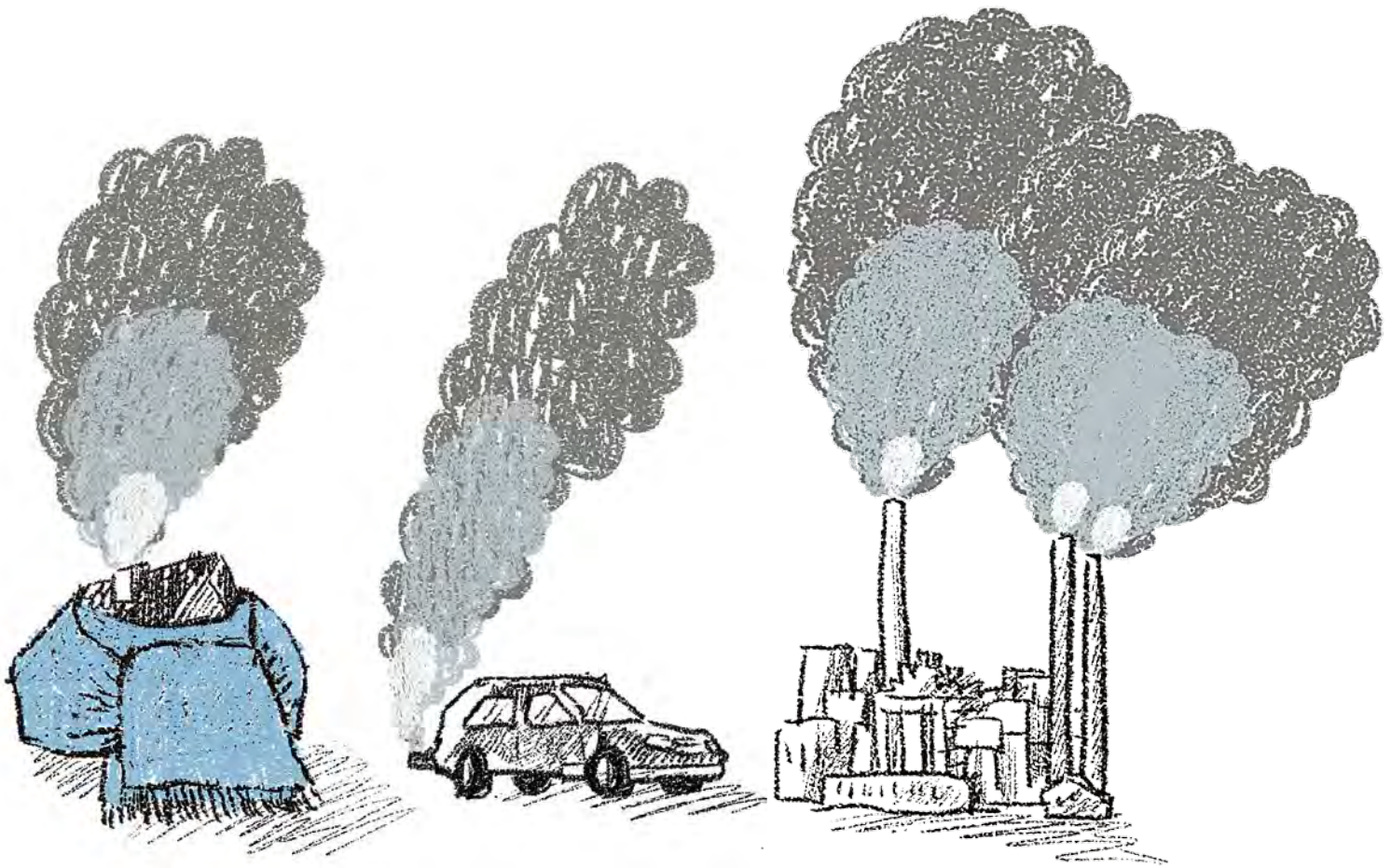
In the 2015 Paris Climate Change Agreement, the signing Parties committed themselves to significantly reduce their greenhouse gas emissions or to keep them at a low level, by

declaring nationally determined contributions (NDCs). In terms of diplomacy, that pledge was a great success. However, analyses performed by the United Nations show that the announced nationally determined contributions are nowhere near enough to achieve the 2 °C goal – let alone 1.5 °C. Even if all pledges to reduce emissions are fulfilled, the world is currently heading for warming of between 2.2 °C and 3.6 °C by 2100.

The mammoth task of going from 100 to zero in practically no time at all

In light of this, the question arises: Is it even possible to achieve the 2 °C goal? In theory, the answer is yes – if the international community succeeds in reducing its overall CO₂ balance to zero for the second half of this century. This is a mammoth task, considering that it is not only electricity demand that will continue to rise. The International Energy Agency in Paris predicts that in 2040, around 30 percent more electricity will be consumed worldwide compared to today. For example, in their projection, China's air conditioning systems alone will need as much electricity as Japan currently consumes in total. Expected growth in food production, which already accounts for around 30 percent of all greenhouse gas emissions, is even greater.





Against this backdrop, scientists have developed a set of measures with which the climate targets could be attained solely by reducing emissions. Consequently, the Paris climate goal would be realistic if, among other things, the following could be achieved in the shortest possible time:

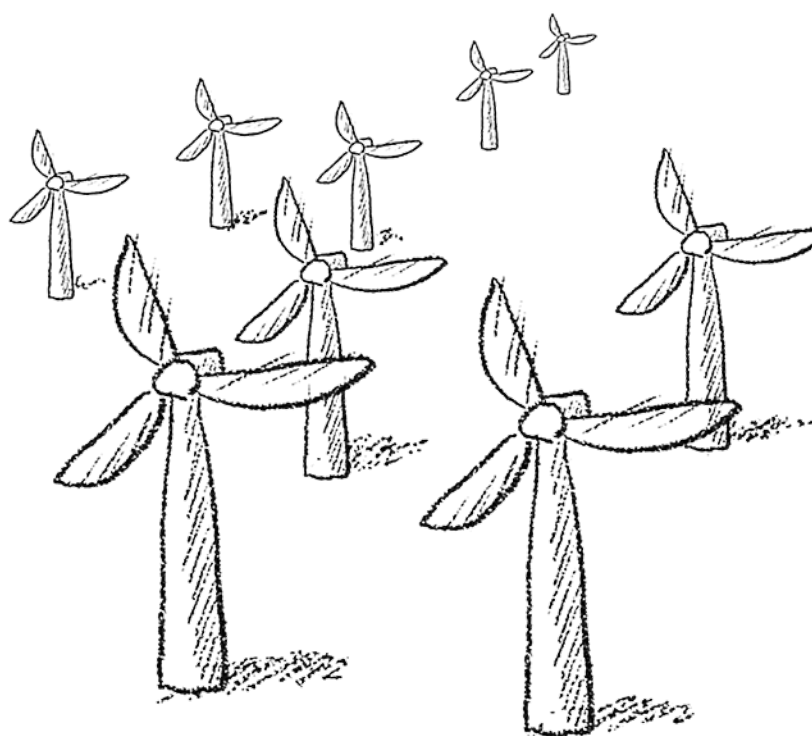
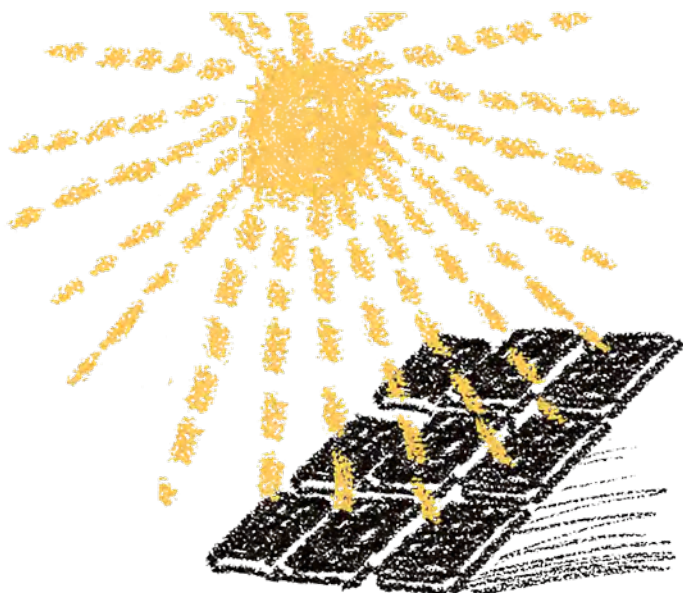
- the electricity sector transitions entirely to renewable energy sources,
- vehicles, machines and heating systems are electrified,
- aircraft and ships are powered by carbon-free fuels,
- only modern, energy-efficient appliances and materials are used in industry and households,
- food production processes are significantly improved,
- people around the world eat significantly less meat, cease to waste food and alter their mobility habits,
- the international community pursues effective climate change policy within the framework of a common global strategy.

Putting a price on carbon

Most economists agree that emitting CO₂ must cost money. The simplest and generally most cost-effective way to enhance climate action would be to introduce a carbon tax. To date,

there are few economic incentives to reduce greenhouse gas emissions worldwide. Around the globe, both the waste product CO₂ and other greenhouse gases are emitted into the atmosphere free of charge and hence without hesitation. A carbon tax would change this and provide incentives to reduce CO₂ – on the one hand through changes in behaviour and on the other through technical innovation. In turn, countries could use the tax revenues to relieve the burden on consumers in an income-neutral way or to finance adaptation to climate change. Virtually all other proposals for more climate action appear complicated or costly in macroeconomic terms. A sufficiently high price for greenhouse gas emissions, by contrast, would be a climate policy intervention that could be used to effectively implement measures to achieve the 2 °C goal.

The world is so reliant on fossil fuels that a slight economic upturn like the one seen in 2017 will be all that is needed to wipe out all emission savings achieved through the use of solar, hydro and wind power within a very short time span.



Focusing on the future


Whether the international community will still be able to implement the climate action needed to achieve the pledged emission reductions quickly enough is questionable. On the one hand, the global economy and our current lifestyles are based on energy from fossil fuels. Changing this situation in a matter of just a few years without introducing painful cuts or endangering economic growth appears unrealistic right now. Ambitious climate action presupposes that targeted greenhouse gas reductions are already included in every forward-looking decision made today – including construction projects, for example. Be it buildings, container ships or industrial plants, everything that is built today must either comply with the strict climate action guidelines of the future or be easily converted to meet them. After all, these new houses, factories, roads, rail networks, ships and other infrastructures will remain in use far beyond the climate-policy deadline of 2030.

So far, however, many decision-makers have lacked this kind of foresight – or to put it another way, there is a huge gap between what those in charge know and what they are actually implementing in their policies. In Germany, for example, CO₂ emissions in the industry and transport sectors continued to rise in 2017. Only the energy sector saw a slight decline. The fact is, that Germany still lags far behind its 2020 target of reducing greenhouse gas emissions by 40 percent relative to 1990. So far, total emissions in Germany have fallen by only 27.7 percent.

And although Germany now aims to reduce emissions by 55 percent by 2030, it lacks the political will to actually introduce a full-blown energy and transport transformation alongside with an apparent lack for suitable ideas. ♦

IN A NUTSHELL

- The share of electricity from renewable energy sources is growing worldwide. Nonetheless, these emission savings are not enough to reduce the total amount of greenhouse gases released.
- Global demand for energy and food will continue to rise, and so will emissions as a result.
- Climate researchers have developed a catalogue of highly-ambitious climate action measures that could halt global warming. But before these measures can be implemented worldwide, there are large hurdles that must be overcome.
- To effectively promote climate action, CO₂ emissions should be taxed. This would also provide incentives to develop new ways to avoid emissions.

An aerial photograph of a lush, green landscape. A waterfall cascades down a rocky cliff in the center of the frame. The surrounding terrain is covered in dense green vegetation, with a network of small streams and paths visible. The overall scene is vibrant and natural.

Climate change is already affecting the Earth in a long-lasting way, forcing humankind and nature to adapt. It is obvious: If we are to limit global warming, we must stop releasing CO₂ into the atmosphere. It remains to be seen whether this will be achieved and suffice, or whether we will perhaps be forced to use targeted methods to remove CO₂ from the atmosphere, thereby completely offsetting remaining emissions (net zero emissions). This approach is fraught with problems, too.

SCOPE FOR ACTION: NEW SOLUTIONS NEEDED

The situation is thus as follows: Without comprehensive measures to prevent emissions, by the end of the 21st century the world's climate will undergo dramatic change. No one can say what human life on earth might look like in such a future. What we do know is that living conditions will have deteriorated in many parts of the world.

To minimise risk, warming must be limited to well below 2 °C. This requires all CO₂ emissions to be stopped or neutralised in good time. The problem is that there remains a huge gap between what we know and the action we are taking.

Can't we simply adapt?

Why doesn't humanity simply concentrate on adapting to a warmer climate? There are successful ideas and projects in place worldwide. In Kenya, for example, the weather service advises interested smallholders on when to sow their crops. This ensures that valuable seed is only sown when there is a real prospect of rain. In some mountain villages in the Himalayas, the inhabitants now collect all their water for domestic use and rainwater to use for irrigation. And mountain farmers and their counterparts elsewhere in the world are now experimenting with new crops that require less moisture to grow and are more resistant to heat than older varieties. Dikes on the German North Sea coast have been made higher in recent years, in the meantime urban planners and architects in many of the world's metropolises are developing ways to better

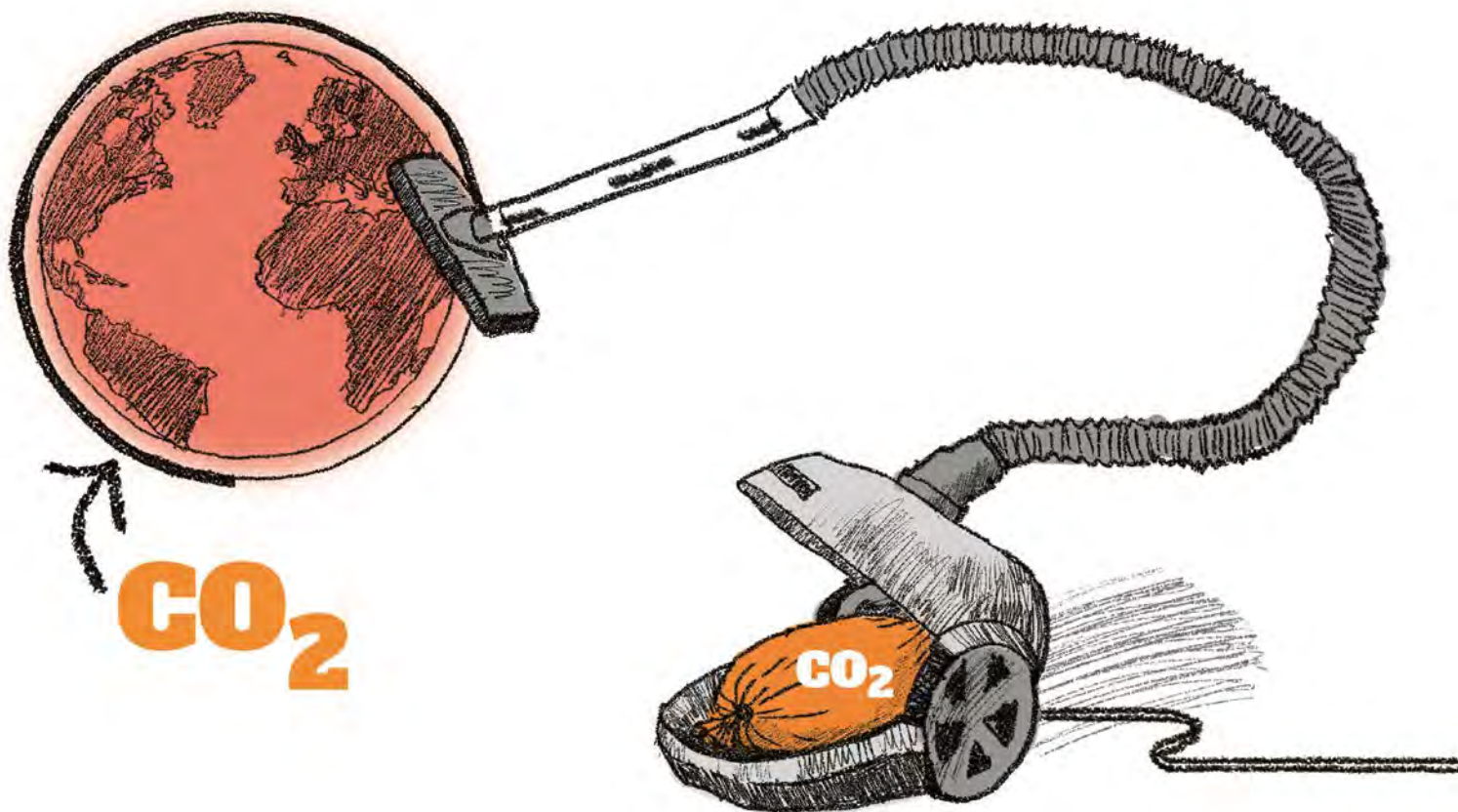
According to the IPCC, climate change will increase poverty and injustice in the world and make humanity overall more vulnerable.

ventilate these large cities and minimise heat accumulation in the streets. Weather experts from all over the world are collaborating to better predict extreme weather events such as severe storms, heavy rain and prolonged heat waves. These and many other adaptation measures help to reduce the risks of climate change. They are indispensable today and will continue to be needed in the future. However, the possibilities for adaptation have a limit.

When the ambient temperature exceeds 35 °C, most people find it difficult to perform simple, everyday tasks. The vast damage caused by hurricanes like Irma and droughts, like those in the Sahel zone, highlight just how vulnerable industries and infrastructures are. Beyond that, adapting to a rapid rise in sea levels would mean abandoning large stretches of densely populated coastal regions, especially in poorer countries. Distribution conflicts over land, water and food would be inevitable, with climate change hitting those countries in Africa and Asia particularly hard, which already belong to the poorest regions today. According to the IPCC, climate change will increase poverty and injustice in the world and make humanity overall more vulnerable.

No alternative to reducing emissions, but is it enough?

The hope of actually achieving the 1.5 °C or at least the 2 °C target is fuelled, among other things, by the most optimistic scenarios contained in the IPCC's Fifth Assessment Report published in 2013 and the Special Report on Global Warming of 1.5 °C issued in autumn 2018. In those reports, climate researchers not only assumed that far-reaching measures to avoid emissions will be implemented by governments worldwide. They also took into account the prospect that in the future, humankind will be able to remove CO₂ from the Earth's atmosphere on a large scale and to store it safely. The longer emission avoidance is postponed, the more CO₂ there is to be removed from the atmosphere, and at ever-faster rates.

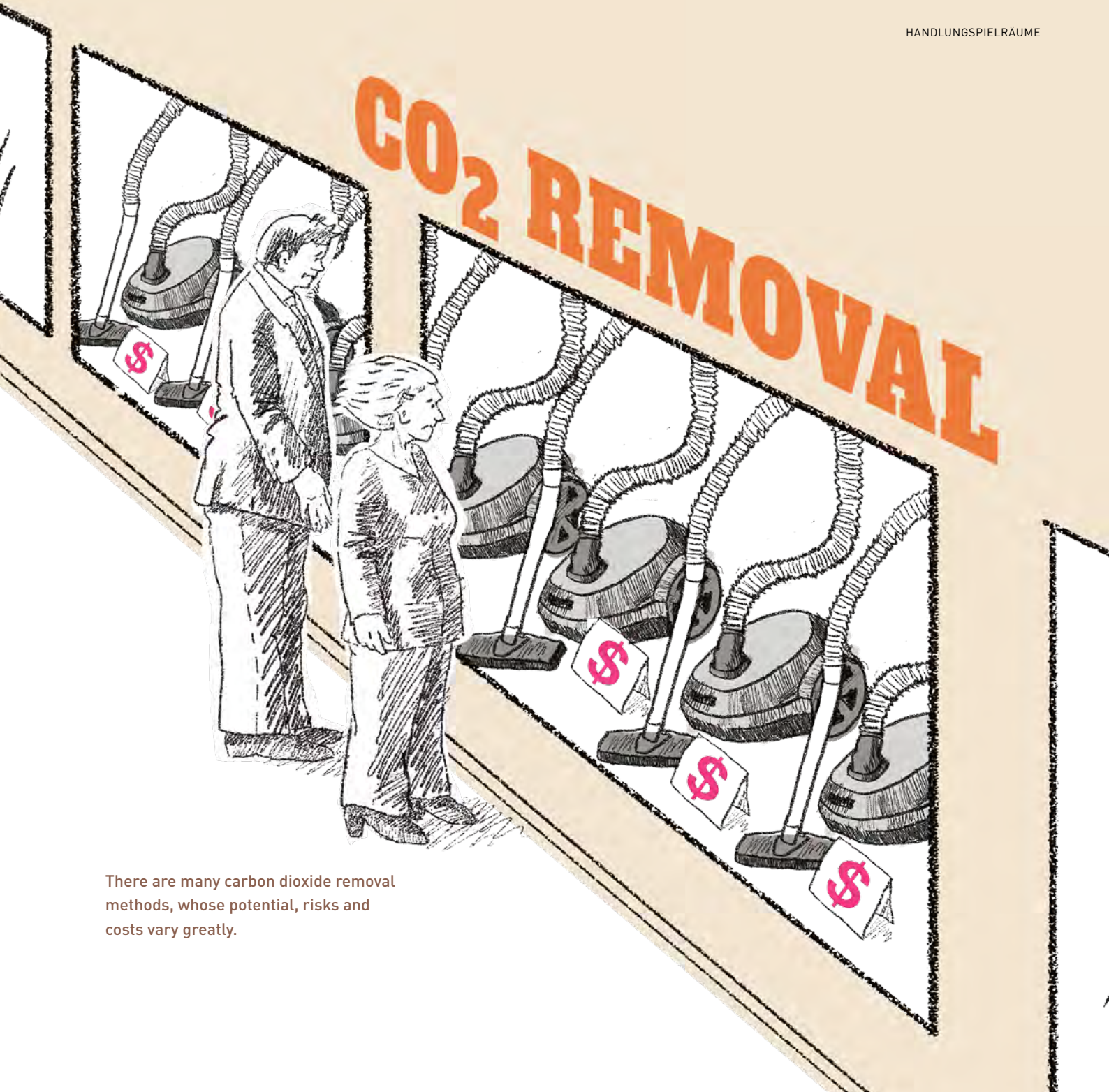


But such deliberate influence on the climate system via an intervention in the Earth's carbon balance is fraught with great uncertainty. It remains unclear, for example, what is the real potential of such methods under discussion at scale and what side-effects come along with large-scale application. Administrative questions also need to be answered: Who, for example, would be liable if unforeseen damage were to occur as a result of deploying such methods?

To date, there are no plans as to how carbon dioxide removal should be implemented as a supplement to substantial emission reductions. Also, the scientific community is currently discussing means of influencing the climate system that directly intervene in the Earth's radiation balance as a way to potentially attain the temperature targets despite excessively high atmospheric CO₂ concentrations. As long as it remains uncertain whether the global society will meet the agreed

climate targets with emission reductions alone, society must also consider other options – such as deliberate intervention in the climate system – so that, in the worst case, we can make an informed, fact-based decision in favour of or against the use of such methods. So what exactly is behind the idea of deliberate intervention in the Earth's climate? What methods are being discussed? ♦

To achieve the Paris climate goal, by 2050 we must be technically capable of removing billions of tonnes of CO₂ from the atmosphere each year.



There are many carbon dioxide removal methods, whose potential, risks and costs vary greatly.

IN A NUTSHELL

- Trying to adapt to climate change without tackling its causes is not a viable alternative. The possibilities for adaptation are limited and both the economies and the infrastructures of most countries are highly vulnerable.
- According to IPCC projections, the 1.5 °C target (and probably the 2 °C target) can only be achieved if – in addition to ambitious CO₂ emission avoidance – CO₂ can be removed from the atmosphere on a large scale.

FURTHER READING

- Climate engineering methods: Can global warming be slowed down by deliberately intervening in the climate system? – p. 22
- The ethical and legal standpoint: Do we have the right or even a duty to deliberately influence the climate? – p. 42
- Limited scope for control: The crux of the chaotic climate system – p. 54



Various methods are proposed to prevent further global warming. They essentially follow two basic strategies: removing CO₂ from the atmosphere or reducing solar radiation. None of the methods discussed has yet reached maturity. Neither their potential nor any risks involved can yet be accurately estimated. For some methods, however, it is already foreseeable that they could have serious side effects.

CLIMATE ENGINEERING METHODS: CAN GLOBAL WARMING BE SLOWED DOWN BY DELIBERATELY INTERVENING IN THE CLIMATE SYSTEM?

The term ‘climate engineering’ (CE) has been in use for some time to denote large-scale technical means of intervening in the climate in order to slow down human-made climate change. It covers two fundamentally different strategies:

1. The first category, referred to as carbon dioxide removal (CDR), changes the Earth system by influencing the carbon cycle. Methods discussed here aim to remove CO₂ from the atmosphere and store it long term. The aim is to remove the main cause of global warming from the atmosphere: the increased CO₂ concentration caused by emissions from fossil fuels.
2. The other group of methods discussed intervene in the global radiation budget. Their aim is for less radiation to reach the Earth’s surface or for more radiation to be released into space. This category of methods is referred to as radiation management (RM). They aim to reduce global warming even though the greenhouse gases remain in the atmosphere – including very long-lived CO₂.

Current status

Scientists around the world have been working on various methods of carbon dioxide removal (CDR) and radiation management (RM) for over 20 years. A number of methods have already been tested in the laboratory or in small field experiments, while many approaches remain theoretical for the time being. Conclusions regarding their effectiveness are so far mostly based on findings from modelling. It is unclear to what extent their use would be feasible in practice and if they would suffice to limit global warming to 1.5 °C or below 2 °C, even in combination with a drastic reduction in emissions.

There are currently no CDR or RM methods capable of being deployed on a large scale. Not enough is known about their

respective potential and side effects. Also, they are not yet technically mature, or there is a lack of strategies for their widespread application. In many cases, field experiments and deployment come up against scientific, legal, ethical or political reservations.

What timeframe and spatial scale are we talking about?

For CDR and RM methods to significantly affect the planetary radiation balance and the CO₂ content of the atmosphere, they would have to be applied on a very large scale and in some cases for a very long time. However, CDR and RM methods differ here in a fundamental respect:

→ RM methods do not have a permanent effect in principle. Instead, they only go on working for as long as the deliberate intervention in the radiation budget continues. As they do not combat the cause of global warming by removing CO₂, RM methods would have to be kept up until the long-lived CO₂ is removed from the atmosphere by natural means or by accompanying CDR measures. The main natural sink is the ocean. This currently absorbs about 20 to 25 percent of the CO₂ emitted today. Uptake of CO₂ by the ocean is very slow, however, taking centuries to millennia. Accordingly, RM methods would have to be kept going, and keep being financed, for many generations and be paralleled by a successful transformation to a carbon-neutral society, possibly with the aid of CDR. This would presuppose a stable world order over many decades or centuries so the international community could pull together and cooperate in radiation management.

→ If CDR could be established on a large scale, it might be possible – in combination with massive emission reductions – to maintain the atmospheric CO₂ concentration at today’s level or even to reduce it below that level. An important distinction is made in CDR, however, between what is referred to as

There are currently no CDR or RM methods capable of being deployed on a large enough scale to halt global warming.

TERMINOLOGICAL CONFUSION

The discussion about deliberate intervention in the climate system has produced a wealth of new terms over the years. This makes the subject hard to approach. For about a decade, the term climate engineering has been used to denote methods of deliberately intervening in the climate system on a large scale to reduce the consequences of human-caused climate change. Terms used synonymously with climate engineering include geoengineering and occasionally climate intervention or climate remediation. All of these terms traditionally cover both carbon dioxide removal (CDR) and radiation management (RM) methods.

RM itself is subject to similar terminological variety. Frequent alternatives include solar radiation management (SRM) and albedo modification. As these do not cover the idea of intervening with the long-wave part of the radiation budget by reducing cirrus clouds, we have opted for RM.

Methods discussed under RM include altering the radiation budget by spreading aerosols in the stratosphere. Examples of methods proposed under CDR are increasing the CO₂ uptake of the oceans or afforesting entire regions. ‘Large scale’ means that the methods significantly affect the planetary radiation balance or the CO₂ content of the atmosphere. Painting a few houses or roofs white or planting a few trees therefore does not count as climate engineering because the global impact is negligible. Reforestation of large areas of land in order to have a noticeable effect on the atmospheric CO₂ concentration and reduce the impacts of climate change would, on the other hand, be a deliberate large-scale intervention in the climate system. This is because turning entire regions into forest plantations not only affects ecosystems and biodiversity but also, for example, the water cycle and the reflectivity of the Earth – and hence the climate system.

RM and CDR basically work in fundamentally different ways. RM acts on the Earth’s radiation budget to reduce warming without removing CO₂ from the atmosphere. CDR acts instead on the Earth’s carbon cycle to take CO₂ out of the atmosphere, meaning that it tackles the main cause of human-induced global warming.

A further term has come into common use for CDR methods in connection with the 2015 Paris Climate Agreement: negative emission technologies (NETs), where negative emissions mean the removal of CO₂ from the Earth’s atmosphere. Occasionally, the term greenhouse gas removal (GGR) is used instead of CDR or NETs in order to include other greenhouse gases besides CO₂. RM methods are not negative emission technologies in principle, even where they have an impact on greenhouse gas concentrations as a side effect.

In the current debate, there are increasing voices that CDR and NETs should no longer be generally counted as climate engineering. This is because CDR helps reduce the CO₂ concentration and thus addresses the cause in the same way as the afforestation already established at a small scale as a mitigation measure. What matters here is the definition of mitigation. The IPCC defines it as “a human intervention to reduce emissions or enhance the sinks of greenhouse gases.” Removing CO₂ from the atmosphere by increasing terrestrial or marine CO₂ uptake comes under sink enhancement. Because of this, based on the IPCC definition, such CDR methods are frequently considered part of mitigation. As climate engineering is highly controversial and viewed critically in science and society, taking most CDR methods out from under the climate engineering umbrella and reclassifying them under mitigation could aid their social acceptance and political implementation.

In this publication, the term climate engineering, which combines CDR and RM, is nevertheless retained as a generic term in instances where attributes (such as large scale and deliberate intervention) and principles are referred to that apply to both categories. This is in line with the terminology in common use. When it comes to actually assessing the opportunities and risks of individual CE options, the less meaningful generic term is frequently irrelevant and unhelpful. In that context, we therefore uphold the distinction between radiation management and carbon dioxide removal. Since there are very different interpretations of the term mitigation, we do not use that term at all and speak instead of emission avoidance when we mean preventing greenhouse gas emissions and of carbon dioxide removal when we mean creating sinks. ◆

permanent and temporary storage. An example of temporary storage is trees. As they grow, trees remove CO₂ from the atmosphere and store it in their wood. Beech trees, for example, can live longer than 400 years and are able to remove the greenhouse gas from the atmosphere for a correspondingly long period. If their timber is subsequently used for construction, the CO₂ remains captured for a long time in buildings. Biochar could possibly store CO₂ for several thousand years. Another key store of CO₂ is the ocean. CO₂ captured in the ocean, for example by algae sinking to the sea floor, returns to the surface and re-enters the atmosphere after about 1,000 years. If the CO₂ dissolved in seawater is neutralised with alkaline substances as proposed in one CDR method – enhanced weathering of minerals – then the greenhouse gas is permanently removed from the system. One permanent storage method consists of locking up CO₂ in rock. Mixed with water, the greenhouse gas is pumped at high pressure into volcanic basalt deposits deep underground. In a natural process, the basalt rock then chemically reacts with the CO₂ to form carbonate minerals similar to limestone, in which the gas is permanently captured.

Should society decide to supplement emission reductions with climate engineering, carbon dioxide removal methods would make more sense in the long term with regard to the climate targets than would radiation management methods. This is because they directly combat the cause by removing human-emitted CO₂ from the atmosphere. Carbon dioxide removal also counteracts ocean acidification. CDR methods are not suitable as a quick fix for the Earth's climate processes, however. Due to the quantities of carbon they would have to remove, it is estimated that they would need five to 15 years to have any effect on the climate. So CDR measures, too, would have to be applied early and for relatively long periods to have an impact. Many methods also require monitoring to ensure that CO₂ storage is permanent.

A further key factor for all methods is scale. Only if applied on a large scale would their impact on the planetary radiation balance or atmospheric CO₂ content be relevant to the problem of global warming. One CDR method under discussion, for example, is afforestation. Capturing significant quantities of CO₂, however, would involve afforestation of huge areas. Yet the potential global area of land suitable for afforestation is limited. The same goes for the large-scale cultivation of biomass plantations. The land taken up is then also lost to other uses, including food production. Biomass-based CDR methods thus have a direct bearing on food security issues.

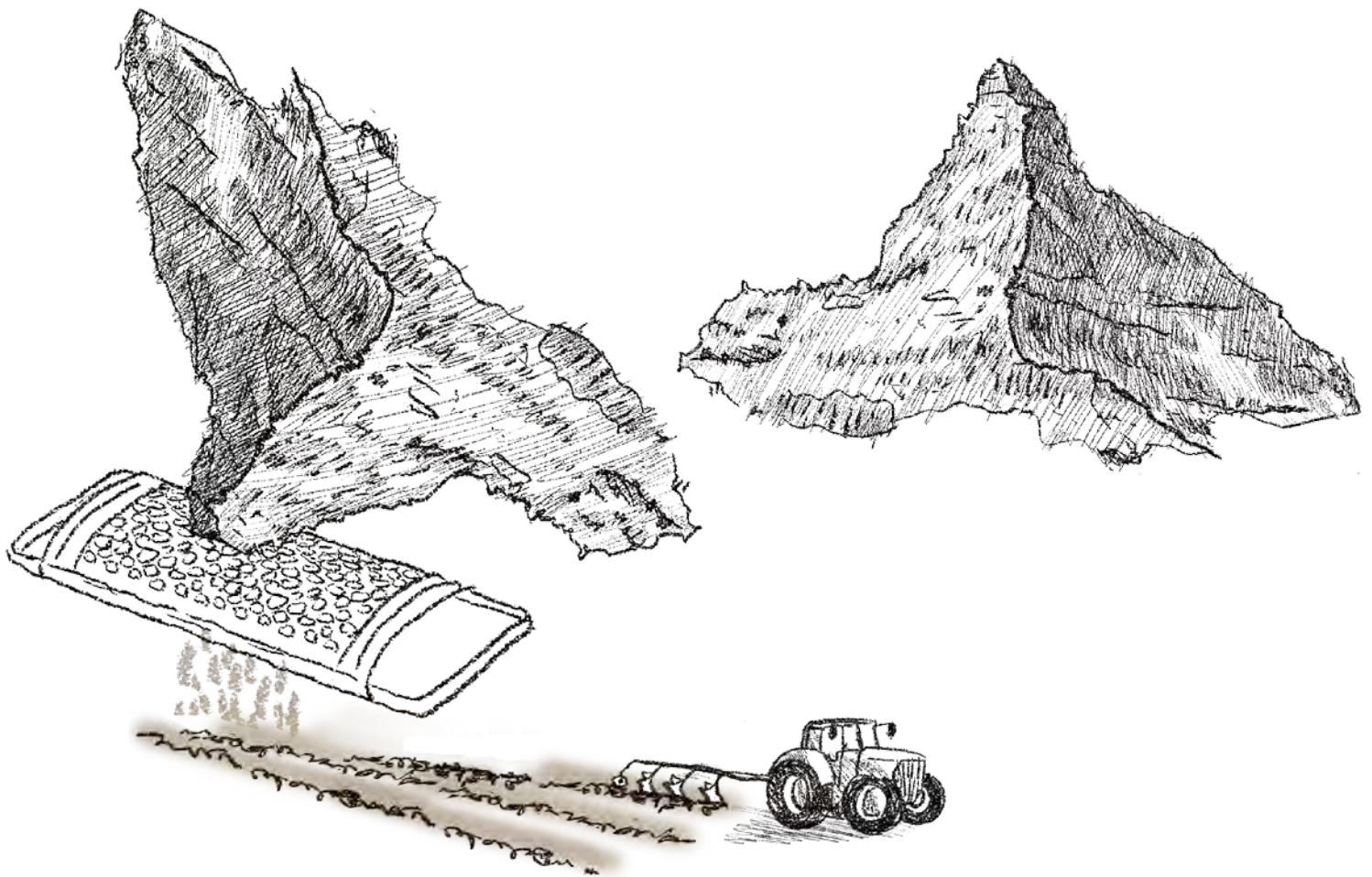
RM and CDR basically work in fundamentally different ways. RM acts on the Earth's radiation budget to reduce warming without removing CO₂ from the atmosphere. CDR acts instead on the Earth's carbon cycle to take CO₂ out of the atmosphere, meaning that it tackles the main cause of human-induced global warming.

One method that could in principle be used without restriction, on the other hand, is what is called direct air capture. This involves the use of machines to remove CO₂ from the air. The CO₂ captured from the air could then be reused by the chemical industry (carbon capture and usage, or CCU). To remove it from the atmosphere for a long time, however, the CO₂ would have to undergo energy-intensive processes in order to convert it into long-lived products. The potential of CCU is not estimated to be very large relative to the quantities of CO₂ needed to attain the climate targets. An alternative would be to store the captured CO₂ in deep rock strata, such as in empty, exhausted natural gas or petroleum deposits. Experts refer to this as carbon capture and storage (CCS; see box on page 29). Geologists estimate that subterranean formations are available worldwide with sufficient volume to take up all anthropogenic CO₂ emissions for the long term and thus remove them from the atmosphere.

The different methods

The various CDR and RM methods vary significantly with regard to their potential benefits and potential risks. For CDR methods, there is also the disputed and difficult question of whether they should properly be considered a form of mitigation or if they indeed count as climate engineering. It is therefore important to look at each method individually.

The following pages present carbon dioxide removal (CDR) methods – subdivided into terrestrial and oceanic applications – followed by a detailed description of radiation management (RM) methods. Estimates are given for the potential and side effects of all methods, although it may not always be necessary to use the full potential in order to attain the Paris climate targets. According to the Intergovernmental Panel on Climate Change (IPCC) assessment report, if rapid progress in drastically cutting emissions were achieved, we then would require approximately 10–20 billion tonnes of CO₂ to be removed from the atmosphere each year towards the end of the century.



CDR METHODS → TERRESTRIAL APPLICATIONS

ENHANCED WEATHERING

Carbon dioxide can be captured by the weathering of carbonate and silicate minerals that are deliberately spread on the terrestrial surface. These minerals could be applied in powder form, primarily on deeply weathered and impoverished, acidic arable soils in humid tropical regions. This would have the positive side effect of improving the soil. As impoverished soils such as ferralsol occur in tropical regions with heavy precipitation, there would be no problem with irrigation. One disadvantage of the method could be the release of heavy metals if unsuitable mineral material were to be used. The use of enhanced weathering is therefore considered a carbon dioxide removal method whose advantages may, on balance, outweigh the disadvantages.

Potential

Among other materials, calculations as to the potential of this method have been done for basalt, a volcanic silicate mineral. Estimates show that spreading three billion tonnes of basalt powder per year could capture around one billion tonnes of CO₂ worldwide. In total, the potential for sequestering CO₂ is estimated at two to four billion tonnes per year, depending on

the land surface and type of mineral used. What has not yet been estimated is the additional potential for capturing CO₂ resulting from improved plant growth due to the nutrients contained in the minerals.

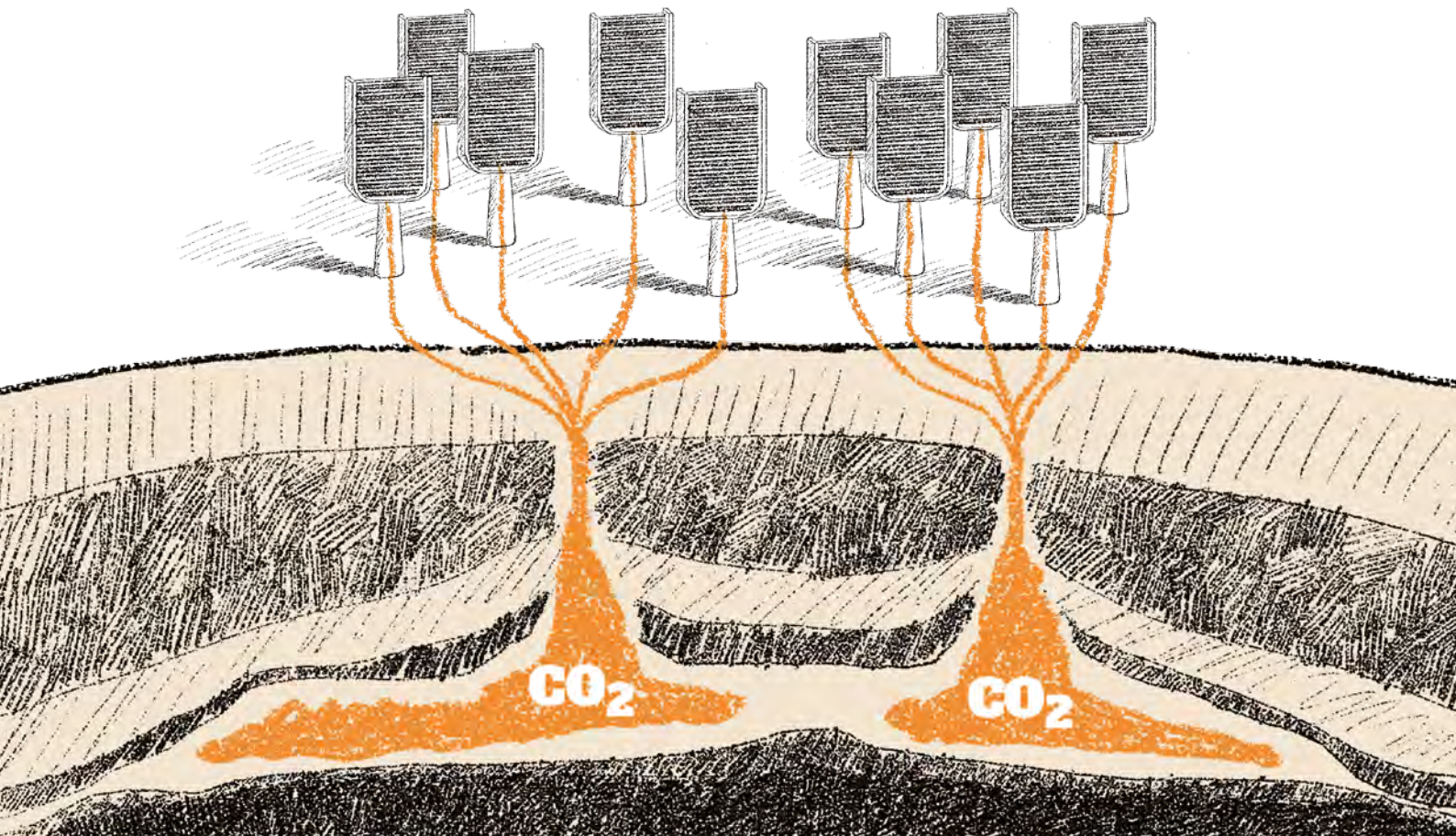
Scale

Fully exploiting the method's global potential would require the use of all agricultural land, plus additional forest land. Up to twelve billion tonnes of mineral would have to be quarried, ground and spread each year. This is comparable to the quantity of coal mined annually.

Application readiness and research needs

Fertilising fields with mineral powders has been done for many years and is already practised in some regions on a large scale. Basalt powder, for example, has been spread on sugar cane plantations in Brazil and Réunion Island since the 1960s. Older scientific publications on the subject are currently being reviewed with regard to the potential for CDR.

Enhanced weathering is also being investigated in small field experiments, in countries such as the USA, Malaysia and Brazil, partly with the aim of improving depleted soils. In principle,



improving impoverished soils would also make them available for food production and other biologically based CDR methods. Global estimates of the method's effects currently remain highly inaccurate, as careful experiments are needed in order to determine important constraints such as the weathering rate or potential side effects due to impurities like heavy metals in the minerals used.

An advantage of enhanced weathering on land is the ability to make use of existing agricultural infrastructure. For it to be used as a CDR method, however, quarrying output would have to be increased many times over. As spreading carbonates and silicates is most effective in tropical regions that in many cases are not economically wealthy, it would be necessary to decide how the costs are to be met (such as for quarrying and transportation).

DIRECT AIR CAPTURE

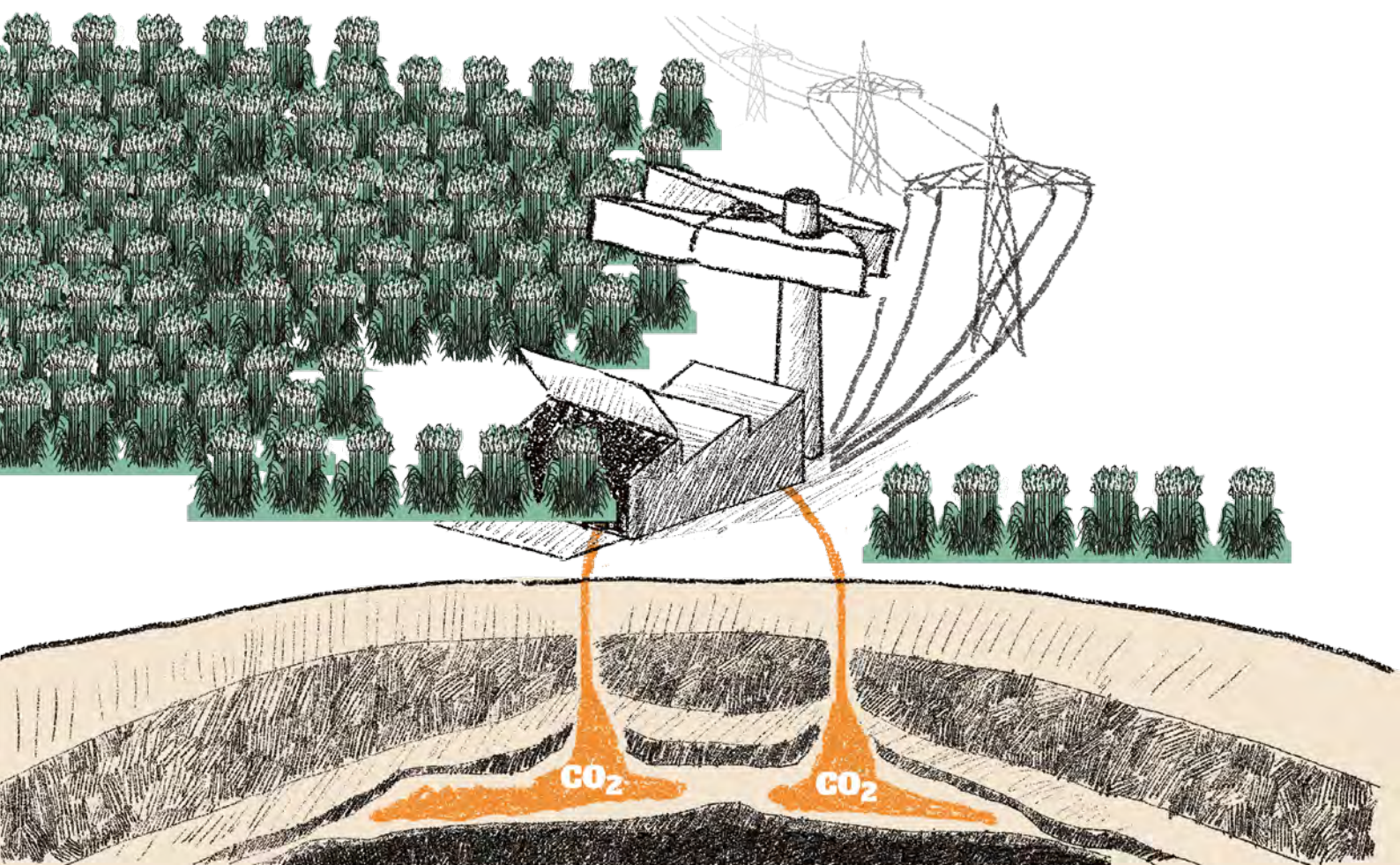
Direct air capture systems filter CO₂ out of the ambient air similar to plants and trees. The CO₂ is filtered out by passing the air over special sorbents and is then liquefied. To remove the CO₂ from the atmosphere for the long term, it must either be reused (carbon capture and usage, or CCU) or stored underground (carbon capture and storage, or CCS).

Potential and scale

If intensive effort is put into its further development, direct air capture could in principle remove unlimited amounts of CO₂ from the atmosphere. However, as CO₂ is contained in air at very low concentration – about 0.04 percent – it would involve filtering enormous quantities of air. That would require huge installations and consume enormous amounts of energy. Estimates of the cost per tonne of liquefied CO₂ vary widely. The average is US\$ 600 per tonne of CO₂. A large pilot plant recently taken into operation in a project in the Province of British Columbia, Canada, aims to attain a price of around US\$100 per tonne. The deciding factor for such plants is that their use only makes sense if they run on renewable energy, since operating them on fossil fuels would emit more CO₂ than they could capture. It is not yet clear where the absorbed CO₂ could be safely stored for long periods or how it could be reused. Air capture can therefore only work on a large scale if the energy for the installations is generated in a climate-neutral manner, sufficient storage capacity is established for the captured CO₂ (CCS) and ideas are found for its subsequent use (CCU).

Application readiness and research needs

The main problem facing the various direct air capture methods in principle is thus energy efficiency. They also depend on the



establishment of CCS infrastructure or the development of CCU applications. Currently, three relatively large and several smaller direct air capture pilot plants are in operation. The captured CO₂ is either put to use (in greenhouses, for example) or injected into geological formations and thus, permanently removed from the atmosphere.

BIOENERGY WITH CCS (BECCS)

Another method discussed in the context of CCS is the cultivation of fast-growing plants that take up CO₂ from the atmosphere. The biomass can be converted to biofuels and combusted for energy with the CO₂ released upon combustion being captured and permanently stored. This is referred to as bioenergy with CCS (BECCS). Suitable crops include miscanthus, poplar, willow and eucalyptus species. All of these produce large quantities of biomass very quickly. Combining biomass power plants with CCS would allow the CO₂ released during combustion to be removed from the environment. Unlike direct air capture, this method has the advantage of generating energy rather than just consuming it. In contrast to

direct air capture, however, BECCS takes up large areas of land and may also need additional water and fertiliser to cultivate the energy crops, thus placing it in conflict with other land uses such as food production. One alternative may be to use algae as the input for BECCS, as this would partly solve the land-use conflict.

Potential and scale

BECCS plays a decisive role in the IPCC emissions scenarios for attainment of the climate targets and has been hotly debated as a key negative emission technology (NET) since the Paris Climate Agreement. Current energy scenarios assume that BECCS could meet at most up to 20 percent of global energy needs, although estimates vary substantially. According to various scientific studies, if BECCS technology were to be developed in the years ahead, between 2.4 and eleven billion tonnes of CO₂ a year could be removed from the atmosphere worldwide from 2050. However, this depends on geological storage capacity being established quickly enough and on a sufficient scale – something that is currently hard to imagine in Germany – at least given the strong resistance from policy-makers and the public.

Reducing CO₂ by the quantity just mentioned would require about one to four million square kilometres of land for the cultivation of energy crops, equating to up to a third of today's global arable land.

Another major problem with BECCS is that, as with afforestation, planting energy crops conflicts with the cultivation of food crops in terms of land, water and fertilisation needs. In view of global population growth and rising food demand, it is now doubted that BECCS can be used as a CDR method on a large scale.

Application readiness and research needs

There are many open questions surrounding the cultivation of energy crops for BECCS, including to what extent large-scale

cultivation would increase the pressure on the Earth's remaining natural land regions, deplete biodiversity and contribute to the extinction of animal and plant species. It is also unclear how far such cultivation can be justified in terms of competition for land and water (with regard to food production and natural regions). This is because massive expansion of irrigated plantations could drastically exacerbate water shortages in some parts of the world. The use of BECCS also depends on geological storage capacity for CO₂ being established at a sufficient scale. It is not foreseeable that such capacity will be available in the near future. Attempts are currently being made to more precisely quantify the economic viability of large-scale BECCS projects.

SPOTLIGHT

CCS: STORING CARBON DIOXIDE DEEP IN THE GROUND

Carbon capture and storage (CCS) refers in general to the process of capturing CO₂ and storing it under the ground. CCS was developed to capture the CO₂ emitted by large point sources such as cement works or coal or natural gas power plants before it enters the atmosphere. The CO₂ is subsequently injected into deep-lying rock formations or exhausted natural gas or oil deposits. CCS itself is not referred to as climate engineering. However, it is needed as a means of storing CO₂ for various proposed CDR methods. Examples include bioenergy with CCS (BECCS) and direct air capture.

About 20 CCS research projects have so far been carried out worldwide to examine how well CCS actually works and the associated risks. In some cases, they have involved building very large CCS pilot plants, some of which have now been in operation for over ten years. An example is the Sleipner project in the Norwegian part of the North Sea, in which CO₂ that has to be extracted during natural gas production is injected into the Utsira sandstone formation. The project also examines how well the sandstone formation is suited to permanent storage of CO₂. Worldwide, the pore spaces in such sandstone formations

offer a large storage reservoir for CO₂. The CO₂ reacts with the sandstone and is thus chemically neutralised. In addition to that, there is storage space freed by exhausted natural gas and oil deposits. Germany has exhausted natural gas deposits with a storage capacity of some 2.5 billion tonnes and sandstone formations with a capacity of over nine billion tonnes.

In principle, CCS technology has been sufficiently researched and made ready for deployment as a result of research work conducted in recent years. Research projects between 1994 and 2005 initially aimed to evaluate the technology, design projects, and analyse the legal and regulatory systems that might be used to manage CCS in the future. A number of very large pilot plants were then built between 2005 and 2015. To continue operating, however, these rely on subsidies as there are hardly any viable CCS business models to date. So far it has not been possible to finance them from trading emission allowances because the price for emitted CO₂ is too low. The only profitable CCS plants are in the USA where the captured CO₂ is sold to the oil industry. Oil companies inject the CO₂ into near-exhausted deposits in order to recover the remaining gas and oil. Many funding programmes for CCS research worldwide, and especially in the USA, are due to expire in the near future.

AFFORESTATION

Reforestation has long been standard forestry practice. It is generally done for timber production or to return cleared forest land to its natural state. Forests have also been planted in recent years to compensate CO₂ emissions. Trees store atmospheric CO₂ in wood by photosynthesis. Depending on their longevity, the carbon can remain sequestered in them for several centuries. Ideally, their timber should subsequently be used in a way such that the carbon stays captured – for example in the construction of buildings. When wood is burned, the carbon is released again as CO₂. Afforestation is spoken of as a CDR method when it is deliberately used on a sufficiently large scale to contribute significantly to removing CO₂ from the atmosphere.

The idea of greening the Sahara and other large deserts goes as far back as the 1970s. However, studies show that the disadvantages outweigh the benefits. Not least, large quantities of water would have to be provided to cultivate the trees. The irrigation would probably cost more than other measures to reduce CO₂ emissions and would drastically exacerbate regional water shortages. Another long-discussed proposal is the afforestation of northern tundra regions. However, that, too, could have negative consequences by decreasing the albedo

effect, meaning the ability of the Earth's surface to reflect solar radiation. Today's tundra is covered in winter with ice and snow. This white surface reflects part of the solar radiation reaching the Earth back into space. By contrast, forests appear darker in winter and they consequently absorb more radiation as heat. A reduction in albedo would conflict with the aim of reforesting the tundra – preventing the Earth from heating up – and would thus be counterproductive.

Massive afforestation in middle and lower latitudes would also increase water exchange with the atmosphere. The leaf surfaces of trees transpire water, which then evaporates. As with an oasis, the ambient air cools as a result. The heat of condensation is released again when precipitation forms elsewhere. The additional water vapour can also affect cloud formation and the radiation balance. Depending on the region, therefore, afforestation can have contradictory local and global effects and, in part, can run contrary to the actual objective of preventing the Earth from heating up.

Potential and scale

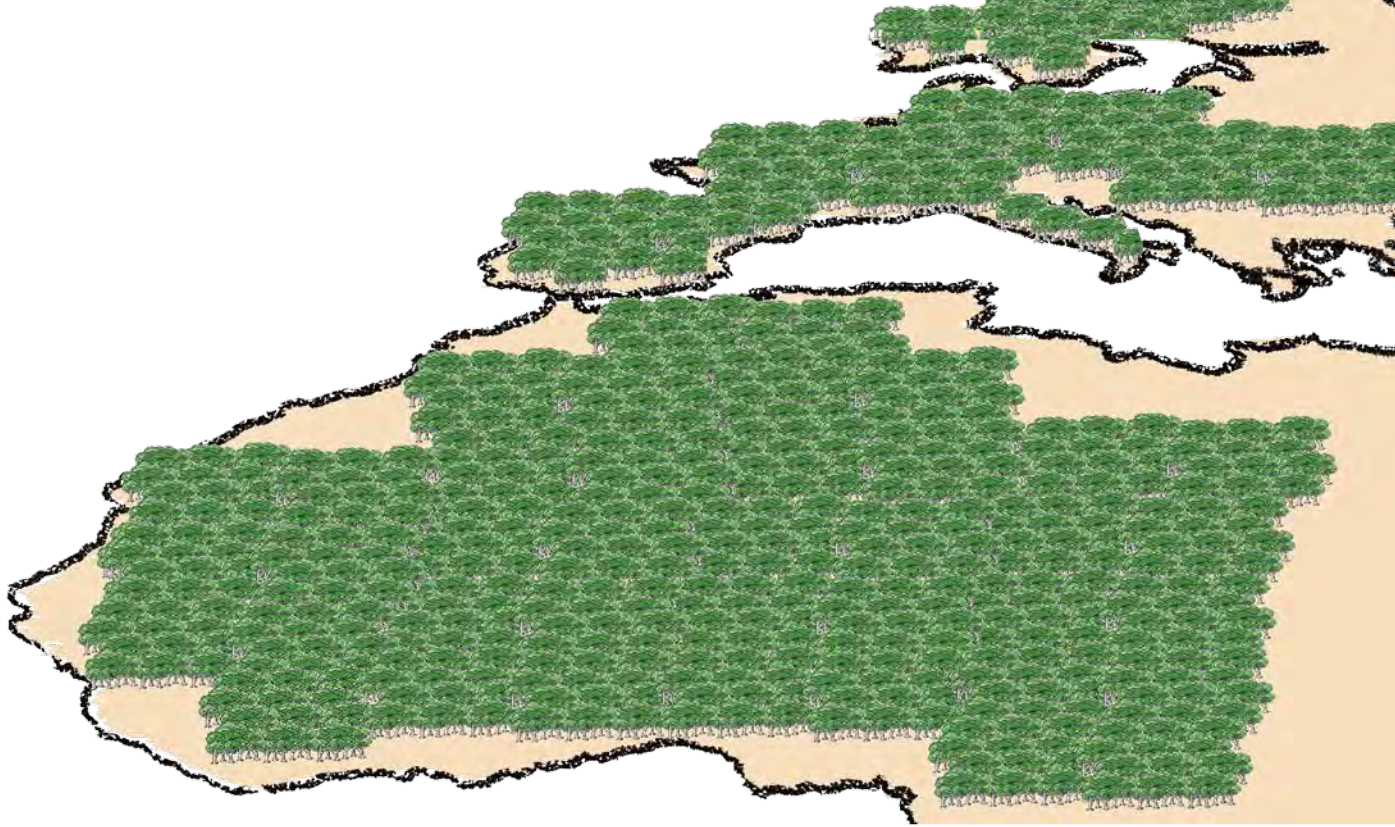
By optimistic estimates, large-scale afforestation could capture large quantities of carbon worldwide. Potentially up to ten billion tonnes of CO₂ per year could be sequestered in trees by 2100. This would involve planting at least eight million

As there are hardly any new funding programmes on the agenda, it is possible that after 2020 existing CCS projects will have to cease operation and no new research projects will be approved.

The International Energy Agency in Paris has determined in scenarios that CCS plants with the capacity for six billion tonnes of CO₂ a year would have to be available for BECCS or direct air capture by 2050 in order to achieve the 2 °C target. That would require a large series of new plants to go into operation in the years ahead. If CCS projects are only funded on about the same scale as in previous years, however, CCS plants with a capacity of only around 700 million tonnes will be available by 2050.

In view of the controversy surrounding CCS and storing CO₂ in the ground, it seems likely that in many countries, it will only be used if further research is done into the opportunities and risks for each location and public acceptance of the technology can be

improved. If CCS research were instead to be further scaled back, that would also rule out the development of expertise in CO₂ storage for BECCS and direct air capture. Thorough geological surveys and the selection of suitable storage reservoirs typically take at least ten years and a further five years are needed to evaluate the specific CCS plant and obtain the necessary permits. If research is now halted, that will further postpone the potential starting date for using CCS in combination with BECCS and direct air capture. It would then probably be too late to achieve the targets under the Paris Climate Agreement with the CDR methods proposed so far. A responsible course of action for the international community would be for countries to appraise the potential for future CO₂ storage on their territory today in order to keep the option for CCS in combination with BECCS and direct air capture open at a later date. International approaches also need to be developed for practicable incentive, control and governance systems for the storage of CO₂. ♦



square kilometres of land on which other land uses have to be abandoned. That is roughly the area of Brazil. Afforestation could thus partially contribute to efforts for removing CO₂ from the atmosphere that are needed alongside drastic emission reductions. If even larger areas were to be afforested, this CDR measure would conflict with other land uses such as pasture or the cultivation of energy or food crops. It is thus estimated that hardly any land will be available for future afforestation projects due to global population growth and the expansion of agriculture.

Application readiness and research needs

Experts have studied the pros and cons of large-scale afforestation closely in recent years. Scientists use mathematical models to try and determine the actual carbon dioxide removal potential of afforestation and the expected consequences for human life and the environment. Increasingly detailed studies also aim to determine, for example, what natural emissions are released from the soil during afforestation, what impacts it has on the radiation and hydrological regime, and what the costs of forest management are. Researchers are also investigating energy-saving and low-emission irrigation and fertilisation methods together with sustainable cultivation strategies that consider ecological and socioeconomic aspects. However, global population growth and the expansion of food production remain unknown, making it hard to accurately assess the potential.

BIOCHAR

A further method that uses the CO₂ uptake of plants for the long-term sequestration of carbon dioxide is the production of a type of charcoal known as biochar. In a process called pyrolysis, vegetable biomass or waste plant matter is heated to several hundred degrees Celsius in the absence of oxygen to leave a solid, coal-like substance. Biogas and bio-oil are produced as by-products and can be used as a substitute for fossil fuels. Materials that can be subjected to pyrolysis include crop residues, cuttings, livestock manure, slurry, sewage sludge and other organic waste. Unlike charcoal, biochar is not meant for combustion. Instead, it can be worked into arable soils, where it remains in the ground for a long time. This is because its stable structure means it breaks down very slowly. The carbon contained in it thus remains sequestered for long periods. Biochar also improves soil properties, in that water and nutrients are better retained in the ground. This enables more biomass to be produced, which could additionally counteract climate change.

An advantage of biochar over BECCS is that it does not necessarily require crops to be grown specifically for the purpose as it can also be produced from waste plant matter. This avoids direct competition with food production. A slightly different picture nevertheless emerges if biochar is to be used on a large scale as a CDR method. To remove several billion tonnes of CO₂ from the atmosphere each year, several hundred million hectares would have to be planted with miscanthus or similarly fast-growing species. These hardly produce any food,



however, and there would consequently again be competition with food production in a similar way to BECCS. One basic advantage of biochar is that the process is technically easy to implement, so in many countries – and notably in emerging and developing countries – it can be produced locally using small installations.

Potential and scale

According to various scientific studies, if the biochar process were to be developed in the years ahead, between 0.5 and two billion tonnes of CO₂ a year could be removed from the atmosphere in future worldwide. A decisive factor, however, is whether biochar is produced from waste plant matter alone or if fast-growing crops have to be cultivated specifically for the purpose.

For CO₂ to be sequestered on the scale of billions of tonnes, that would require a very large area of land. But biochar could still contribute to a certain extent even if it were to be produced from waste plant matter alone. There are estimates that about ten percent of annual European CO₂ emissions could be offset by turning biomass waste into biochar throughout Europe. This would not need additional land.

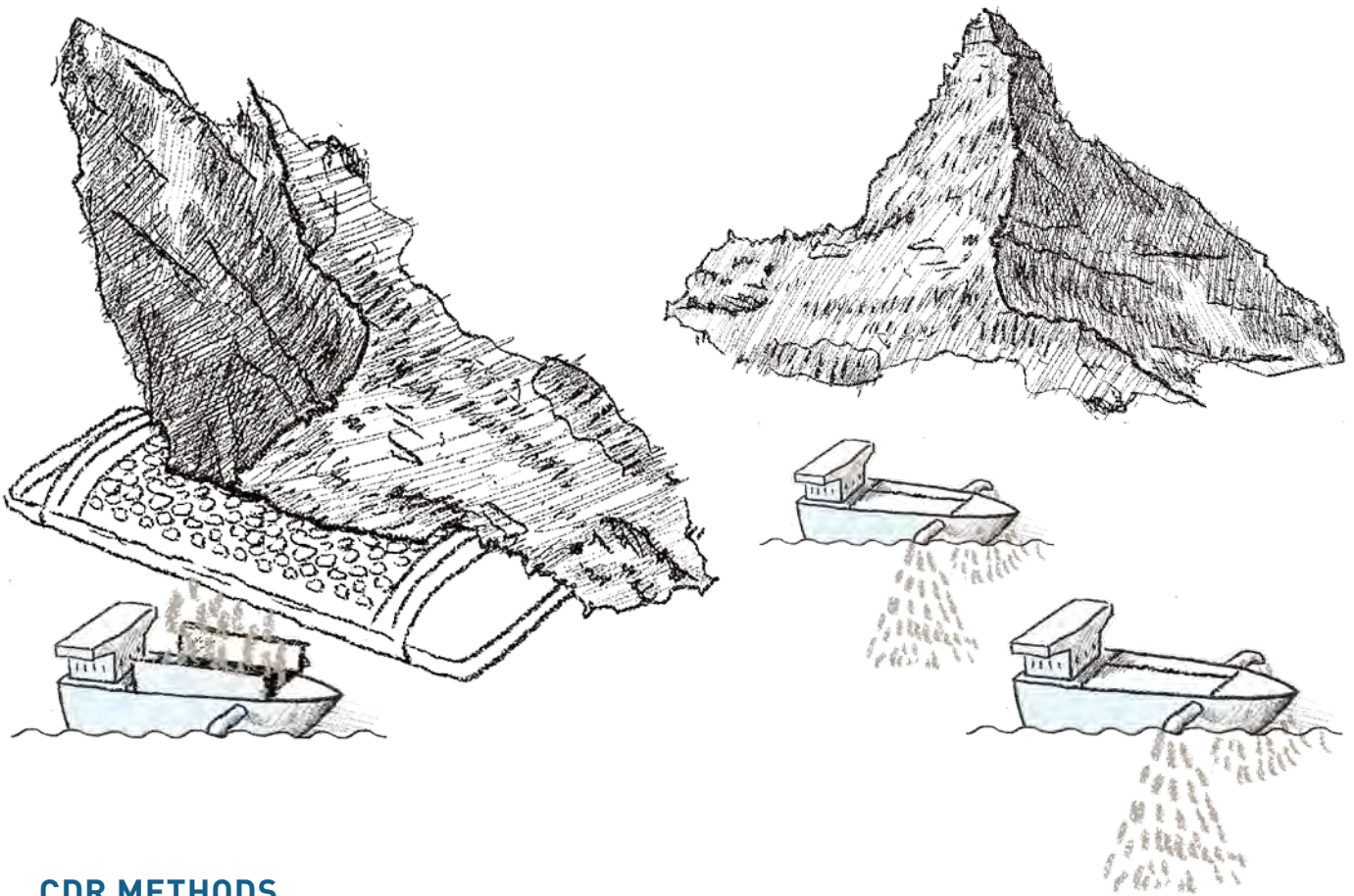
Application readiness and research needs

Biochar is not only good for improving soil quality. Research is also being conducted into the use of the waste heat from biochar facilities and the use of biochar as a fertiliser carrier, as a substitute for sand in building materials, and as carbon for medical applications. With regard to the bio-oil component, research is being done on using it to make bioplastics.

The technology for producing biochar is mature and has already been developed to an industrial scale in large pilot plants. However, it is unclear how much biochar can be spread on agricultural land or in the environment in general. While it has the potential to sequester carbon for the long term, there is still a lack of detailed studies on how it behaves in large quantities in the environment.

SOIL CARBON ENHANCEMENT

Another area of discussion is how far soil carbon uptake can be improved by modifying agricultural techniques. Experts refer to this method as soil carbon enhancement. The technologies grouped under it mostly count as natural climate solutions. Numerous individual research projects have been carried out on this topic worldwide in recent years. Among other things, it has been shown that soil can be made to store significantly more carbon by working in more harvest residues into the soil or by sowing cover crops. Other studies have investigated whether a similar effect can be achieved by cultivating deeper rooting crops or perennial cereals. Ploughing also plays a part. If deep ploughing is dispensed with and sowing is adjusted accordingly, biological decomposition processes in the soil are slowed down and carbon accumulates. According to various scientific estimates, global soils could store between 0.7 and eleven billion tonnes of CO₂ annually as a result of adapted agricultural techniques. There is a large range of uncertainty involved, however, as it is unclear how permanent the sequestration will be and what part is played by one-off effects such as the switch from deep to shallower ploughing.



CDR METHODS → OCEANIC APPLICATIONS

ENHANCED WEATHERING

About a quarter of the CO₂ emitted by burning fossil fuels is absorbed by the oceans in natural processes. This leads to the formation of carbonic acid and is responsible for the increasing acidification of the oceans. Ocean acidification can have far-reaching adverse effects on food chains and biodiversity; it also increasingly causes the dissolution of calcareous sediments and organisms such as corals. This is countered by natural weathering, in which minerals are released as certain rocks break down. These minerals are washed from land to sea, where they react with carbon that becomes permanently captured in the form of bicarbonate and carbonate ions. This changes the chemical properties of sea water, making it more alkaline. When this process takes place in surface water in contact with the atmosphere, the CO₂ removed from the water by weathering can be replaced by CO₂ from the atmosphere.

In this way, enhanced weathering, which has already been discussed above under terrestrial methods, is also being considered as an oceanic application of CDR. Alkaline substances such as powdered silicate or carbonate rock are directly introduced into the surface waters of the oceans in order to chemically bind CO₂. The material can be mined or industrially produced on land, shipped out to sea and spread

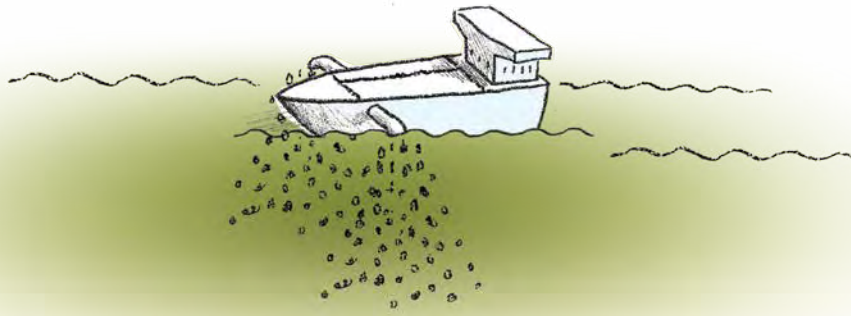
in the water. Use of this method would not only enable the oceans to absorb more CO₂. It would also have the positive side effect of counteracting ocean acidification.

Potential

In principle, there are enough minerals worldwide to bind all CO₂ emissions. However, these minerals would have to be mined and ground to a fine powder or chemically modified in an industrial process so that they dissolve quickly in water and do not sink into the depths before reacting with CO₂. Recently, new studies have estimated the potential of enhanced weathering. The outcome was that if work on establishing this CDR method were to begin immediately, between ten million and five billion tonnes of CO₂ could be removed from the atmosphere per year from 2050 onward.

Scale

For enhanced weathering to have a global effect, the quantity of minerals needed would mean establishing a completely new large-scale mining industry or a large-scale mineral production industry. This is because compensating global CO₂ emissions would require the spreading of minerals in quantities comparable to the volume of coal mined today. The fine mineral powder would also either have to be dissolved in seawater at land-based plants and subsequently discharged



into the sea or carried out to sea by large cargo vessels. In total, this CDR method would be costly and energy-intensive and could also have major environmental impacts on land.

Application readiness and research needs

The potential effectiveness of enhanced weathering on a global scale, its cost and whether it is viable in energy terms is currently being investigated by modelling and, in part, in small-scale laboratory experiments. Data from larger, field experiments covering a restricted geographical area would be needed in order to make the modelling more precise. This would make it possible to more accurately determine how much additional CO₂ would be absorbed by the mineral enrichment of seawater. At the same time, knowledge could be gained about the effects of increased mineral concentrations on marine life. Some minerals contain iron, which has a fertilising effect in the sea, but may also carry toxic impurities that could have unintended side effects on marine ecosystems.

IRON FERTILISATION

Plants on land and algae in the sea obtain energy using photosynthesis. In the process, they absorb CO₂ from the air. Oceanic phytoplankton alone account for about half of global photosynthesis and thus absorb large quantities of CO₂ from the atmosphere. The stored CO₂ is then transferred via the food chain to other marine organisms such as small crustaceans, fish and whales. These organisms sink when they die. The majority of their biomass is decomposed by bacteria, whereupon the CO₂ stored in the organisms is released back into the surrounding water and eventually comes into contact with the atmosphere again as a result of ocean circulation. A small portion of their biomass sinks to the ocean depths where it is sequestered in sediment on the sea floor. Part of the CO₂ originally captured in plankton is consequently removed from the atmosphere for a long time.

Since a quarter of the world's oceans are naturally deficient in plant nutrients and in particular iron, experts began work some

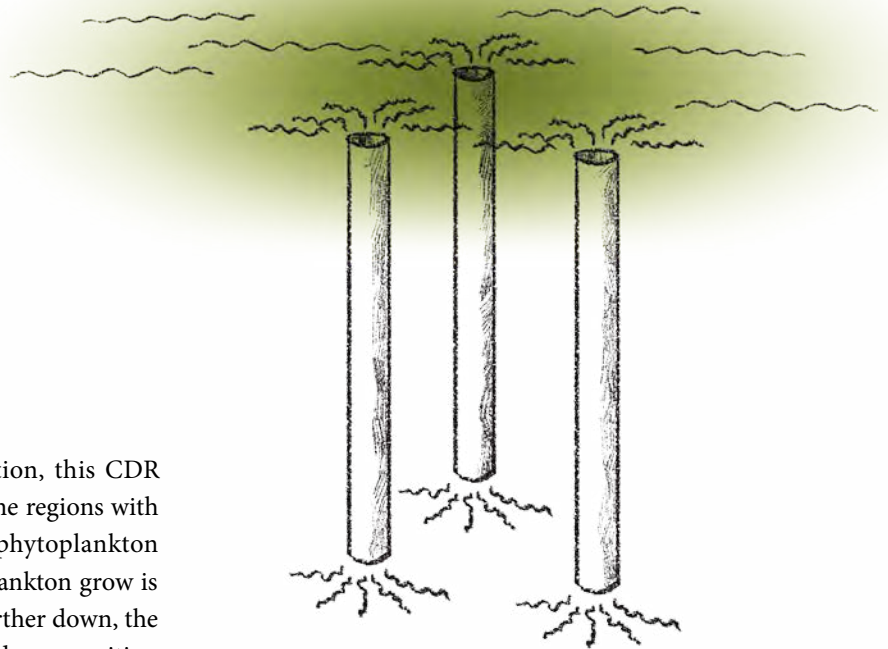
years ago on developing the idea of artificial iron fertilisation. Fertilising with relatively small quantities of iron would stimulate plankton growth significantly, thus increasing the absorption of CO₂ from the atmosphere. This would ultimately lead to more CO₂ being transported in dead biomass to the ocean depths. Experiments in the laboratory and at sea have shown that phytoplankton indeed do grow vigorously after the introduction of iron powder.

Potential and scale

The experiments show that iron fertilisation increases plankton growth and CO₂ uptake. However, only a small proportion of plankton actually sink to the depths and remove CO₂ from the atmosphere for the long term. According to various scientific studies, were iron fertilisation to be developed on a large scale in the years ahead, between 200 million and two billion tonnes of CO₂ a year could be removed from the atmosphere worldwide from 2050. To have a global effect, however, at least the entire Southern Ocean would have to be constantly fertilised with iron.

Application readiness and research needs

After several field experiments, many scientists are now abandoning the idea of iron fertilisation as a CDR method, partly because of the unpredictable side effects on marine ecological communities. It could thus have effects in the oceans that are familiar from coastal areas over-fertilised with nutrients today. The excess nutrients could cause large plankton blooms whose oxygen-depleting bacterial degradation leaves areas that are low in oxygen or even anoxic. A further side effect could be the increased formation of nitrous oxide, a potent greenhouse gas that can rise from the sea into the atmosphere. This would partly reverse the effect of the CDR method. A further mechanism would also be counterproductive: Modelling shows that once fertilisation ceases, it is highly likely that much of the CO₂ absorbed by the oceans would return to the atmosphere over timescales of decades to centuries. The atmospheric CO₂ concentration could consequently rise again after the measure comes to an end.



ARTIFICIAL OCEAN UPWELLING

In a similar way to artificial ocean fertilisation, this CDR approach aims to provide nutrient-poor marine regions with additional nutrients in order to stimulate phytoplankton growth. The sunlit ocean zone where phytoplankton grow is low in nutrients. Just a few hundred metres further down, the situation is quite different. There, bacterial decomposition of biomass gradually sinking from the surface to the depths releases numerous nutrients back into the water – but also CO_2 that is likewise a product of bacterial decomposition. This means the deeper ocean zones are generally rich in nutrients. Off some coasts, such as the coasts of Namibia and Peru, this nutrient-rich water is brought by currents from greater depths to the surface. These upwelling zones are consequently especially rich in plankton and fish. The idea of artificial upwelling is to use large pumps and tubes to bring water from deeper zones to the ocean surface in order to stimulate phytoplankton growth – and with it the uptake of CO_2 from the atmosphere.

Potential

Several years ago, a company applied for a patent for the construction of floating pumps that could be powered by wave energy. In total, however, this method has relatively minor potential of less than a billion tonnes of CO_2 per year. This is mainly because the nutrient-rich deeper ocean water is also rich in CO_2 , which is brought up to the surface and consequently counteracts the fertilisation effect.

Scale

The results of computer modelling show that very large numbers of pumps would be needed to capture a climatically significant quantity of CO_2 by increased phytoplankton growth. With the pump technology mentioned above, several million pumps would be needed worldwide to attain significant upwelling volumes. In total, artificial upwelling would have to occur over about 50 percent of the ocean's surface – an enormous technical challenge.

Application readiness and research needs

Artificial upwelling is currently being tested in research projects in China, Japan and Europe. However, the main aim of those projects is to see if providing nutrients from the depths can increase fish production. There are currently no large-scale experiments in the context of climate engineering. Modelling shows that artificial upwelling also has its problems. Redistributing cold water to the sea surface would cool the atmosphere above the sea as a positive side effect. This effect would reverse, however, as soon as the pumps are switched off. The heat transported downwards by the redistribution would quickly well up to the surface again and escape into the atmosphere, which would very quickly intensify global heating. According to the models, this effect would even be stronger than if artificial upwelling had never been used. Temperatures would be higher than in a business-as-usual scenario – a scenario in which climate mitigation action continues at its current slow pace – for decades or even for centuries. In the end, most researchers have now distanced themselves from the idea of artificial upwelling as a CDR method, partly also because of the unpredictable consequences for marine habitats.



RADIATION MANAGEMENT

The temperature of the Earth's atmosphere is, put simply, determined by three variables connected with solar radiation. The most important of these is incident short-wave solar radiation, which supplies the Earth with energy. The second is the reflection of this radiation by clouds, by particles in the Earth's atmosphere or by ice in the polar regions. These immediately reflect part of the incident solar energy back into space. The third variable in the global heat budget is long-wave heat radiation. This arises when the land or ocean surface releases solar energy back into the atmosphere. Part of the long-wave heat radiation released by the planetary surface is absorbed by greenhouse gases and then re-emitted in all directions – including back downwards, causing the same radiation to heat the Earth again. So it is the long-wave radiation that causes the greenhouse effect. By contrast, almost all radiation management (RM) methods aim to increase the reflection of incident short-wave solar radiation.

RADIATION MANAGEMENT → REFLECTIVE AEROSOLS

One idea is to release reflective particles (aerosols) in the upper layers of the atmosphere – the stratosphere (15 to 50 kilometres altitude) – to reflect short-wave solar radiation back into space. Less solar radiation then reaches the Earth's surface, thus reducing global warming.

SULPHATE AEROSOLS

The discussion of reflective aerosols centres on sulphate aerosols. Volcanic eruptions naturally emit large quantities of sulphate, a compound of sulphur, into the stratosphere. It has long been known that these ash particles reflect short-wave sunlight. For large volcanic eruptions, this can lead to global cooling.

The idea of slowing down global warming by spreading sulphate aerosols in the stratosphere was first proposed as early as the 1970s. As the stratosphere has no precipitation to wash away the sulphate, the particles remain at high altitude for a relatively long time – estimated to be one to two years.

Potential

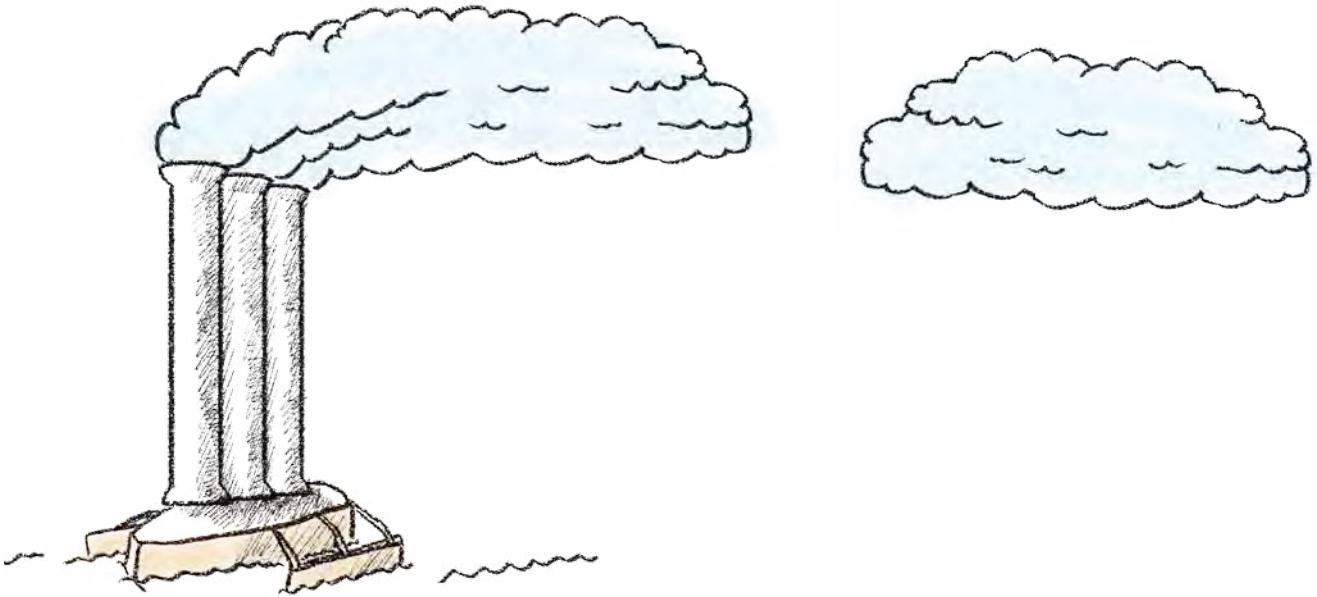
As large volcanic eruptions show, spreading sulphate aerosols in such quantities in the stratosphere could have a cooling effect of several tenths of a degree Celsius. However, recent studies underscore that the quantities of sulphate needed for substantial cooling are larger than previously assumed. Also, at excessively high concentrations, the particles would clump together and fall out of the sky more rapidly. There is also the fundamental question of how spreading the necessary quantities of sulphate could be technically implemented. A patent has existed for some years for sulphate to be spread by commercial aircraft by way of an additive in aviation fuel. US researchers are pursuing the idea of spraying aerosols using a hose lifted into the stratosphere by balloon.

Scale

The eruption of the Philippine volcano Pinatubo in 1992 caused an estimated 15 to 20 million tonnes of sulphur dioxide to be carried into the stratosphere. This resulted in a global cooling of, on average, around half a degree Celsius in the months that followed. Although a volcanic eruption – unlike deliberate radiation management – is a singular event that carries a lot of material into the stratosphere at one stroke, this example illustrates the scale on which sulphate aerosols would have to be spread in the stratosphere in order to have a significant impact on the climate.

Application readiness and research needs

This RM method remains hypothetical for the time being because as yet there is no mature, economically viable technology for transporting the required quantities of sulphate to altitudes of 20 to 25 kilometres. Also, despite a number of



studies on the subject, the risks of this global measure are still unclear. It is largely unknown, for example, to what extent the shading effect at high altitudes might change the evaporation of water at the Earth's surface and thus the global water cycle. Another unknown is whether the sulphate could increase stratospheric ozone depletion. The sulphate particles would also reduce the quantity of incident solar radiation reaching the Earth's surface in general and so to a certain extent darken the sky. It is largely unknown what net effect that would have on, for example, plant growth or solar power generation.

RADIATION MANAGEMENT → CLOUD MODIFICATION

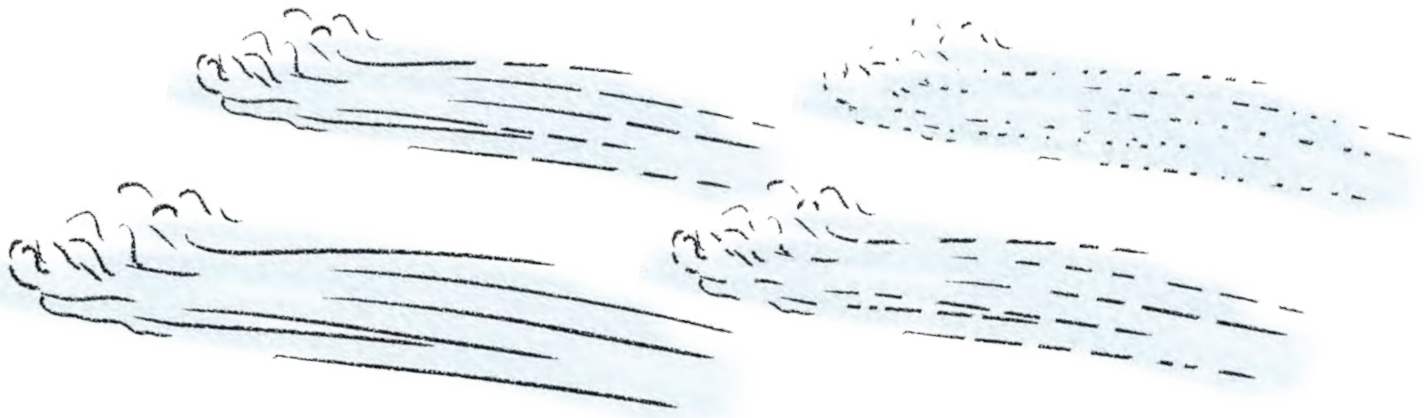
Clouds play a major part in the Earth's heat balance. They act here in contradictory ways. On the one hand, they reflect part of the short-wave solar radiation and so have a cooling effect. On the other, they absorb long-wave heat radiation emitted from the Earth's surface and radiate some of it back down. This greenhouse effect results in warming. RM methods that address both mechanisms have been discussed for over 20 years. It is unclear to what extent artificially altering the clouds on this scale would influence and change the water cycle and air circulation in the lower levels of the atmosphere. Scientists fear that it could trigger changes in the climate in various regions of the world.

MARINE CLOUD BRIGHTENING

As early as the 1980s, clouds forming around ships' exhaust plumes above the sea under certain conditions were noticed on satellite images and those clouds reflect short-wave sunlight back into space. The reason why ship tracks cause clouds to form over remote marine areas especially is as follows: The air above these sea areas is usually particularly clean. It has hardly any particles for airborne moisture to condense around. Releasing particles artificially in such regions – as happens with ship exhausts – increases the number of condensation nuclei and more cloud droplets form. Some years ago, the idea was proposed of spraying saltwater over the oceans, as the salt crystals in the water make for good condensation nuclei. This would make it possible to create artificial clouds, of a cloud type known as stratocumulus, that intensify the reflection of short-wave sunlight and result overall in a cooling of the Earth. It is not yet known, however, if this would lead to regional or supraregional changes in the climate.

Potential and scale

This method is considered to have very large potential. It is estimated that about three percent of the Earth's surface is particularly well suited for artificial modification of stratocumulus clouds. Southern Ocean regions are considered to be especially promising, and most of all the marine areas off Namibia and Peru. Seeding clouds there could offset up to 35 percent of the current greenhouse effect of CO₂. The individual clouds only last for a few hours to a few days. Sea water would therefore have to be sprayed continuously above the surface of the tropical marine regions by thousands of vessels around the globe.



Application readiness and research needs

Further research is needed to determine whether this method is economically viable and environmentally compatible. Energy-efficient spraying technologies would also be needed. It also has to be kept in mind that the method only makes sense if the equipment and vessels run on renewables-generated electricity. The basic technical challenge is how to propel the saltwater aerosols to altitudes at which stratocumulus form (from several hundred to 2,000 metres).

THINNING OF ARCTIC WINTER CIRRUS CLOUDS

Instead of increasing the cooling effect of the clouds, it is also possible to decrease their warming effect by influencing cloud dispersion. An RM method is thus being discussed that involves dispersing or at least altering cirrus clouds that occur at altitudes of 5,000 to 13,000 metres. Cirrus clouds consist of ice crystals that reflect both short-wave solar radiation and long-wave heat radiation. Which way they act depends on their altitude, the geographical latitude, and also the shape of their ice crystals. In most cases, they reflect long-wave heat radiation back to the Earth's surface. Cirrus clouds therefore tend to contribute more to global warming. This effect is particularly pronounced during the dark polar winter, when the cooling effect from reflection of solar radiation is not there. Dispersing or thinning the cirrus clouds then, or modifying the properties of their ice crystals, would allow long-wave heat radiation to escape into space: The Earth would be able to expel more heat. This could theoretically be achieved by seeding ice nuclei in the atmosphere. The artificial ice nuclei would cause the formation of larger ice crystals that fall more rapidly, thus depleting the clouds.

Potential

The method's potential cannot currently be quantified. It is possible that polar cirrus clouds cannot be influenced in the desired manner and that the method is ineffective. In the optimum case, a number of models calculate a potential 1 °C

global cooling effect. Dispersing cirrus clouds would have the basic advantage of affecting heat radiation rather than solar radiation. The method may therefore be better at offsetting the effect of greenhouse gases. Since the impact on the radiation balance as a result of cloud thinning or dispersal would vary considerably from region to region, scientists expect changes in both the climate and the water cycle in the affected regions. There could also be major meteorological side effects with an impact on regional weather.

Scale

Scientists estimate that the material expense for spreading the ice nuclei would be relatively small. It may be enough to spread the particles in suitable locations using commercial aircraft. The quantities of material needed would be in the range of a few kilograms per flight.

Application readiness and research status

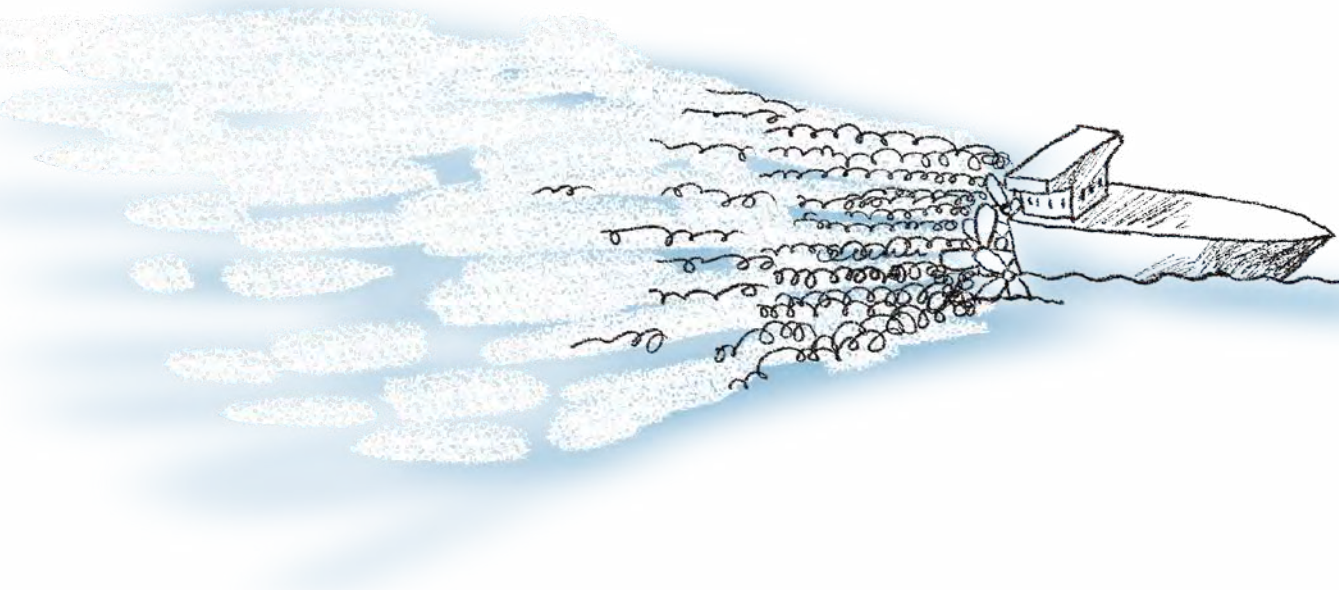
Because not enough research has yet been done into the formation and properties of polar cirrus clouds, it is not known how well they can be dispersed in practice. It is consequently so far not possible to precisely quantify the method's effectiveness.

RADIATION MANAGEMENT → ALBEDO MODIFICATION

Methods have also been discussed in recent years for enhancing the Earth's reflectivity, or albedo. The intended aim of these methods would be to reflect more short-wave radiation back into space. They include various ideas:

CULTIVATION OF REFLECTIVE CROPS

The albedo of farming land can be increased by growing high-albedo crops. Light-coloured cereals, for example, reflect more sunlight than plants with dark-green leaves and more still



than forest. This method is estimated to have little potential, however, because not enough farmland is available worldwide on which agriculture could be geared towards RM needs. In the vast majority of cases, agriculture must cater to the nutrition needs of the world's population.

PROVIDING REFLECTIVE SURFACES

Another possibility is enhancing the albedo of cities and deserts. White roofs and road surfaces would only have a minor effect globally because of the small areas involved. At best, it is possible to influence the local climate and save energy costs.

MICROBUBBLES/SEA FOAM

Microscopically small air bubbles in the sea are known to be good at reflecting sunlight. Such bubbles form naturally by wave motion. It is also conceivable that ships could be equipped with special aeration systems to produce large quantities of artificial microbubbles. These would be expected to have a lifespan of several months to several years. This means they could have a measurable effect in total. So far, however, the approach is not much more than an idea. Further research is needed into its feasibility and environmental impacts.

SEEING THE BIG PICTURE

CE methods have to be applied on a huge scale if they are to change the climate. This means they could, inadvertently, conflict with other human development goals. That applies equally to carbon dioxide removal (CDR) and radiation management (RM) methods. Scientists are already able to outline the potential areas of conflict: Every hectare that is reforested or turned into biomass plantation for climate purposes may be a hectare too few in the long term when it comes to feeding the steadily growing world population. Futuristic visions such as afforestation of the Sahara fail at obstacles such as the lack of water. Enhanced weathering of large quantities of minerals could harm biodiversity in rivers and coastal waters.

As with climate change itself, the side effects of CDR and RM methods are unevenly distributed. They create winners and losers by favouring or disadvantaging specific population groups or countries. To prevent political tensions, cross-border side effects must therefore be taken into account from the outset and proposals made for solutions or compensatory measures. Also, from the moment people start deliberately influencing the climate, every hurricane, every drought and every flood could potentially lead to political upheaval because it will be hard to say exactly who or what caused the weather phenomenon.

One thing that is certain is that RM methods cannot restore the climate to its former state as we know it today. This is because CO₂ and reflective particles added to the atmosphere act very differently. CO₂ influences heat radiation from the Earth. As heat radiates quite evenly from around the planet, this

effect is relatively similar globally. Reflecting particles added to the atmosphere, on the other hand, influence incident solar radiation, and this varies considerably both from place to place and over time. It is at its strongest in the tropics during the daytime. In regions subject to polar winter, on the other hand, the particles have no effect on the radiation balance. It would also have a very diverse effect on rain and the distribution of precipitation. All in all, the advantages and disadvantages of RM are likely to be spread unevenly across the world's regions, leading to major political tensions and demands for financial compensation. Radiation management methods also harbour the risk of what is called termination shock. This refers to the fact that while global warming could be limited for a time by means such as spreading sulphur particles in the upper atmosphere, the cooling effect would be lost again if particle spreading ceased and the particles fell back to the surface. The temperature would then rise at a far faster pace than it would have without any intervention in the climate. In the event of such abrupt warming, many animal and plant species would presumably have great difficulty adapting to the new conditions.

Generally speaking, it is currently nearly impossible to predict the consequences of RM methods, and also of many CDR methods if applied on a large scale. However, the limits of climate engineering are not only of a natural or technological, but also of a political character. The governance and control of climate engineering is an unresolved challenge.

Plenty of methods, but which to choose?

As the list of the various CDR and RM methods shows, there is a wealth of ideas that could potentially be used in the future alongside efforts to reduce emissions. Some, such as afforestation or the production of biochar, are already technologically mature, while others are no more than ideas. One thing that is certain is that rather than relying on one single method, there has to be a mix of methods selected according to location and the state of the climate. It is also important to remember that many CDR methods also directly affect the radiation budget by modifying the albedo and the water cycle. Similarly, many RM methods also cause changes in the carbon cycle, notably via temperature effects acting on biological processes. Thus, it would not always be possible to tease apart the effects, and side effects, of CDR and RM methods used at the same time.

Deploying a portfolio of CE methods could also lead to interactions between their respective effects. This would basically resemble the situation of a patient fighting an illness with a cocktail of drugs where it is not known precisely how they will affect the individual patient or how they interact with each other. Not enough research has yet been done into the scale of interactions and how to make the most of them. It may be difficult to split out the effectiveness and side effects of individual methods and regulate their use accordingly. International agreement on their deployment and a coordinated approach would therefore be essential requirements.

Whether CDR or RM methods are deployed alongside emission reduction efforts will ultimately depend on policy decisions and social values. This is because the use of climate engineering is not only a question of technical feasibility. On the contrary, it also touches on fundamental social questions such as intergenerational equity. ♦

IN A NUTSHELL

- CDR methods help to combat the cause of global warming by removing CO₂ from the Earth's atmosphere. RM methods instead merely combat the symptom of global warming.
- CDR and RM methods are only climatically significant if used on large scales. At such scales, however, all these methods harbour certain risks.
- None of the CDR or RM methods is mature enough to be deployed on a mass scale. Many methods are so far no more than theoretical proposals that at best have been tested in small field experiments.

FURTHER READING

- The ethical and legal standpoint: Do we have the right or even a duty to deliberately influence the climate? – p. 42
- Limited scope for control: The crux of the chaotic climate system – p. 54

SPOTLIGHT

THE CLIMATE POTENTIAL OF NATURAL CLIMATE SOLUTIONS

A concept that frequently comes up in the search for means to limit global warming is the idea of natural climate solutions (NCSs). These are ways of reducing greenhouse gas emissions caused by intensive land-use or of increasing carbon dioxide take-up by natural sinks. Scientists distinguish between two types of NCS: restoration measures and management measures. The first category covers approaches for returning landscapes and ecosystems to their natural state as carbon sinks, such as reforestation rainforests, mangrove swamps and boreal forests, or restoring former peatlands, salt marshes and seagrass meadows. Measures on or in the sea are often referred to as blue carbon approaches.

Management measures aim to improve the management of forest, arable land, grassland and peatland in order to increase the carbon content in their soil and vegetation and reduce their overall release of greenhouse gases. Field trials show that promising emission reductions can be obtained by means such as combining tree planting with arable crops or using manure or compost instead of artificial fertiliser.

Natural solutions could potentially have a huge climate impact if implemented on a global scale. Most are ready for deployment today, are cost-effective, and combine climate action with nature conservation, which is why they find favour with environmental organisations. According to recent studies, NCSs alone could boost carbon sinks on a scale equivalent to one-third of the emissions savings needed to achieve the 2 °C target.

However, there are also obstacles and limits to the global implementation of NCSs. Restoration measures need large areas of land that would then cease to be available for food production. The same applies to water resources. There is also the question of whether demand for timber and other materials could still be met with sustainably managed forests. One particular challenge is that there is no one-size-fits-all solution because different ecosystems have different requirements. Solutions that work in Europe cannot simply be transferred to other regions of the world but would have to be adapted.

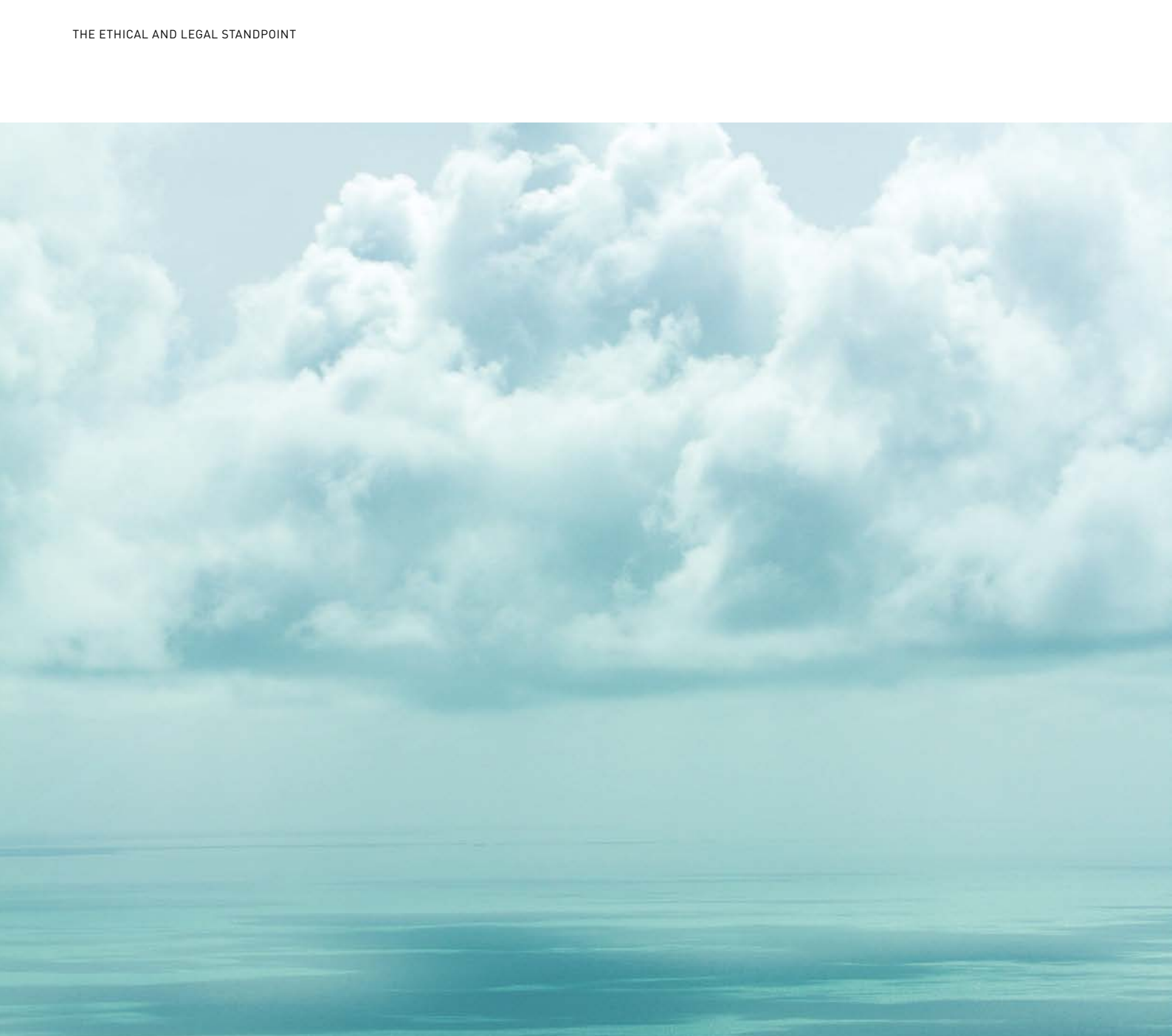
The world would also need new policy instruments for the agricultural sector in order to enable carbon-oriented soil

management. NCSs could be promoted by introducing a carbon tax. A good monitoring network would have to be set up to oversee the activities. It is also essential for the many stakeholders to be involved (farmers, consumers, retailers, etc.).

Decision makers should also bear in mind that the climate impact of natural climate solutions is finite. Carbon stored in the soil or in plant biomass only stays there as long as there is no adverse change in the climate, sustainable land use is kept up and, for example, trees are not felled and burned. It has also been shown that the climate balance of ecosystems such as peatlands and forests can tip over time, say when methane (also a greenhouse gas) is emitted or the land surface becomes darker in colour, which can drive additional heating.

The scientific community is divided on the question of how sensitive natural climate solutions themselves are to future climate change. Some researchers expect the CO₂ absorption capacity of ecosystems to fall, while others predict that it will increase. It is undisputed, however, that deploying NCSs would have many positive side effects. These include improvements in air and water quality and the local climate, enhanced soil nutrient availability, increases in biodiversity and soil water retention, and heightened resilience of ecosystems to extreme climate-related events such as droughts. Scientists also expect large synergies. If a carbon tax were to be used to pay for the implementation of natural climate solutions, that would create a new income source for rural populations. ♦





Anyone wanting to influence the Earth's temperature on a large scale intervenes in the planet's energy and material cycles, and affects socio-political structures in ways that are difficult to predict. This raises the question: Are we allowed to use climate engineering, or do we even have a duty to do so given how global warming endangers both ecosystems and people?

THE ETHICAL AND LEGAL STANDPOINT:

DO WE HAVE THE RIGHT OR EVEN A DUTY TO DELIBERATELY INFLUENCE THE CLIMATE?

What are the arguments for or against researching, testing and using specific methods? This cannot be answered on grounds of technical feasibility alone. Just because something is possible does not mean it is allowed. Ethicists therefore focus on the moral justification for and evaluation of options and measures. They reconstruct and analyse the arguments for and against. Law scholars, in turn, examine whether potential measures can be reconciled with the prevailing provisions and principles of international law.

Importantly, the ethical and legal arguments apply to carbon dioxide removal methods and radiation management methods in different degrees. The decisive factor in all of this is that the various approaches subsumed under climate engineering differ substantially in their aims, their spatial and temporal scales, their impacts and their associated risks. There are also distinctions between the moral and political issues that arise in light of the different methods used. In many cases, different issues have to be discussed in relation to radiation management than in relation to carbon dioxide removal. For the latter, a further major distinction has to be made between ocean-based and land-based methods. This means that blanket judgments on the admissibility or inadmissibility of climate engineering as a whole are unconvincing and do not help move the debate forward. It is possible to argue in favour of carbon dioxide removal (CDR) and against radiation management (RM) (or vice versa) or perhaps only for one specific method used in CDR or RM.

Always no more than the second-best option

A typical underlying assumption that ethicists examine, for example, is the belief widespread in the 1960s and 1970s that for problems that cannot be solved by policy means, a quick and ideally low-cost ‘techno fix’ must be sought. This argument is based on the assumption that technology can buy the time needed for a policy solution to be found.

Translated into the context of climate engineering (CE), this means that because it will take several decades to achieve full-blown transition of the global economy to carbon-neutral energy sources, climate engineering must be given serious thought. There are, however, a number of arguments against the combination of buying time and a techno fix.

False sense of security

One particularly important argument in the debate is that research and development of climate engineering methods involves a ‘moral hazard’ that the risks associated with a rise in greenhouse gas emissions could be increasingly ignored. Along this line of thinking, the theoretical feasibility of climate engineering could give people a false sense of security. Especially with RM methods as a kind of ‘ace up the sleeve’, it would close their eyes to the dangers of climate change. In the hope that the worst can thus be prevented, people would be even more reluctant than ever to change their lifestyles and support the transition to a low-carbon economy.

Is it morally justifiable to maintain our energy-intensive lifestyles and pass on their side effects to future generations? Given the potential for conflict, can we expect climate engineering methods to augment emission reduction?

What are the arguments in favour of or against researching, testing and using specific methods? This cannot be answered on grounds of technical feasibility alone.

With this attitude, however, humanity would put off the risks associated with the various methods for the future and neglect their responsibility to act on behalf of generations to come. Would it be acceptable to ignore and pass on those risks? If intergenerational equity is to be the benchmark, we must leave our grandchildren and great-grandchildren a world in which their opportunities are no worse than those available to the generations alive today.

That responsibility applies in particular to the poorer regions of the world. It means humanity must now limit climate change to the greatest extent possible, develop and finance adaptation strategies, and prevent both climate and environment-driven mass human migration. If we are to take our responsibility for future generations seriously, we are also obliged to prevent the use of CE from posing a dilemma for our descendants, who may have to either continue CE methods despite serious side effects or discontinue them and thus perhaps even accelerate climate change. This applies especially to RM methods because RM would not reduce atmospheric greenhouse gas concentrations. Without accompanying CO₂ reduction measures, RM methods would postpone the responsibility for finding a solution into the future.

In some cases, however, the same risk analysis also applies to CDR methods, as these too are associated with considerable risks due to scale needed for them to have an impact on the climate. As long as humankind continues to release increasing levels of CO₂ into the atmosphere, more and more areas of land and sea will be needed to offset those emissions using suitable CDR methods. For some such methods, especially afforestation, it would have to be ensured over very long periods of time that the carbon that has been stored is not re-released sometime in the future. Given the growing world population and the need to expand food production, land-intensive CDR strategies – such as bioenergy with carbon capture and storage (BECCS) – could prove extremely conflict-prone when it comes to land use. In many cases, land used for CDR is no longer available for food production. The effects of BECCS on land prices, land

ownership and thus on the agricultural livelihoods of large numbers of people would also have to be taken into account. In addition, establishing huge plantations of fast-growing grass and tree crops could deplete both water reserves and biodiversity. The question of irrigating BECCS crops alone highlights the resource-related conflicts that could arise, bearing in mind that around 70 percent of global freshwater withdrawals go towards the irrigation of agricultural land.

Is it morally justifiable to maintain our energy-intensive lifestyles and pass on their side effects to future generations? Given the potential for conflict, can we expect climate engineering methods to augment emission reduction? If, with regard to the global climate and to nature, we see equity between present and future generations as the yardstick for our actions, these questions are of tremendous importance.

The hubris trap

The fact that people tend to over-estimate their own abilities speaks against large-scale intervention in the Earth's climate. This also applies to researchers and engineers. The argument of over-estimating one's own capabilities is known as the hubris argument. The term 'hubris' comes from ancient Greek and means excessive pride or overconfidence.

Even after years of intensive research into the various methods of climate engineering, it would be irresponsible to believe that we humans fully understand and master the effects of these methods on the systems to be influenced – especially as many of the methods have not yet been technically implemented and cannot easily be tested in the field. First and foremost, this concerns the scale of their intended and unintended effects, their socio-political impacts and hence their direct and knock-on costs. It can be assumed that new problems will arise as CDR and RM methods are used over time.

Saying goodbye to the natural world

A third argument against climate engineering results from the question as to the extent to which RM methods in particular would change our relationship with nature. Do technical interventions in the climate mean a final departure from the natural Earth system? The fact that we have changed the world's climate unintentionally by using fossil fuels does not mean that we have free license to influence it intentionally. To take deliberate control of climate processes would be to take our confidence in the predictability and controllability of interventions in the Earth's cycles to the extreme.



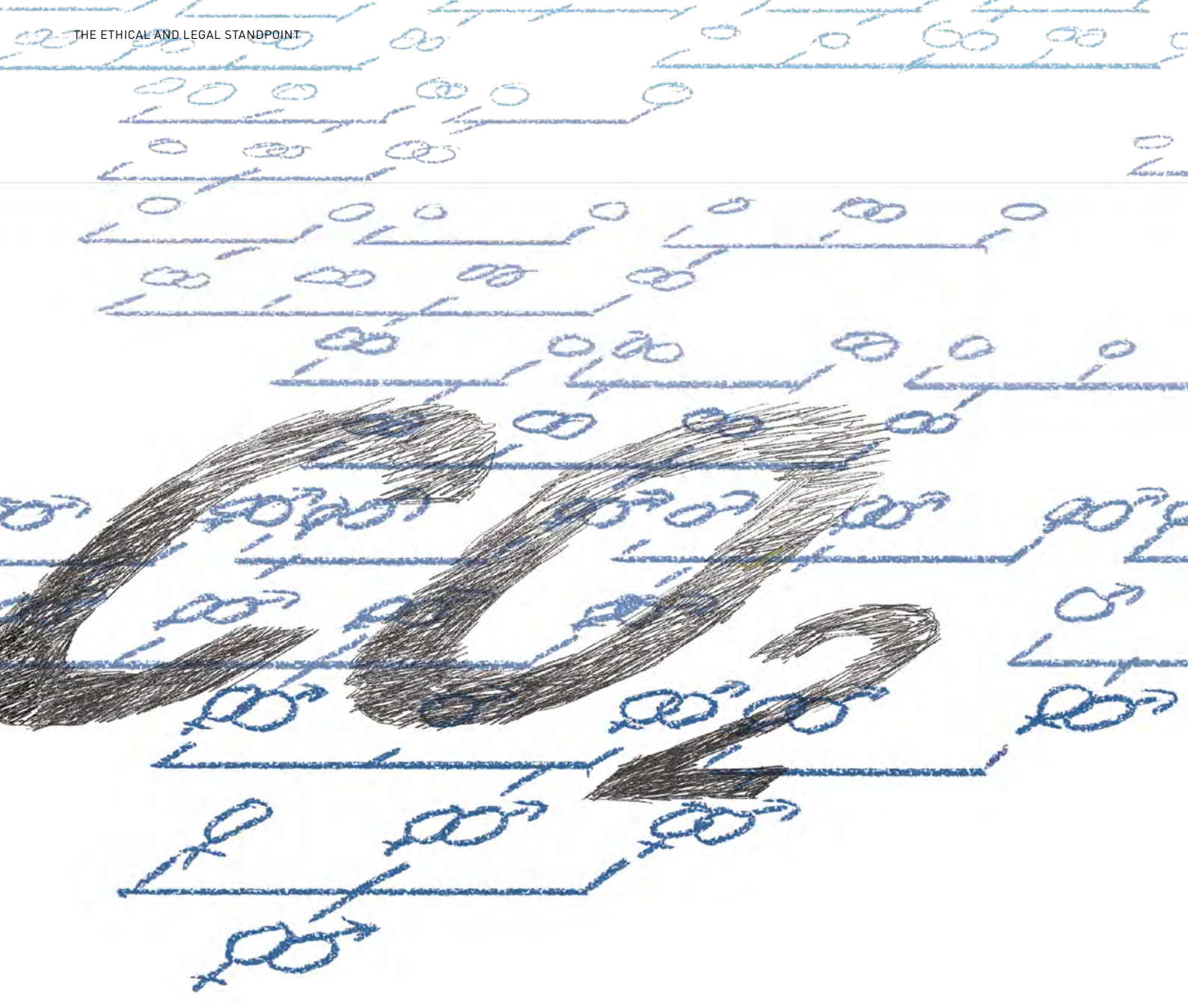
It is mostly radiation management methods that have so far been discussed as an expression of total human dominance over nature. Measures such as afforestation do not necessarily stand in stark contrast to the idea of nature conservation, which requires that people respect nature and reduce their own impact. It would certainly be possible to combine CDR strategies with strategies for natural adaptation to climate change, biodiversity conservation and ecological restoration. These mainly apply to forests, peatlands and soils and are also referred to as natural climate solutions. However, large-scale restoration measures can also be seen as major interventions in ecosystems. This could also put them in direct competition with other sustainability goals such as food production. If storage of significant quantities of carbon is to be ensured over long periods of time, then even ‘natural’ solutions tend to require active management and hence an intervention in nature.

The problem of goal prioritisation

The United Nations has set out 17 Sustainable Development Goals (SDGs) to ensure sustainable development throughout the world. While one of these is to combat climate change, the

UN sustainable development strategy is also about poverty reduction, food security, peace, natural resources and water supply. Implementing the SDGs is a complex task – one that poses a tremendous challenge for humankind. Given the complexity involved, it is self-evident that every CE method has the potential to conflict with the UN SDGs. This applies especially to water reserves, biodiversity and food security. But positive effects are also possible – for example, improving soil fertility by enriching arable soils with powdered minerals (enhanced weathering). CDR methods that realistically promise positive interactions with other SDGs thus deserve greater attention both from the science community and from policymakers.

If CDR or RM methods are used, situations may arise in which – depending on the method involved – goals would have to be weighed against one another. One example would be land-based CDR methods such as cultivating crops for bioenergy or biochar. Large-scale use of such methods could jeopardise both biodiversity conservation and production of adequate food supplies. How to resolve goal conflicts of this



It is true that every tonne of CO₂ released today increases the pressure on future generations to act.

kind is hotly debated. In the end, the decisive factors will be the choice of priorities and of who should benefit and who should not. This in turn comes down to values and is thus a fundamental matter of ethics. A policy answer should only be provided on the basis of sufficient ethical arguments. There will be no simple algorithm that can be used to resolve the conflicting goals. This makes superordinate policymaking structures all the more important.

How convincing are the ethical arguments in favour of climate engineering?

Despite these critical arguments against CDR and RM methods, there are also aspects that speak in favour of researching and potentially using them. Put in simple terms, the central arguments are as follows:

→ **Intergenerational responsibility**

The impacts of climate change will primarily affect future generations. This is why we must equip our offspring with knowledge of both CDR and RM methods so they can decide for themselves how to use them when the time comes. This argument is also known as ‘arming the future.’

→ **Emergency response**

We need climate-regulating methods to be able to intervene in the climate quickly and effectively in an emergency. This is known as the ‘emergency’ argument and applies solely to RM.

→ **Buying time**

By carefully applying RM methods for a limited period, humankind can buy time to use CDR methods in order to effect large-scale reductions in atmospheric greenhouse gas concentrations without further warming in the interim.

→ **Lesser evil**

If humankind is not able to reduce greenhouse gas emissions quickly enough, the evils involved in using CDR or RM would be less than those involved if they are not used. This is also known as the ‘lesser evil’ argument.

No RM research without investment in emission avoidance

Are any of the above arguments convincing? It is true that every tonne of CO₂ released today increases the pressure on future generations to act. If global warming is to be limited to below 2 °C by the end of the 21st century, they will have to remove more CO₂ from the atmosphere in an even shorter space of time. The task thus becomes bigger the longer effective climate action is delayed.

Some experts – not least given the moral hazard mentioned earlier – consider it unethical to use the possible need of future generations as an argument to begin developing RM methods now rather than resolutely implementing measures to reduce emissions. Anyone who is not prepared to adapt their own lifestyle to help meet the climate targets should not use the argument of safeguarding the future to justify investment in the research and development of RM. This approach is also referred to as the conditionality argument: A state should, therefore, only be allowed to embark on RM research and development if it meets certain climate policy conditions relating to its climate policy integrity and credibility. Given the risks mentioned and the hubris trap, which stakeholders can in all good conscience be entrusted with RM methods, and who gets to decide? This has led environmental ethicists working on the DFG Priority Programme to develop a principle on which RM research should be based: States may only conduct research on radiation management if they pursue ambitious climate policies and make appropriate contributions to international

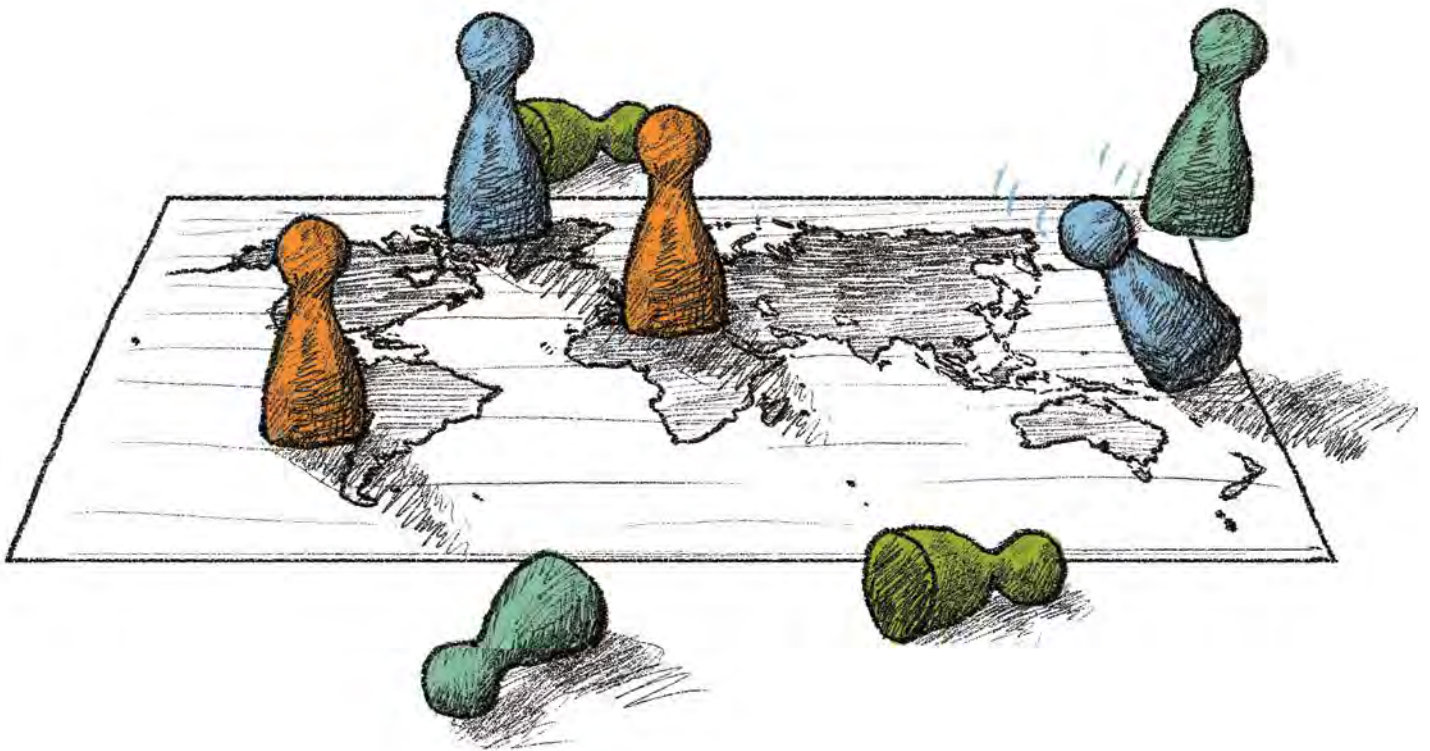
carbon offsetting funds. This conditionality argument relates first and foremost to field research at various scales, whereas laboratory research and modelling are subject to the principle of academic freedom.

Emergency scenario: Playing with fire

Arguments in favour of the use of climate-regulating RM in emergency situations must also be subjected to critical appraisal. The decisive question here is: What constitutes a climate emergency? An emergency does not simply exist or occur – it has to be declared. The ‘tipping points’ in the climate system are often cited as examples. These are far-reaching changes in the climate as a result of which the living conditions of many millions of people would worsen. They include the melting of the West Antarctic ice sheet, weakening of water mass circulation in the North Atlantic and the disruption of monsoon rains in West Africa.

It appears that interventions in the Earth’s radiation budget could indeed reduce the increase in the global mean temperature at least for the duration of RM deployment. It remains questionable, however, whether radiation management would be able to prevent some of the tipping points mentioned from being reached. On the one hand, the changes will probably already be in full swing before we even notice the first clear signs of a tipping point. On the other, given the inertia in the affected processes, even drastic measures might no longer exert any real influence in a given situation. It would then be practically impossible to prevent a tipping point from being exceeded. In other cases, however, the slowing down of the temperature rise could lead to a weakening of dangerous feedback processes. A rapid cooling of the Earth could, for example, stop the Arctic permafrost from thawing and thus prevent the release of large quantities of methane stored in the ground.

It would in any case be naïve to believe that debate surrounding an emergency connected with drastic changes in climate and related tipping points could be conducted solely on the basis of scientific facts. A state of emergency always has to be declared politically. Doing so presupposes agreement in society about the conditions for making such a declaration. Will a rapid rise in sea levels or years of drought in certain regions warrant declaration of a climate emergency, or will political and social unrest be needed as well? When is an event or situation deemed so bad that it must be interpreted as an emergency that legitimises the use of radiation management methods?



In the end, the decisive factors will be the choice of priorities and of who should benefit and who should not. This in turn comes down to values and is thus a fundamental matter of ethics.

For example, would the New Orleans floods caused by Hurricane Katrina have been enough for a planetary climate emergency to be declared?

In reality, different values, perceptions and interests always play a role when assessing exceptional situations. The decision to declare a state of emergency – whether climate-related or not – is always a political act in the course of which political interests are pursued. One particularly alarming aspect in all of this is the fact that emergency situations can cause democratic principles to be forgotten or ignored. In this way, they give certain people power and options for action that they would not have without a state of emergency or that in normal circumstances would be unlawful. For this reason alone, philosophers, environmental ethicists and social scientists warn against taking up the argument of emergency response in the CE debate without prior critical appraisal.

Using radiation management to buy time – but on three conditions

Despite all this, the idea of being able to use radiation management to reduce the temperature quickly and effectively also gives rise to hope. It could enable humanity to buy the time urgently needed to develop technologies for emission-neutral lifestyles, implement climate action and remove sufficient quantities of carbon from the atmosphere. Some scientists believe that this approach is the only convincing argument in favour of deploying RM methods, but they attach three conditions to any form of application.

→ First, a clear deployment strategy would be needed, based on extensive scientific evidence. However, given the lack of relevant research to date, much research and testing would

have to be done in the coming decades before humankind could actually intervene in the Earth's radiation budget to any great extent. It would be necessary to move quickly from small-scale experiments to large-scale trials, with a fluid boundary between experiment and trial.

→ Second, applying the conditionality argument, any deployment would have to be accompanied by major investment in emission reductions and environmentally compatible CDR measures so as not only to combat the symptoms of global warming, but also its cause.

→ Third, for intergenerational equity, the deployment would have to be for a limited time from the outset. The initiators of radiation management measures would therefore need a clear exit strategy whose implementation would have to be monitored. The phase-out should not be abrupt, but gradual. The 'buying time' argument thus presupposes great moral and political trust in the implementing actors.

Summing up at this point, it can be said that two basic insights should be taken into account when considering climate engineering. First, use of CE methods cannot and must not be a substitute for vast reductions in greenhouse gas emissions. The guiding rule must be that the causes of problems have to be resolved. Second, the use of CE methods does not put an end to shifting risks into the future. On the contrary, in certain circumstances the use of CE can even increase the risks for future generations. In principle, these insights apply equally to CDR methods with non-permanent CO₂ sinks and to the use of RM. The various CDR and RM methods continue to have different specific risk profiles. A drastic reduction in emissions, combined with ecological restoration and adaptation assistance conducive to the SDGs, could lead to a lower-risk future scenario. From an (environmental) ethics standpoint, this scenario would deserve to be given greater attention in science and policymaking, and to undergo priority study with a view to potential and side effects.

SPOTLIGHT

CLIMATE ENGINEERING ON TEST DRIVE: HOW MIGHT FIELD EXPERIMENTS BE CARRIED OUT?

The potential of the various CE methods and the risks associated with their use can be assessed in three different ways: Computer simulations with mathematical models of the climate system, laboratory experiments and field experiments. When it comes to field experiments, one advantage is that they are carried out under real conditions and often produce results that cannot be obtained on a computer or in a laboratory.

To reliably assess both the global impact and the side effects of a specific method, field experiments would need to be carried out on a large scale. If, for example, it is to be investigated how the Earth's radiation balance changes as a result of water droplets being released into the atmosphere, a great deal of water would have to be released into the air. Even if the

field experiment were carried out on the territory of a single country, air currents could rapidly carry those water droplets across large distances, regions and national borders. In some cases, the scale of a field experiment would thus come close to regular deployment conditions.

A few small-scale scientific field experiments involving CDR and RM have been conducted so far. One example is the Indo-German LOHAFEX project (the name combines the Indian term for iron, 'loha', and the acronym FEX for 'fertilisation experiment'), in which a German research vessel introduced several tons of iron sulphate into the South Atlantic in 2009 to induce an artificial algal bloom. Environmentalists were outraged and feared that the algal bloom would adversely affect marine flora and fauna. In the end, with the ship already on its way to the field study site, the Federal Ministry of Education and Research (BMBF) was forced to have the experiment independently assessed – not least due to pressure from the

Do legal arguments speak for or against the use of climate engineering?

The fundamental question as to whether researching into and deploying CE methods is lawful has to be assessed on the basis of international law to the extent that the impacts of a CE experiment or its use cannot be limited to the territory of the state involved and its effects would also be felt in neighbouring states or beyond.

Whether or not specific CE methods are lawful is assessed method by method based on the relevant international agreements and customary international law.

Under international law, there are so far no rules that generally and comprehensively regulate climate engineering research or deployment. It is also considered unlikely that the international community will one day produce a comprehensive international agreement on climate engineering. National interests and CDR and RM methods differ to far too great an extent. There is not even a binding definition of climate engineering in international law: Whether or not specific CE methods are lawful is instead assessed method by method based on the relevant international agreements and customary international law.

This case-by-case approach has two advantages: First, the legal assessment is based on the facts of the specific case. This means, for example, that a planned CDR or RM project will always

Federal Ministry for the Environment (BMU). The assessment concluded that the project was harmless in environmental terms and compliant with international law. The experiment therefore continued.

Another example is the Stratospheric Perturbation Experiment (SCOPEX) planned by a group of researchers from Harvard University. This field experiment envisages using a balloon to release about one kilogram of artificial aerosols at an altitude of 20 kilometres. The idea is to form a particle cloud through which the balloon would fly and carry out scientific measurements. These would provide information about the aerosols' physiochemical behaviour and thus about the effects and side effects of the method itself. When exactly the experiment will take place and whether any effects can actually be measured on such a small scale remains to be seen. There are also recent plans to conduct CDR field experiments funded by private industry. For example, an iron fertilisation experiment is planned off the Chilean coast. First and foremost, this is intended to show to what extent fishery yields can be boosted by increased algae growth. In another project being conducted off the Chinese coast, powerful pumps are to be used to bring nutrient-rich deeper ocean water up to the ocean surface to stimulate algae growth.

Thus, while CDR and RM experiments have already been carried out and others are planned, they are not regulated internationally. Field experiments are only subject to applicable national law. However, as with potential large-scale use of CE methods, controls and rules are also urgently needed for field experiments, because it cannot be ruled out that they could cause harm in other regions (see 'Climate engineering methods', page 22).

In general, rules are needed to require that states be transparent, allow general access to experiment-related data and publish the results – including, and especially, if an experiment has negative or undesirable outcomes. In 2017, an international team of scientists from the University of Calgary published a Code of Conduct for Responsible Geoengineering Research. The Code also proposes rules for conducting field experiments, such as mandatory environmental impact assessments and social impact assessments before an experiment begins. To provide a factual basis for constructive public debate on CE experiments, the Code also calls for the public to be fully informed and involved at a time when all options remain open. ♦

be evaluated on the basis of a specific agreement governing the relevant subject matter. For iron fertilisation projects, this would be the *Protocol to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter* (London Protocol; see box on page 52). In the case of CE experiments involving cloud seeding, the relevant agreements would be those on long-range transboundary air pollution and protecting the ozone layer. The second advantage is that the international community is more willing to adapt existing international law to new requirements if this is done cautiously, one step at a time. Without a large majority or even consensus among nation states, changes are ruled out.

The Paris Climate Change Agreement commits Parties to establish more carbon sinks and thus increase the storage capacity for carbon dioxide as a greenhouse gas. Carbon dioxide removal methods, such as afforestation and bioenergy with carbon capture and storage (BECCS), are not explicitly mentioned in the Agreement, but are incorporated indirectly. Radiation management (RM) technologies, on the other hand, are excluded because they do not capture CO₂. The term climate engineering was avoided when drafting the Paris Agreement.

After in-depth analysis of the various CE methods, legal experts conclude that carbon dioxide removal measures tend to give rise to fewer legal concerns than radiation management measures. For all CE methods, however, the state implementing them must at least follow the principle of prevention (this is still contested with regard to the precautionary principle) and have due regard to the existing rights and territorial integrity of other states. This includes, for example, carrying out an environmental impact assessment before deciding on the feasibility of a CE project. If a state were to plan CE measures on its own, meaning without agreement and without prior assessment, and if those measures affected neighbouring states, the measures would contravene international law. But even if a project fulfilled all the criteria, the final decision would still represent a balancing of risks. ♦

Carbon dioxide removal methods are not explicitly mentioned in the Paris Climate Change Agreement, but are incorporated indirectly. RM technologies, on the other hand, are excluded because they do not capture CO₂.

IN A NUTSHELL

- From an ethical perspective, it is impossible to make blanket judgements about the admissibility or inadmissibility of climate engineering as a whole. The reason for this is that the methods differ from each other to such an extent that an assessment can only be made for each individual case.
- Countries should only be allowed to research radiation management methods if they invest in emission avoidance as well.
- So far, there is no internationally binding definition of climate engineering. Instead, whether specific CDR or RM methods are permissible is assessed method by method on the basis of international agreements and customary international law.
- Carbon dioxide removal (CDR) methods tend to raise fewer legal concerns than radiation management (RM) methods. However, the following applies to all possible measures: Those who use CE must follow the principle of prevention and take other countries into account.

CE REGULATION UNDER INTERNATIONAL AGREEMENTS

When asked about the legal limits of deploying CE, legal experts primarily consult three international conventions, each of which covers partial aspects:

- The London Convention (Convention for the Prevention of Marine Pollution by Dumping of Wastes and Substances) and its successor, the London Protocol – relevant to marine CDR methods.
- The Convention on Biological Diversity (CBD), potentially relevant to both CDR and RM methods.
- The Vienna Convention for the Protection of the Ozone Layer (RM methods only), including the associated Montreal Protocol on Substances that Deplete the Ozone Layer.

The London Protocol as paradigm

The London Convention of 1972 was one of the first international treaties to make marine protection an international responsibility. It was amended in 1996 by the London Protocol for those states or Parties that signed the new protocol. Both instruments were developed primarily with the intention of regulating the discharge of hazardous waste and other substances into the oceans. Because CDR methods, such as iron fertilisation, also introduce substances into marine waters, the Convention can apply where such cases are concerned. Criticism is levelled at the fact that not quite 90 states have acceded to the Convention, while the London Protocol has only attracted 40 Parties, meaning that neither has universal validity. The Convention is, nonetheless, regarded as one that sets globally binding standards for marine protection. This is partly because the London Convention is flanked by the UN Convention on the Law of the Sea, the maritime law regime recognised by almost every country in the world. For example, the UN Convention on the Law of the Sea indirectly declares the standards contained in the London Convention and potentially also those set out in the London Protocol as applicable to all states, even those that have not signed them so far.

International conventions are designed to enable additions and allow specific rights and obligations of the signatory states to be extended and supplemented at a later date. This makes it possible to apply conventions to new phenomena unknown at the time of negotiation. It is also a great advantage when it comes to marine CDR methods, and has made it possible in recent years for the London Protocol to be gradually extended to include CDR. Although the amendments have not yet entered into force because they have to be ratified by the Parties to the London Protocol, the first step has been taken. For example, the scope of application has been made broader so that in future, marine geoengineering (marine CDR) can be regulated under the Protocol. Although only iron fertilisation has been included in the list of CDR measures so far, the Parties have agreed that the scope of the Protocol can be widened to cover other substances released into marine waters, such as those used in enhanced weathering. The Protocol has thus been made future-ready. Legal experts are confident that the London Protocol can serve as a paradigm for how international treaties can be adapted to regulate international use of CDR. Discussions are still underway, however, as to when the introduction of substances via CDR measures would be contrary to marine conservation in a given instance. The extent to which introducing substances influences or alters marine habitats plays a role, and this is an aspect that needs to be examined using an assessment framework before an experiment is carried out. Hence the admissibility of a CDR measure under the provisions of the London Protocol always depends on the specific case.

Biodiversity conservation so far the priority

By its very nature, the London Protocol relates only to substances discharged into the sea and thus only to some of the measures in the global CE portfolio. Additional regulatory frameworks are consequently needed. One example of such an international framework is the Convention on Biological Diversity (CBD). The CBD was negotiated with the aim of conserving biodiversity and entered into force in 1993. Under the CBD, every state has the obligation to use its natural resources sustainably and to prevent transboundary harm. With 196 Parties in total, the CBD applies almost universally. The US has not ratified the CBD, however, and is not bound by its provisions.

At the CBD Conferences of the Parties in both 2010 and 2012, unanimous decisions were adopted according to which the CBD should also be observed in matters of climate engineering. This means, among other things, that “in the absence of science-based, global, transparent and effective control and regulation, mechanisms for geo-engineering and in line with the precautionary approach [...] no climate-related geo-engineering activities are carried out that may have impacts on biodiversity until an adequate scientific basis for the justification of such activities exists.” However, prevailing opinion is that these stipulations are not binding.

Unlike the London Protocol, the CBD is not designed to regulate specific activities. Instead, its potential role in regulating climate engineering is to identify categories and procedures for monitoring and assessing climate engineering’s potential impact on biodiversity. The problem is that the obligations contained in the CBD are formulated in relatively weak terms. In this respect, it remains to be seen how and to what extent they can be applied in cases of climate engineering. But given the large number of Parties, they could well have a great knock-on effect in policymaking terms.

The challenge of proving harm

A current debate is underway as to when and under what conditions specific international frameworks actually apply. This is seen in the example of the Vienna Convention for the Protection of the Ozone Layer. Parties to the Vienna Convention are obliged to prevent the environmental release of substances that can destroy the ozone layer. They are only obliged to intervene, however, when it is clearly evident that a certain class of substances or a certain process is harmful. Causal proof is required in each case. The Vienna Convention could in principle apply where salt water droplets are released to induce cloud formation or when particles are introduced into the stratosphere, because both of these RM methods could contribute to ozone layer depletion. The problem, however, is that such proof can only be provided if RM experiments are carried out on a grand scale.

The examples outlined above show that there are already several frameworks that can be used to govern and manage CDR and RM activities between their parties. Ultimately, however, these conventions and agreements are only effective if the signatory states not only enshrine corresponding rights and obligations in their national legislation, but also enforce them. Without this kind of arrangement, effective regulation of the methods involved would be impossible to achieve.

It is also essential that states coordinate their CE measures and report their activities so they can act as one worldwide. If CE measures are actually implemented in the future, then a global accounting system will be needed to keep records of the individual activities in the various countries and their contribution to both the carbon dioxide and the radiation balance – not least to determine whether the global goal of reducing carbon emissions will actually be achieved.

An example from a different policy arena shows that it is possible to coordinate activities on an international scale: The International Atomic Energy Agency in Vienna is a scientific and technical organisation to which member states report their activities worldwide, and is also responsible for the monitoring and further development of related safety standards. It remains to be seen, however, whether a general accounting and monitoring system for climate engineering could be established along similar lines. ♦

Nobody today can say for sure whether climate engineering methods will really have the desired effect if used. One reason is the complex nature of the climate system. That rules out any notion of a tailored climate. It also means that in case of dispute, it will be impossible to prove what CE method caused what kind of outcome.



LIMITED SCOPE FOR CONTROL: THE CRUX OF THE CHAOTIC CLIMATE SYSTEM

CE methods aim to slow down or even reverse human-made climate change. They would need to be far-reaching enough to drive substantial change in the Earth's climate system. While CDR goes at the cause of global warming and its effectiveness can be measured directly in terms of CO₂ captured, the climate impacts of RM methods would have to be verified. Then again, some CDR methods, such as afforestation or soil carbon management, also change the albedo and the water cycles and thereby have a different effect on the climate than that brought about by reducing CO₂ emissions. Atmospheric radiation, in turn, interacts with the many other components of the climate system, whose inner workings are not merely complex but chaotic. This makes the effects of any CE measures extremely difficult to monitor.

Scientists speak in this context of climate noise, climate fluctuations and the natural variability of the climate system. There are three causes:

→ First, the climate is influenced by external factors, such as slight shifts in the intensity of incident solar radiation or the quantity of fine particles released into the atmosphere by volcanic eruptions. Quantifying these factors remains a major scientific challenge.

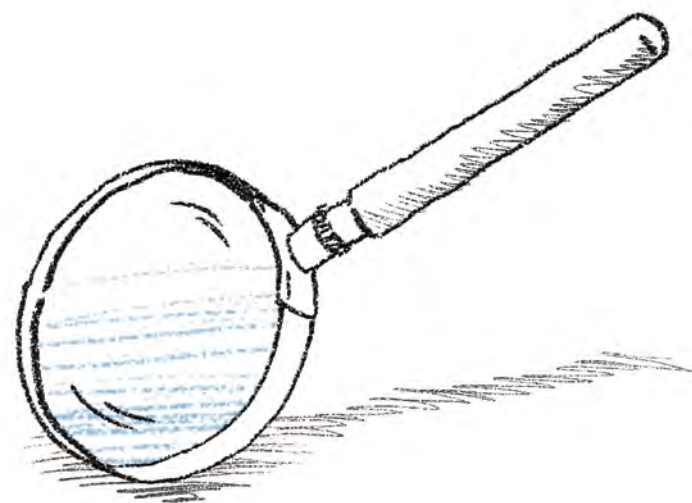
→ Second, the various components of the climate system react to changes on different time scales. If the sun, for example, shines more intensely on the Earth, the increased energy supply in the bottom layer of the atmosphere has an effect after only a few days or weeks: The air temperature rises. In contrast, decades, centuries or even millennia pass before such a warming can be detected in the depths of the ocean.

→ Third, the climate fluctuates because, in many cases, its components interact in various ways. Some respond faster and more directly; others change after a delay or only indirectly. The system is therefore never in equilibrium and is subject to more or less regular fluctuations. Among other phenomena, this is well illustrated by the natural yet unpredictable oscillation between El Niño and La Niña in the tropical Pacific. This regular reversal of the air and ocean currents between Australia and the west coast of South America impacts the global climate. But what role does climate noise play in the climate engineering debate?

Natural climate variation or climate engineering: looking for clues in models

Climate noise makes it difficult to measure and monitor the effects of any CE measures. It presents scientists with the challenge of pinpointing the precise causes of climatic changes while distinguishing natural variations from changes brought about by CE.

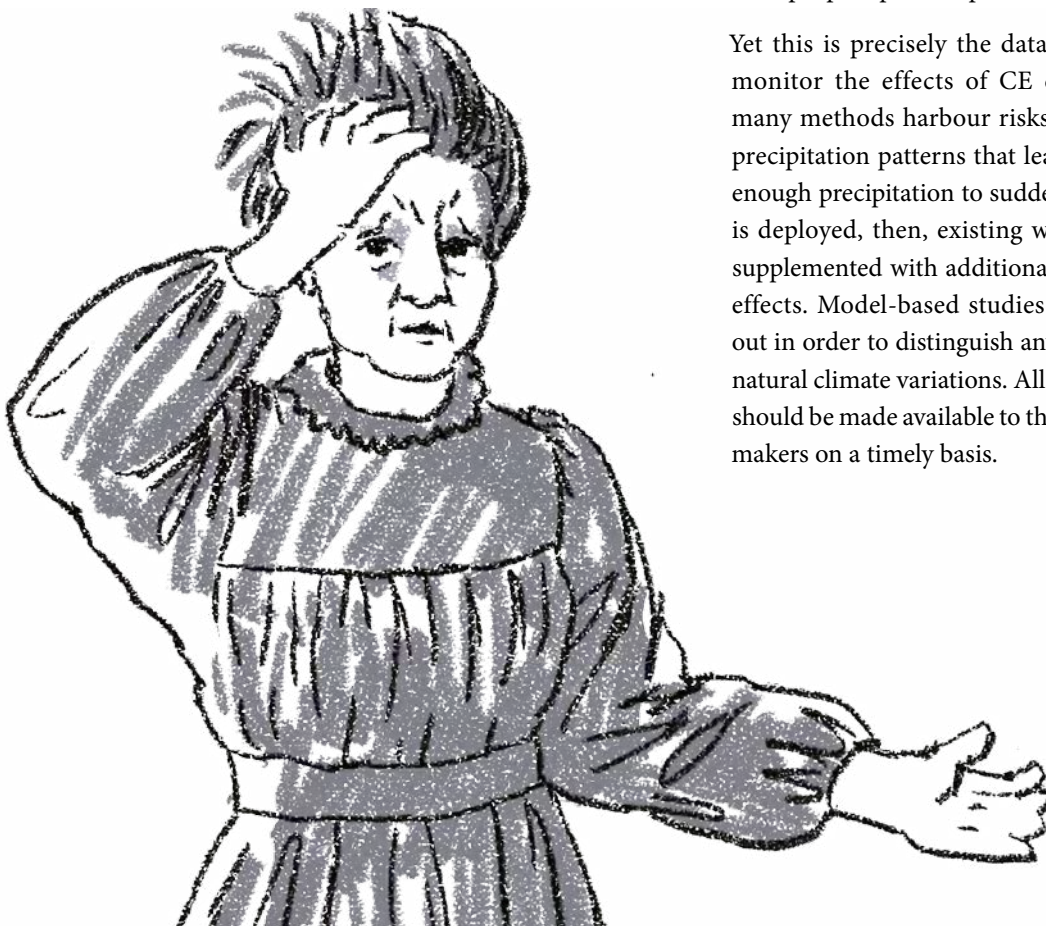
Just how difficult this is can be seen from recent research into the influence of human-made climate change on extreme weather events such as heat waves or winter storms. Put simply, climate modellers collect all available observational data immediately after an extreme event and match that data against a range of simulations. By including human-induced greenhouse gas emissions in the calculations for some simulations and leaving



In case of dispute, it would be hard to attribute specific climate effects to the use of a CE method.

them out in others, they can afterwards compare them to gauge the human contribution to the probability and severity of the extreme event. This attribution would not be possible without modelling.

How far this approach could be used for CE measures cannot yet be tested. Unlike in extreme weather research, CE researchers lack observation data for comparison purposes. There are exceptions, such as large volcanic eruptions, whose dust clouds can serve as a comparison for RM measures, and historical land-use change which can guide afforestation assessments. Any other conceivable use of CE, however, has to be simulated by scientists, because so far there have not been any large-scale field experiments.



Uncertainty in the results from modelling makes it hard to estimate the effectiveness of CE methods. This is also why neither CDR nor RM methods can deliver a tailor-made climate. The Earth's climate system is too complex and too chaotic and its processes are consequently too hard to predict for humans to be able to get the climate they want at the turn of a dial. Climate engineering also cannot rule out extreme weather events. Storms, heat waves, heavy rain or cold spells would still occur in a world with a deliberately influenced climate, but probably with differences in frequency and character (such as more cold snaps but fewer heat waves) and at different places compared to a world without climate engineering.

A monitoring network in case things go wrong

If a nation or even the international community one day decides to use CE methods, a dense global measurement network should be put in place beforehand in order to generate sufficient observation data to monitor their use. While satellites and weather stations already collect temperature and other atmospheric data throughout the world, the global monitoring network still has deficits in many regions with regard to for example precipitation patterns and quantities.

Yet this is precisely the data that scientists would need to monitor the effects of CE deployments. This is because many methods harbour risks when deployed, like a shift in precipitation patterns that leads regions that previously had enough precipitation to suddenly suffer from droughts. If CE is deployed, then, existing weather observations should be supplemented with additional measurements to monitor the effects. Model-based studies would also have to be carried out in order to distinguish any impacts of CE deployment on natural climate variations. All knowledge acquired in this way should be made available to the public and to relevant decision makers on a timely basis.

Monitoring climate effects and attributing them to specific CE methods would be even harder if humankind deployed multiple CE methods simultaneously. Measuring and monitoring their climate impact in detail could be very difficult because of the numerous interdependencies in the climate system. It is true that individual parameters would be measurable, such as the radiation effects of particles spread in the stratosphere or the atmospheric carbon dioxide concentration. Attributing how much each CE method contributed to any temperature decrease, however, could confront science with a new challenge.

An approach for peaceful dispute resolution

The difficulties in measuring, monitoring and attributing the effects of any deployment of CE would also pose a new challenge in international dispute resolution. How should a court proceed, for example, if State A filed for compensation for suffering a drought from its neighbour State B because State B spread sulphur particles in the stratosphere: What rules would apply in such a case? Who could be held liable? What evidence could be presented?

Economists, jurists, philosophers and climate scientists from the DFG Priority Programme on Climate Engineering have gone into these urgent questions and identified three problem areas:

1. Modelling data instead of photos, fingerprints and DNA traces

In disputes over climate engineering, neither party would be able to present evidence such as photographs, fingerprints or DNA traces. They could only derive assertions about the impact of CE from model simulations, which would have to show how the weather or climate would have changed with and without CE. The problem here, however, will be that there is and will never be one universal standard model. On the contrary, the choices of climate models is already so large that both parties would be almost certain to find a model whose results back their own standpoint.

2. Lack of comparative data

Any climate engineering method deployed would change the Earth's climate system to a certain extent. From then on, nobody would be able to say how the climate would have changed without the manipulation. In case of dispute, the court would therefore lack reliable comparative data. The 'world without CE' could only be represented by models and any assumptions about it would involve uncertainties.

3. Lack of empirical knowledge

Courts often base their decisions on empirical knowledge. When attributing blame for road accidents, for example, they use expert witnesses who have analysed hundreds of similar cases and can compare accident causes. In the case of climate engineering, there would be no such empirical knowledge. The only comparison would be with a simulated world without CE, which would only be represented by models.

But how should courts handle model-based evidence of this kind? Researchers are currently looking into new forms of liability schemes, like applying proportional liability. This is based on the principle that parties to a legal dispute about impacts of CE would each be held liable to the extent that they contributed to the risk of the impacts. Thus, in the example above, if State B contributed 45 percent to the risk of the drought with its deployment of CE, it would be held liable for 45 percent of the crop failure in State A.



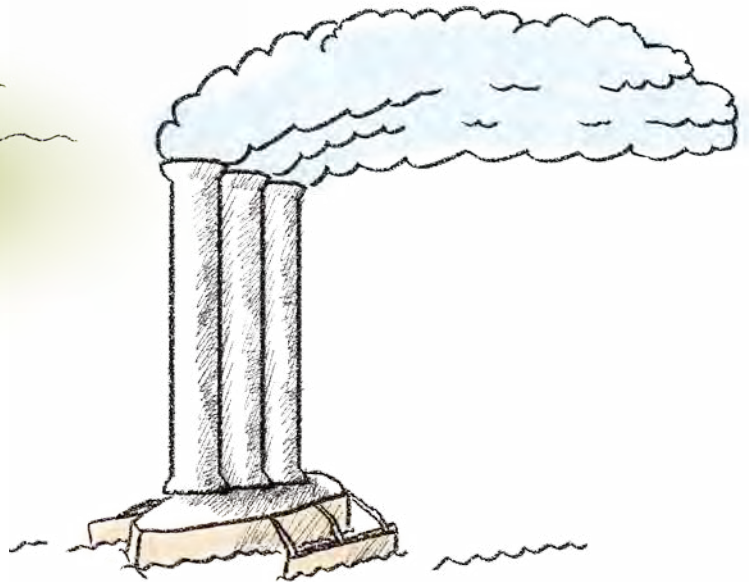


This approach is based on the fraction of attributable risk (FAR) concept that is already successfully applied in extreme weather research. There, scientists calculate the contribution of human-made climate change to an extreme weather event by comparing numerous climate models suitable to the case in question. However, these models do not derive a single value as a result, but a range of values.

It is questionable whether such FAR models would meet the standard of evidence required by international courts. In the USA, for example, expert witness testimony must meet what is called the Daubert standard in order to be admissible as evidence. This is a set of criteria used to verify that a technique – in the case of CE this would be FAR modelling – corresponds to scientific principles. There are four key questions:

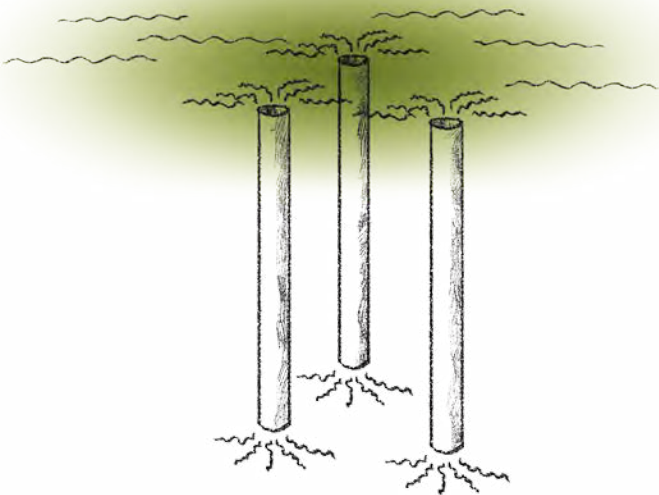
- Can the technique be empirically verified?
- Has it been subject to peer review and publication?
- Is there information about the technique's uncertainty and is that incorporated in the assessment of the findings?
- Has the technique been generally accepted within the relevant scientific community?

The DFG researchers consider that this strict set of criteria would be unsuitable for determining whether modelling of extreme weather events corresponds to basic scientific principles – for two reasons: Firstly, FAR models do not lend themselves to empirical verification, precisely because the known uncertainties imply that climate models cannot precisely predict how the climate system will change. Secondly, the uncertainty in FAR models is hard to quantify because the assumed reference system is a hypothetical world as it would have been without climate engineering.



Applying the criteria of the Daubert standard would therefore lead to FAR values not being admitted as evidence. Dispensing with the criteria entirely would not be a solution either. This would open up the possibility of too many FAR values being admitted as evidence. The parties to a case would then be able to introduce unreliable FAR values, thus making it impossible for a court to decide on the basis of the actual facts. Consequently, the Daubert standard would have to be modified for the courts to be able to make legally sound decisions on model-based evidence.

The international community hence needs to not only agree on whether or not it wants CE methods to be used in principle and what procedural rules to establish for the purpose, but also on what guidelines should be applied in the event of dispute. One possibility might be an international tribunal that all nations would agree to be bound by and that would apply a modified Daubert standard. There is currently no court competent to adjudicate international disputes around CE deployment. ♦



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- Natural variability in the climate system would make it hard to monitor and verify the effectiveness of any CE measure. If multiple CE methods are applied at the same time, it may be hard to attribute the effects of each method.
- Before CE methods are deployed, a dense observation network should be put in place which tracks similar to meteorological services changes in important climate parameters and uses modelling to determine if those changes can be attributed to the deployment of CE.
- The fact that the effects of deploying CE can only be verified and attributed by modelling poses major challenges for international dispute resolution. For this reason, DFG researchers are looking into a new liability approach under which parties that caused impacts would owe proportional liability. At the same time, there is a need for internationally agreed rules for dispute resolution and a set of criteria for the admissibility of model-based evidence.

FURTHER READING

- Climate engineering methods: Can global warming be slowed down by deliberately intervening in the climate system? – p. 22
- The ethical and legal standpoint: Do we have the right or even a duty to deliberately influence the climate? – p. 42
- SPOTLIGHT Modelling – p. 11

In most countries, politicians shy away from open discourse on climate engineering. The potential areas of conflict are simply too great. Yet public debate would be needed in order for informed social and political decisions to be made on climate engineering in the future.



POLITICAL DISCOURSE: A LONG-OVERDUE DEBATE

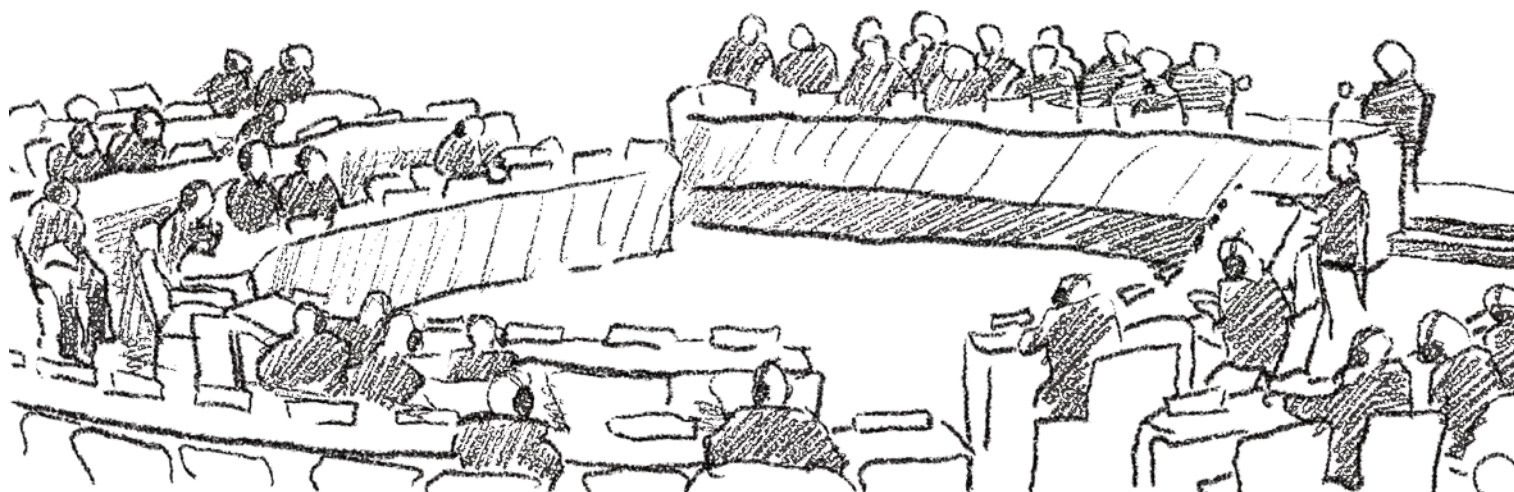
It is becoming increasingly likely that humankind will have to use CDR methods, but perhaps also RM, to meet agreed climate targets or alleviate massive climate change. The issue should thus take a more prominent place on both research and policy agendas. Although climate engineering is the subject of intense and controversial international scientific debate, no state has yet developed a clear CE policy – either on CDR or on RM – or encouraged wide-ranging public debate on climate engineering. Although individual states such as Sweden have put CDR methods on their policy agenda to achieve a net zero emissions target, the major political debate has yet to take place. Many governments are reluctant to address the issue in a broad and open way due to fear of social resistance and the need to admit failure with regard to emission avoidance.

For this reason, various initiatives around the world are working to embed at least CDR more firmly in the climate policy debate. The overall aim is to initiate transparent debate in various political bodies, especially the UN, on achieving the climate targets and thus on climate engineering alongside emission reduction.

Does climate engineering research influence the policy agenda?

Political scientists repeatedly stress that when it comes to the question of how CE options should be assessed and how they can be managed and controlled in the future, scientists also make a decisive contribution to what is discussed politically and when. Thus, the way in which CDR and RM methods are discussed by policymakers is partly determined by the research topics and methods currently being discussed by scientists. An example of how research influence politics in this way is the summary for policymakers published with each report of the Intergovernmental Panel on Climate Change (IPCC). These summaries contain estimates of future climate trends based on a range of scenarios up to the year 2100.

A public discourse on the pros and cons of different methods of carbon dioxide removal in relation to the climate targets must be conducted transparently and be science-based.





The IPCC, whose task it is to advise policymakers on climate science issues, stresses the need for carbon dioxide removal to achieve the agreed climate targets. For truly honest and transparent climate policy, policymakers must take this matter seriously and conduct the necessary political and social debates on the conceivable options.

The scenarios correspond to different development paths for the world population, the economy and renewable energy use, and can lead to different carbon dioxide concentrations and temperatures. Carbon dioxide removal, mostly by bioenergy with carbon capture and storage (BECCS), is considered an important approach in the IPCC scenarios and could make a significant contribution to achieving the 1.5°C or 2°C target.

Incorporating BECCS in the climate scenarios has had the consequence of increasing the emissions budget. Future emission reductions of well over 100 percent, which in the climate scenarios are achieved using BECCS, will initially allow increased emissions. This makes the Paris climate targets attainable in theory; in practice, it requires the use of carbon dioxide removal methods. Climate policy tends to emphasise the attainability of climate targets, but not the large-scale use of carbon dioxide removal needed for the purpose. A public discourse on the pros and cons of different methods of carbon dioxide removal in relation to the climate targets must be conducted transparently and be science-based.

And society's attitude to CE?

In Germany, CDR methods such as BECCS are largely unknown: In a representative survey, 71 percent said they had never heard of it. After reading a short informative text about the method, about a quarter of respondents said they were against the use of BECCS. The carbon capture and storage (CCS) component met with even stronger objection, with 43 percent of respondents against it. There had already been protests against the use of this technology.

Such methods are accordingly rejected by a large part of the population. This is why politicians have so far been afraid to have anything to do with the subject of carbon dioxide removal. There are also fears that it would be seen as a political move away from the current strategy of emission avoidance. CDR and RM methods could be used as an excuse for lower levels of ambition in reducing carbon dioxide emissions.

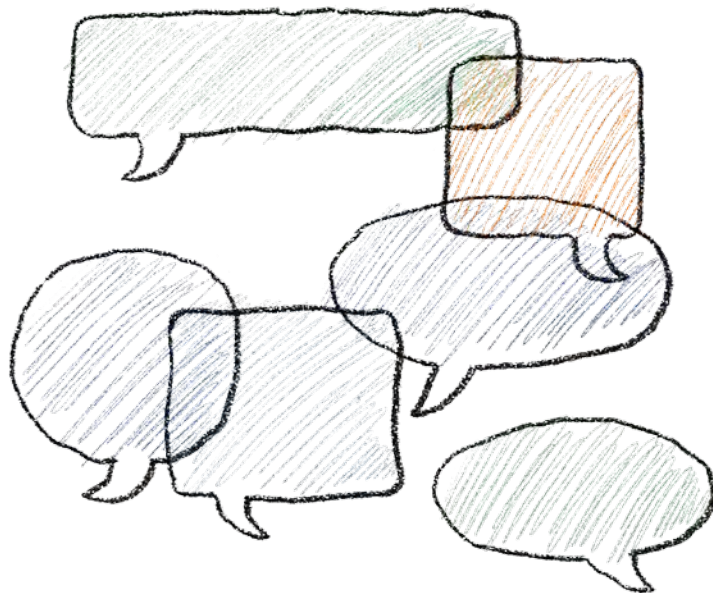
A decision for or against climate engineering can only be made at policy level in the hope that an agreement reached at that level reflects social consensus.

This is why it is necessary to hear those who are already affected by climate change in some way today or who will be affected by it in the future.

Survey participants who were informed in detail about climate change, the 2 °C target and the potential offered by the BECCS method were less willing to avoid carbon dioxide emissions than those who in the same timeframe were only informed about climate change. Yet, in a very similar study on RM methods, respondents showed an increased willingness to avoid emissions. It would thus appear that the two approaches do not influence people's willingness to avoid emissions to the same extent.

How the population would ultimately react to carbon capture and storage schemes remains to be seen. All such schemes could lead to protests or reduce people's willingness to avoid emissions. Policymakers who under those conditions advocated carbon capture methods such as BECCS as a complementary measure to emission avoidance would thus be taking a political risk. However, the IPCC, whose task it is to advise policymakers on climate science issues, stresses the need for carbon dioxide removal to achieve the agreed climate targets. For truly honest and transparent climate policy, policymakers must take this matter seriously and conduct the necessary political and social debates on the conceivable options.

A decision for or against climate engineering can only be made at policy level in the hope that an agreement reached at that level reflects social consensus. This is why it is necessary to hear those who are already affected by climate change in some way today or who will be affected by it in the future. For example, the Citizens' Forum created in the course of the climate engineering research conducted by the DGF has shown how difficult it is for citizens in an industrialised country like Germany to see things from the perspective of those in emerging and developing countries. Forum participants found it difficult to imagine that people from Africa's desert regions could perhaps have very different views about the urgency of the need for climate engineering and, in the event of a vote, would decide and vote differently, too. ♦



IN A NUTSHELL

- For fear of tackling an unpopular topic, many politicians shy away from initiating public discourse on climate engineering. But this would be hugely important to form opinions on the development of strategies for how we wish to attain the promised climate targets.
- The science community must help to initiate this discourse and provide comprehensive information for the purpose. It should also be aware of and reflect on the influential role it plays.
- Decisions for or against any use of climate engineering should only be made in dialogue with the population. This requires comprehensive public education about the opportunities and the risks of CE measures.

CE GOVERNANCE: A TURBULENT START TO INTERNATIONAL NEGOTIATIONS

In spring 2019, the Swiss government made the first ever attempt to put the issue of international standards for climate engineering governance on the United Nations agenda. It submitted a proposed resolution to the United Nations Environment Programme/UN Environment Assembly (UNEP/UNEA), calling for an international assessment summarising the current state of research on climate engineering and existing and potential governance approaches. The proposal referred both to carbon dioxide removal (CDR) and to radiation management (RM) methods, and had the backing of ten other countries. At the fourth session of the UNEA in Nairobi, delegates from UNEA member countries discussed the Swiss proposal in what resulted into a heated debate. As no agreement was reached, Switzerland eventually withdrew the proposal.

So has the idea of adopting overarching approach to climate engineering governance already failed at that first attempt? Observers stress that the proposal and the subsequent negotiations revealed five key issues that are highly controversial and need to be clarified in further discussions. These are:

1. Which expert body could and should carry out the assessment proposed by Switzerland on behalf of the UNEA? Could the Intergovernmental Panel on Climate Change (IPCC) produce a report of that kind? Or would an alternative panel of experts, either existing or perhaps newly created, have to be set up for the task? In contrast to other global environmental assessments, the CE assessment would not only have to assess the causes and impacts of global environmental changes, but would also have to include proposals for regulating the risks and opportunities of the various CE methods used.
2. What political venue could and should be given the mandate to negotiate international CE governance approaches? Could the negotiations take place under the auspices of the UN Framework Convention on Climate Change? Or would an overarching, cross-sectoral and multilateral forum like the UNEA be needed in order to take account of the

environmental and geopolitical impacts of CE interventions on other areas such as biodiversity and security of water and food supply?

3. How could and should CE methods be integrated into the existing portfolio of climate policy instruments? Would they be seen, for example, as a component of mitigation strategies? What might the consequences be for current and future policies to mitigate of and adapt to climate change? Would CE measures perhaps be seen as a substitute for achieving drastic emission reductions and thus undermine emission reduction efforts?
4. A fourth point of contention concerned the precautionary principle emphasised in the Swiss proposal. In its most general form, this prescribes that given the risk of significant or irreversible damage, a lack of complete scientific certainty should not be seen as a reason to postpone implementation of cost-effective measures to prevent environmental harm.

The precautionary principle is contained in most international treaties and instruments of potential relevance to climate engineering (such as the CBD, the UNFCCC and the London Protocol). Although it always relates in that context to how government decisions on the environmental impact of a particular action are to be reached in cases of scientific uncertainty, the precautionary principle has been adapted to suit each case relative to the legal consequences resulting from its application. It is not possible, therefore, to argue in general terms that the precautionary principle prohibits action that could be harmful to the environment. What counts instead are the provisions of the relevant treaty – although this can lead to problems if action (such as a large-scale climate engineering experiment) falls within the scope of multiple international treaties, each of which implements the precautionary principle differently.

Even within individual treaty regimes, application of the precautionary principle has resulted in controversy. Under the London Convention, for example, both those for and those against permitting carbon captured at power plants to be deposited on the seabed have argued their cases based on

the precautionary principle. This shows that there is still no uniform way to assess whether the precautionary principle has already become accepted as customary international law and as such must be observed by countries as a binding legal principle irrespective of how it is implemented in a given treaty. The US in particular has always been opposed to the idea of the principle applying as customary law.

Legal experts have thus proposed that the precautionary principle should be conceived of as a mode of target attainment that governs if and when there is an obligation to take measures to protect the environment. In the case of frequently occurring conflicts between different protected interests (climate action versus marine environment conservation, for example), it would be used to decide if and when protected interests must be weighed against each other using the proportionality principle. The problem here, however, is that the underlying principles and modalities for this kind of approach remain controversial and are in need of further analysis, especially in respect of CE.

5. The fifth and final question was: What basic procedure should be followed in the search for governance approaches? Would it make sense to strive for a method-neutral approach that encompasses all CE methods? Or is it advisable to assess and govern CDR and RM methods separately, and thus to develop method-specific governance approaches?

Proponents of the method-specific approach criticised the Swiss proposal because in it, CDR and RM methods were to be looked at together, meaning in a method-neutral approach under the catch-all concept of climate engineering. But then the critics also argued that the CE methods differ so widely in their characteristics and spatial and geopolitical consequences that it is difficult to compare them and account for them by a single approach. CE methods would instead have to be regulated by specially tailored governance approaches. In a more detailed assessment of the various methods (such as a legal appraisal), it would appear more helpful to use more specific designations for the methods in question rather than using generic terms.

New approaches to governance of CDR and RM

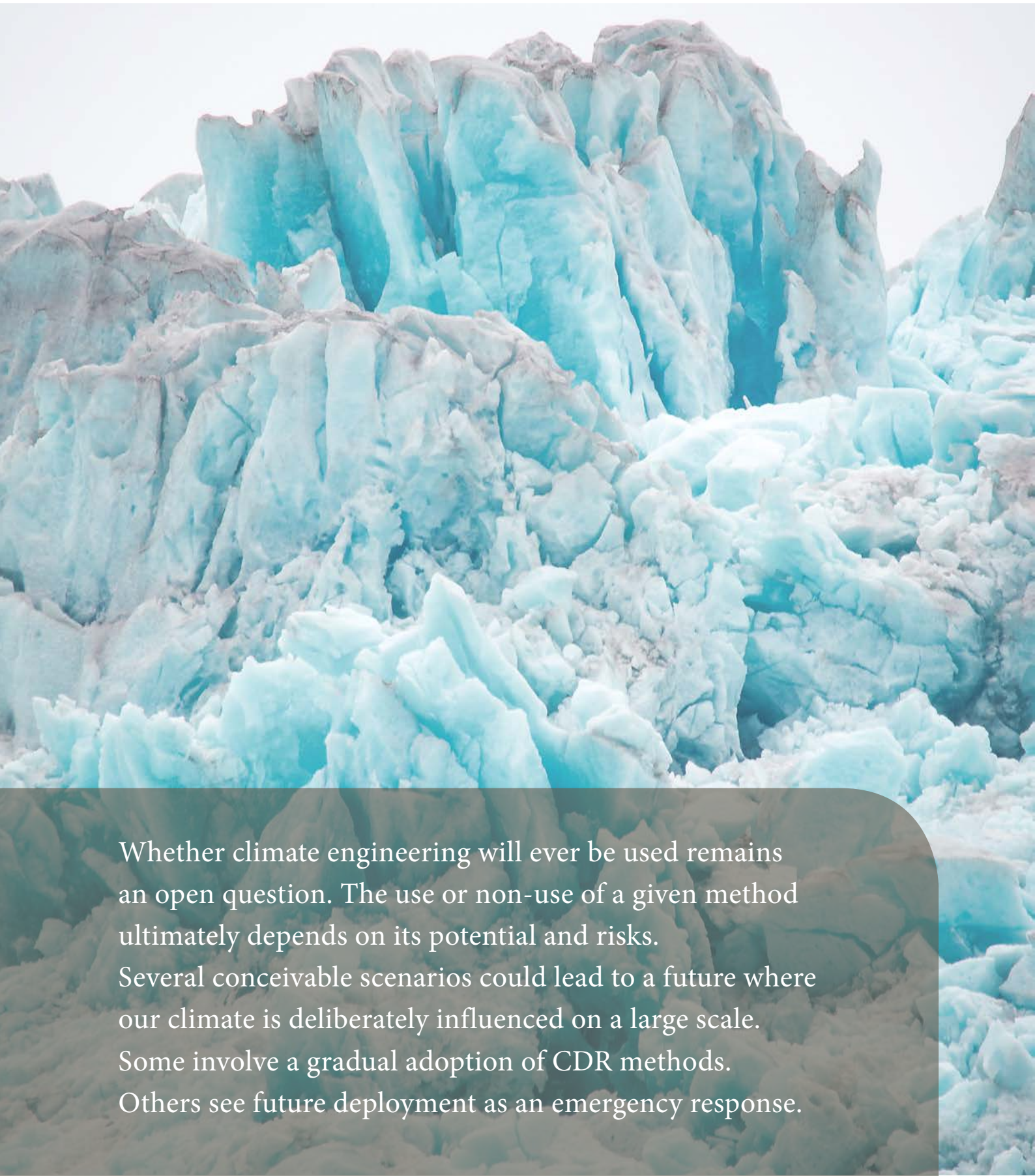
It is an open question how the negotiations in Nairobi would have proceeded if Switzerland had submitted two separate proposals – one for CDR and one for RM. Leading scientific panels such as the IPCC differentiate between CDR and RM categories.

With regard to CDR, initial assessments have come to the conclusion that the few existing international conventions and policy regimes will not be sufficient to enable CDR to be used on the scale required by the IPCC to achieve the 1.5 °C target. What is also clear is that as broad a range of methods as possible should be promoted and that premature commitment to one particular method is to be avoided. Incentives must be created to promote both research into and application of the various methods, and to further develop the regulatory approaches offered under the Paris Agreement.

For RM methods, an intensive dialogue is needed on the standards for and principles for their governance before any large-scale deployment – even if this means that RM methods are then rejected. The scientific recommendation is to develop RM-specific governance approaches in a step-by-step process because the technical and political risks involved cannot be foreseen. This would allow a flexible approach, responding to unintended risks by adjusting procedures as needed.

Given the development and security implications of many CE methods, an inclusive governance approach is needed where as many countries and as many societal stakeholders as possible have to be included in the debate from the outset. To place future policy decisions on a robust scientific basis, data and information systems should also be developed to enable independent monitoring of CE deployment. The aim must be to expand international cooperation in CE research in order to fully understand the regional and geopolitical impacts, and to be able to respond to undesirable impacts and risks.

This means that for policymakers, busy times lie ahead. The debates held at the fourth UNEA session provided important impetus, catalysing a much-needed debate on the future of global environmental governance. ♦



Whether climate engineering will ever be used remains an open question. The use or non-use of a given method ultimately depends on its potential and risks. Several conceivable scenarios could lead to a future where our climate is deliberately influenced on a large scale. Some involve a gradual adoption of CDR methods. Others see future deployment as an emergency response.

OUTLOOK: SCENARIOS FOR THE TRANSITION TO A WORLD WITH DELIBERATE CLIMATE INTERVENTION

Before any CDR or RM method can be deployed on a large scale, many in-depth questions would have to be answered – not only on management and control, but also on the potential, feasibility and side effects of the various methods. Answering such questions is difficult, because for many CDR and RM methods, not even geographically limited field experiments will suffice to gauge their limits and side effects prior to large-scale deployment. Knowledge deficits and uncertainties will remain as a result. Scientific analyses, based on scenarios of future developments, serve in the performance of integrated impact assessment and the identification and quantification of uncertainties.

In theory, any state could deploy climate engineering methods if it can rule out the possibility of neighbouring states being affected. This is almost impossible to determine, however, because both CDR and RM measures can have transboundary negative environmental impacts when applied on a large scale – although the effects of land-based CDR methods tend to be more regionally restricted than those of other CE methods. One consequence of cross-border effects could be political tensions. For this reason, internationally agreed rules of procedure and institutions for dispute resolution are needed before CE methods can begin to be used.

Climate engineering has repeatedly attracted heavy criticism in public debate in recent years, for example with regard to risks and side effects, sustainability and ethics. This raises the question of whether, or in what circumstances, it will ever be possible to use CDR or RM. Some experts consider it realistic for CDR methods to be introduced in a strategy of small steps. As the example of afforestation shows, there could be a seamless and fluid transition from today's climate action and nature conservation measures to climatically significant use of CDR. It is also thought to be realistic that certain methods will have a firm place in the energy landscape of the future, alongside energy efficiency and climate action – a scenario that moves away from the black-and-white 'CDR or no CDR'.

The examples that follow illustrate conceivable paths and scenarios for a transition to a world with deliberate climate intervention on a large scale. This is a neutral compilation and is provided for the sole purpose of outlining the range of conceivable scenarios.

1. Gradual transition from climate action to carbon removal

Various companies have long offered customers the option of offsetting their CO₂ emissions from air travel or consumption. Consumers pay a certain amount per purchase or per mile flown in order, for example, to finance reforestation projects in suitable regions. The companies benefit from an image gain, which gives them a competitive advantage. Consumers, for their part, can reduce their carbon footprint without having to change their lifestyles to any great extent. As a result, in this scenario, there is an increase in locally adapted afforestation and restoration of peatlands and coastal ecosystems (such as seagrass meadows and mangrove swamps). Storage of carbon on pasture and arable land is increased by spreading biochar and adopting specific agricultural practices. This can improve soil fertility and the resilience of agricultural ecosystems. These measures are also compatible with nature conservation. But verification is needed – by measurements or computer modelling – to ensure that the net climate balance is positive. In wetland and peatland restoration, for example, the additional absorption of CO₂ must not be cancelled out by increased emissions of the greenhouse gas methane.

It is true that substantial quantities of CO₂ are removed from the atmosphere in this way. But the measures are not enough to limit climate change. In this scenario, demand for offsetting measures increases. The methods are then included in emissions trading schemes, which becomes economically worthwhile when the price of CO₂ rises. There are proposals for finance schemes involving international offsetting mechanisms. The methods implemented reach a scale where conflicts ensue with other human objectives: conflicts over water, about land for food production, and with regard to nature conservation concerns such as avoiding biodiversity loss. Computer models also show that large-scale afforestation projects change precipitation patterns.

What began in individual states without harming the population or neighbouring states thus reaches a scale that calls for close cooperation between all parties involved, from farmers to consumers to politicians. Policymakers start to realise, albeit rather late, that there is a need for regulation and introduce control and steering mechanisms with assistance from international bodies.

2. Carbon removal as an integral component of ambitious climate policy

In this scenario, the Parties to the Paris Climate Agreement have met their agreed 2030 CO₂ emission reduction targets (nationally determined contributions, or NDCs). At the same time, a policy initiative is launched to further step up emission reductions beyond 2030 in order to achieve the long-term 2 °C target. This internationally agreed and differentiated climate policy for the period beyond 2030 also includes an increase in the price of CO₂, which contributes to a drastic reduction in CO₂ emissions. In addition, the electricity and heat sectors are decarbonised in a complete switch to renewable energy. Most of the transport sector now runs on electricity, eliminating large quantities of emissions from motor fuel. Energy efficiency measures are implemented. Yet it is evident that all of these measures are not enough to limit global warming to 2 °C. To stabilise the temperature, emissions of CO₂ and other greenhouse gases must be reduced to zero in all countries – and for equity reasons in the richer countries first. Some emission sources nevertheless remain. For example, greenhouse gases are still released in industry and agriculture. It also becomes evident that the ambitious climate policy efforts have come too late and that the remaining budget for the 2 °C target will be exceeded before too long. Industrialised countries thus begin to build huge CCS infrastructures in order to reduce their industrial emissions and store CO₂ extracted from the atmosphere by direct air capture. In this way, the remaining emissions are neutralised and the budget that has already been exceeded is also offset over time. Governments that have not been able to expand CCS infrastructure quickly enough face the challenge of importing CO₂ emission allowances to offset the remaining residual emissions. When it comes to importing allowances from tropical countries, however, it must be borne in mind that large-scale afforestation and biomass cultivation require a lot of land, and that this could lead to displacement of indigenous peoples, rising food prices and impacts on both biodiversity and the water cycle. At the same time, the growing BECCS industry and the sale of emission permits could lead to increased prosperity, more jobs and improved quality of life. To create the conditions for fair and sustainable design of the policy initiatives, technology development and transfer policies are pursued. An international authority keeps inventories of greenhouse gas emissions and of the carbon savings achieved by removing carbon from the atmosphere. It also coordinates the measures implemented on a global scale.

3. Coastal countries deploying ocean-based CE

A different scenario presents itself for the adoption of climate engineering by coastal countries: As part of their climate action strategy, states use ocean-based technologies to remove carbon from their territorial waters. Initially, alkaline minerals are introduced during the construction of coastal defences. This provides practical experience with regard to weathering performance, CO₂ removal potential and ecologically tolerable limits. The coastal countries obtain agreement for enhanced weathering of alkaline minerals to be recognised under the EU Emissions Trading Scheme (ETS), subject to compliance with strict water chemistry thresholds. This creates financial incentives that lead many companies to step up the development of basalt dust spreading technology. Due to strict environmental standards for basalt extraction, high transportation costs and narrow seawater chemistry thresholds, individual companies shift extraction and oceanic spreading of basalt dust to Australia. After the ETS is expanded to cover Australia, the mining industry there begins large-scale basalt extraction in order to advance CO₂ removal via enhanced weathering in the ocean. After a decade, carbon removal amounting to one billion tonnes of CO₂ per year is achieved in European and Australian territorial waters alone. But off the coasts of Australia, due to lax environmental standards, algae and fish die-off becomes a recurring problem. Amendments to international agreements for the protection of marine ecosystems to include the introduction of basalt dust lead to binding upper thresholds for chemical intervention in seawater worldwide.

4. Rain on demand

From about 2030, encouraged by new research findings, China, Saudi Arabia and India try out cloud modification to regulate precipitation over their territory. Many other countries are interested in the possibility of increasing agricultural productivity and creating more agreeable weather. Even if the success of the measures is disputed, demand for cloud modification rises. Companies invest in further research and development of cloud modification technology. A new industry starts to emerge, hailing a new era in agricultural production. Global distribution of clouds is now more even. And controlled precipitation is possible for all – for all who can afford it, that is.

There are also localised changes in temperatures. The basic principle seems to be working, so work starts on modifying marine stratus clouds to counteract the global rise in temperature. Warnings of possible changes in ocean currents and resulting changes in the global climate system, or of negative effects such as the absence of rain in areas where clouds are not modified, go ignored. The benefits of the new weather have most people convinced – and the cloud modifying industry assures the world that its technology has no notable side effects.

5. Increase in extreme weather events makes radiation management a must

Around the year 2030, it is becoming increasingly clear that most countries will continue to fall far short of their declared emission reduction targets. Extreme weather events such as droughts, tropical storms and floods are becoming far more frequent worldwide. In the eyes of the public, measures to reduce greenhouse gas emissions and adapt to climate change are no longer sufficient to counteract its effects. In many countries, calls are becoming louder for reflective particles to be introduced into the stratosphere because that works faster than reducing greenhouse gas emissions or using CDR. In addition to countries that are directly affected, the method is supported by countries highly vulnerable to sea-level rise or glacial melt, and also by a number of NGOs. A coalition of the willing forms to promote the use of radiation management methods, even though, right now, the long-term effects cannot be foreseen. Critics fear that once implemented, the method will push reduction of greenhouse gas emissions into the background. Its proponents thus commit to combining the deployment of RM methods with increased use of measures to reduce emissions and remove CO₂. An international body is created to monitor and control the use of RM and greenhouse gas reduction. But many questions remain unanswered: Will the promises and pledges be kept? Does the new international body have sufficient authority and power to control and limit deployment? Will spreading reflective particles really result in fewer extreme events, or will there soon be calls to stop?

Is CE research needed?

It remains to be seen whether any of the scenarios outlined above will actually occur as described or in similar form. There is still far too little known about the effectiveness and outcomes of the various CDR and RM methods, and about how their use might be shaped in policy terms. The issue continues to be given little space on the global policy agenda. This is an unsatisfactory situation given the fact that CDR methods at minimum could presumably become a serious option in efforts to combat climate change. Exploration of the different methods and ways to use them with the minimum possible conflict is of great importance both in evaluating our options for dealing with climate change and in consciously shaping our future – irrespective of whether the methods are actually ever used. ◆

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SPP 1689 CONTRIBUTORS

Thorben Ammann, Universität Hamburg

Christian Baatz, Kiel University

Nico Bauer, Potsdam Institute for Climate Impact Research

Silke Beck, Helmholtz Centre for Environmental Research GmbH – UFZ, Leipzig

Lena Boysen, Max Planck Institute for Meteorology, Hamburg

Dieter Gerten, Potsdam Institute for Climate Impact Research

Timo Goeschl, Heidelberg University

Jens Hartmann, Universität Hamburg

Nina Janich, Technische Universität Darmstadt

Kristine Karstens, Potsdam Institute for Climate Impact Research

David Keller, GEOMAR Helmholtz Centre for Ocean Research Kiel

Elmar Kriegler, Potsdam Institute for Climate Impact Research

Mark Lawrence, Institute for Advanced Sustainability Studies, Potsdam

Thomas Leisner, Karlsruhe Institute of Technology

Nadine Mengis, GEOMAR Helmholtz Centre for Ocean Research Kiel

Christine Merk, Kiel Institute for the World Economy

Andreas Oschlies, GEOMAR Helmholtz Centre for Ocean Research Kiel

Konrad Ott, Kiel University

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Julia Pongratz, Ludwig-Maximilians-Universität München

Alexander Popp, Potsdam Institute for Climate Impact Research

Alexander Proelß, Universität Hamburg

Johannes Quaas, Leipzig University

Martin Quaas, Leipzig University

Wilfried Rickels, Kiel Institute for the World Economy

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Contact: Ulrike Bernitt
info-ce@spp-climate-engineering.de
www.spp-climate-engineering.de

Editing and general management: Ulrike Bernitt

Text: Sina Löschke // www.schneehohl.net and
Tim Schröder // www.schroeder-tim.de

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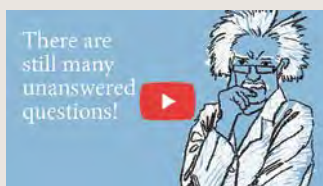
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The German Research Foundation’s Priority Programme 1689 set out in 2013 to evaluate climate engineering (CE) as an option and estimate the impacts of any deployment. The highly interdisciplinary priority programme was launched in 2012 by a number of scientists concerned to reduce the considerable uncertainties about the impacts of the various CE methods on the environment and society, and thus to provide the basis for a responsible approach to climate engineering. As well as the scientific and technological dimension, this has also involved research into social, political, legal and ethical aspects over the last six years. SPP 1689 encompasses 20 universities and research institutes from German-speaking countries. It does not involve field experiments or research on the specific development of CE methods.

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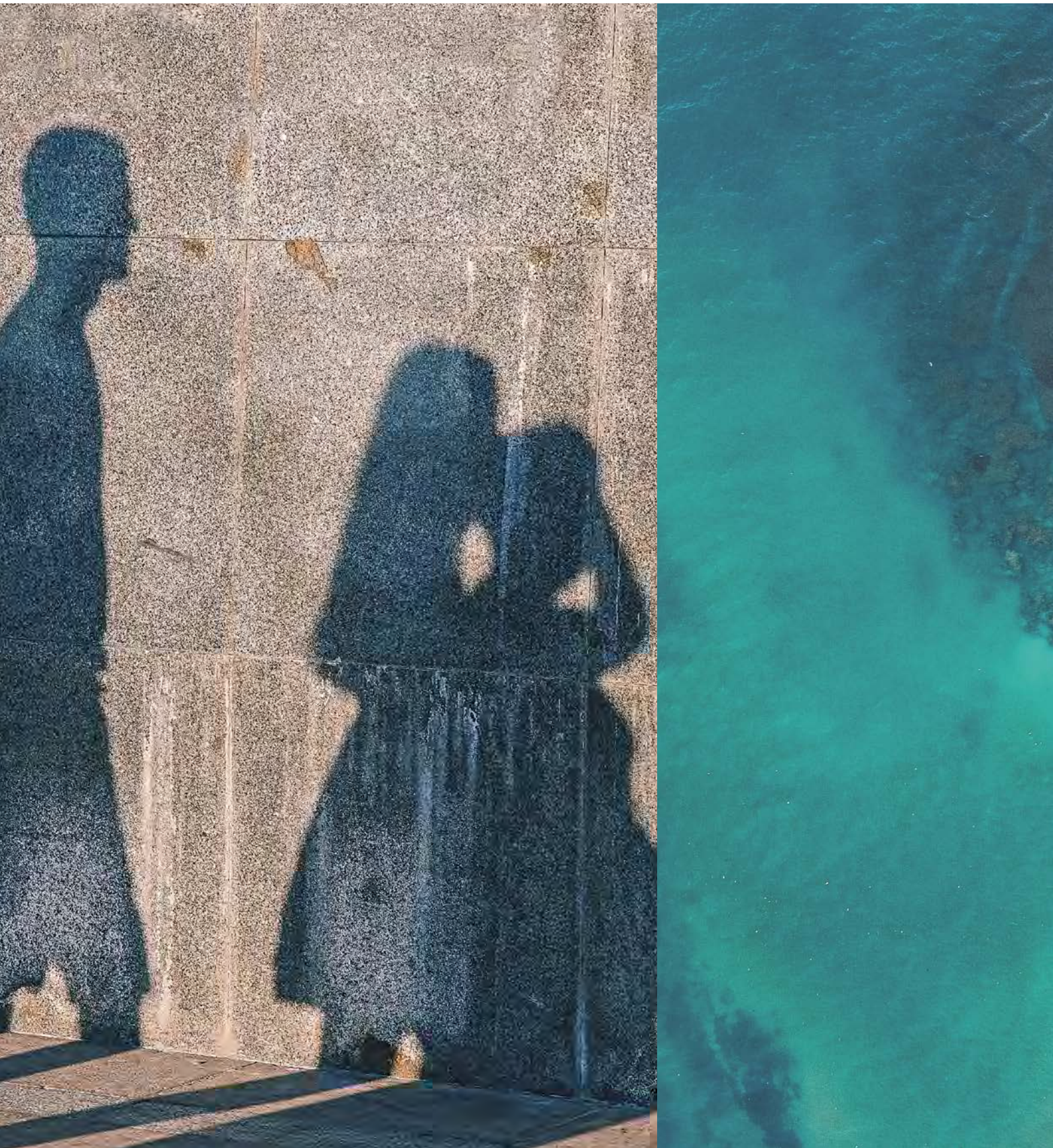
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