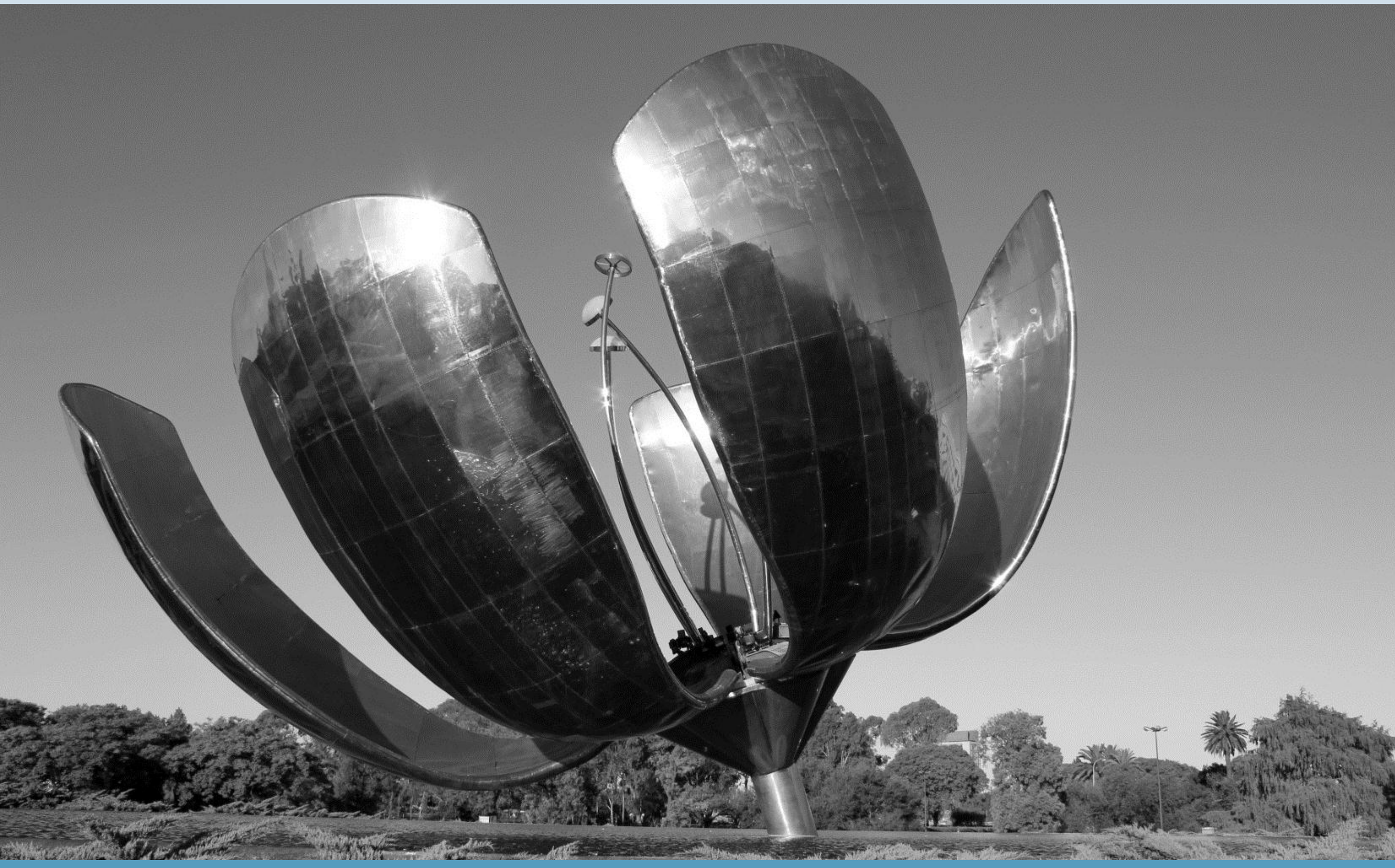
Climate Engineering

Avoiding Pandora's Box through Research and Governance

Matthias Honegger, Axel Michaelowa and Sonja Butzengeiger-Geyer



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Matthias Honegger
Climate Policy Intern
Perspectives GmbH
honegger@
perspectives.cc

Axel Michaelowa
Senior Founding Partner
Perspectives GmbH
michaelowa@
perspectives.cc

Sonja Butzengeiger-Geyer
Managing Director
Perspectives GmbH
butzengeiger@
perspectives.cc

- The gap between the emissions reductions required by the 2°C target and those actually undertaken is growing. Thus, climate engineering as an alternative proposition to mitigate climate change is expected to become increasingly relevant and likely to enter the mainstream discourse on climate mitigation within a decade.
- The term 'climate change mitigation' should be broadened to include all measures that limit the extent of climatic changes. Carbon dioxide removal is akin to classical biological and geological sequestration. Solar radiation management could mask – and thus in the broader sense mitigate – climate change as long as the intervention is continued.
- Given the high perceived attractiveness of solar radiation management due to costs two orders of magnitude less than those of equivalent emissions reductions, the level of risks must be established with a high degree of certainty, and accompanying measures need be in place, before the option can be seriously contemplated.
- In order to prevent potentially catastrophic unilateral deployment or military use, international governance is required to coordinate research in all disciplines concerned with climate engineering in the long term and make its results publicly accessible. A Special Report on Climate Engineering by the IPCC would provide an ideal basis for such international norm building concerning research, development and deployment.
- In order to avoid capture by interest groups and prevent premature irreversible decisions, climate engineering governance and monitoring under the UNFCCC could be based partly on approaches used in nuclear weapons control and terrorism prevention.

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Climate engineering[1] (CE) has been defined as the deliberate large-scale manipulation of the planetary environment to counteract anthropogenic climate change. Proposals for modifying weather or climate have been offered for more than a century. Only after 1965, however, have these ideas focused on trying to cool the climate and thus counteract warming caused by greenhouse gases (GHGs). In 2006, Nobel Prize Laureate Paul Crutzen published a discussion paper on stratospheric sulphur injection. This gave rise to a growing amount of attention, among the public as well as the scientific community, to the entire field, which had long been sidelined. Many of the relatively recent ideas have entered the emerging debate since 2006; some have received further attention in the form of related small-scale scientific experiments (e.g. the effect of iron on algal growth and concept studies of the technical feasibility for stratospheric sulfur particles).

The path taken by the international climate policy regime is appearing less and less sufficient, given the growing gap between actual emissions reductions and requirements for achieving the 2˚C target agreed internationally. As we are currently headed towards an average temperature increase of 3-4˚C, a climate emergency – a situation of sudden heavy impacts by extreme events or an acceleration of temperature increase due to e.g. methane releases in the Arctic – cannot be ruled out. Such an event would create pressure for rapid responses.

Public awareness of climate engineering is still very limited, and public opinion is likely to be shaped by the initial framing of the issue in popular media in the coming years. As the 5th IPCC Assessment Report to be published in 2014 will take the issue up for the first time, CE will soon be elevated from a science-fiction-like curiosity into mainstream climate policy discourse. It is crucial that this discussion be based on the best information available. We want to provide some pathways and signposts for the years to come. This paper presents the types of CE under discussion, with tentative cost estimates as well as the risks and uncertainties attributed to these options. Subsequently we discuss the arguments for and against research and development of CE, showing that well-governed CE research is necessary and that there are valid arguments for making CE part of the discourse on climate change mitigation. We then develop a set of fundamental guidelines for governance of CE research and monitoring to avoid potentially dangerous developments. Finally we sketch the next steps for CE and international cooperation on climate change mitigation.

Types of climate engineering: Costs and risks

CE comes in two main forms, with very different characteristics: carbon dioxide removal (CDR), and solar radiation management (SRM)[2]. CDR aims to reduce the concentration of CO_2 in the atmosphere and is thus closer to the conventional mitigation approaches as illustrated in figure 1. The following sub-types of CDR have been proposed, arranged by the estimated cost-risk trade-off based on the available literature.

Direct air capture through artificial means
Chemical weathering of rocks
Biomass energy with carbon sequestration
Increasing ocean alkalinity with lime
Ocean fertilization (Fe, N, P)

[1] The term geoengineering (or geo-engineering) has been used in the literature and is still being used for large-scale engineering projects, only some of which are related to climate change. The term CE is thus more accurate to solely describe technologies that intentionally affect climate and is used here for climate related geo-engineering.

[2] Shepherd, W.; Cox, P.; Haigh, J.; Keith, D.; Launder, B.; Mace, G.; Mackerron, G.; Pyle, J.; Rayner, S.; Redgewell, C.; Watson, A. (2009) *Geoengineering the climate: science, governance and uncertainty*, Royal Society, London.

The options afforestation, reforestation and soil sequestration have relatively low risks and costs, but face implementation barriers for large-scale applications in terms of e.g. land-use conflicts. Proving the additionality of such projects presents a major challenge in itself.

As to SRM, it either reduces incoming short-wave solar radiation or increases outgoing long-wave thermal radiation[3].

Increased albedo of land (urban areas, arable land, desert)
Marine cloud whitening
Stratospheric aerosols

Space reflectors cannot yet be properly assessed due to the highly tentative characteristics of the technology proposed.

The mitigation costs of both cloud whitening and stratospheric aerosol seeding are currently estimated to be two orders of magnitude lower than those of GHG emission reduction, while land albedo changes are comparable in cost with emission reduction measures.

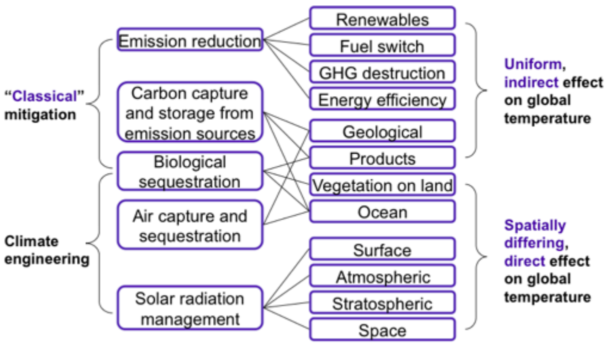

Figure 1: *Taxonomy of the broadened climate change mitigation term including carbon dioxide removal and solar radiation management. Source: authors.*

From the rough cost estimates available and a first look at risks, the general trade-off between costs and risks of the different approaches can be seen – the more costly CDR options generally have lower uncertainties and their risks are not as systemic as those of the seemingly cheap SRM. The nature of the risks of CDR and SRM technologies are described in box 1 and 2 respectively.

[3] Rickels et al. (2011) use the term 'Radiation Management'. Due to the semantic problem of 'radiation management' being linked to radiation related to nuclear fission, we retain the term SRM for both incoming and outgoing radiation.

Box 1: Risks of CDR

Carbon Dioxide Removal methods can be expected to have lower risks than SRM methods because they return the climate system closer to its natural state and their radiative forcing effect is homogenous. Some risks are attributed to measures that require massive mining and transportation. Even greater risks can be attributed to approaches that affect the oceanic food-web, as secondary effects within oceanic ecosystems can result in a net increase rather than net absorption of greenhouse gases and possibly affect biodiversity adversely.

The reason why the non-surface related SRM options generate great systemic risk is that they directly and unequally affect temperature gradients in the atmosphere, which determine the behavior of this complex system in ways that possibly cannot be foreseen. Given our incomplete understanding of the atmosphere (e.g. the considerable uncertainties as to the role of aerosols in the climate system) and its many feedback mechanisms, applying short-term cost-benefit calculations better suited for other technological investments would be inappropriate and dangerous in the case of SRM.

Box 2: Risks of SRM

Solar Radiation Management methods present a high-leverage interference in the climate system with largely unknown consequences. Atmospheric and stratospheric SRM might succeed in masking the average temperature increase, but temperatures and rainfall will be affected unevenly creating significant changes in atmospheric circulation, with potentially severe impacts on ecosystems and agriculture. SRM needs to be sustained through continuous action; if it stops the climate will abruptly jump to an 'unmasked' state of warming or even overshoot. The brightening of land surfaces presents a lower risk. While mitigating climate change, SRM does not reduce acidification of oceans due to further increases of atmospheric CO_2 concentrations.

Given the probabilistic nature of climate change damages and benefits, the concept of systemic risk is crucial in policy decisions concerning mitigation, especially when CE is included. Non-systemic risk can be quantified in an insurance policy, but quantifying CE risks presents a seemingly insurmountable challenge. Insurance has trouble addressing large, unknown risks with low return periods so quantifying the probability and damage of a governance failure leading to climate collapse might simply be impossible. This issue, however, applies both worlds: The one with possibly insufficient emission reductions, as well as the one, where risky CE measures additionally play a role in mitigating climate change. Because climatic developments are irreversible to a large degree, only long-term cost-benefit calculations can be adequate. In view of the systemic risks and irreversibility of climate changes, rather than aggregating risk and cost-benefit into one single policy variable – as previously done in economic analyses of CE technologies – we propose a different approach. To balance various mitigation options we suggest dealing with risk and cost-benefit separately: Balancing the risks of insufficiently mitigated climate change against the risks of deploying specific CE technologies should come before any aggregated cost-benefit analysis is attempted – since the latter can to date only be based on sketchy quantifications of the risks. If at a later stage research allows us to develop more sophisticated analyses of the risks associated with CE approaches, long-term cost-benefit assessments of different mitigation options can be based on these risk quantifications. Significant difficulties in quantifying risks of governance failures as well as uncertainties due to the systemic nature of atmospheric changes are however likely to remain.

A research moratorium?

In view of the unprecedented risks of key SRM options, some analysts[4] have queried whether CE should even be researched. To some degree, the topic has been effectively taboo within the scientific community not least due to its implications on climate policy.

The supporters of research argue that CE could be developed as an insurance against dangerous climate change, or see it as an important array of options for improving the cost-effectiveness of mitigation or even the silver bullet to avoid the necessity of international agreement. Even those who focus on the dangers of CE acknowledge that a moratorium could play into the hands of rogue states and actors who would not hesitate to use their CE technology. Yet others hope that research and public attention might 'unmask' the flaws of CE, and thus contribute to greater willingness to reduce emissions.

Critics of research especially fear that SRM will lead to a 'sword of Damocles' poised over our heads for centuries: An unplanned termination of the SRM activities could bring a sudden jump in temperatures with devastating effects if no substitute technology could step into the breach. Moreover, unplanned side effects of SRM on atmospheric circulation and precipitation could make the cure worse than the disease, at least for some regions in developing countries.

Some aspects call for caution, but might not be seen as a black-or-white issue concerning CE research. Moral hazard could be triggered, reducing the willingness to engage in immediate and strong emissions reductions. Similarly, stepping up CE research might restrain research on emissions-reduction options and climate science, due to limited resources and human capacity. As yet, few CE approaches seem able to deliver a low-risk, low-cost solution that could safely replace emissions reductions; therefore, any decrease in emissions reduction or research efforts should be avoided. Other concerns center on the risks of testing CE. Even if the scale of tests were increased only gradually, some effects might become apparent only in large-scale tests. The risks of such tests could be equal to those of actual deployment. Without coordinated research, such tests might be carried out unilaterally and without proper monitoring.

The possibility of military or terrorist use of CE technologies would add a further threat, on the scale of nuclear weapons. Arguably the best policy for controlling and preventing such secretive engagement is transparency and public awareness of the issue, leading to norms for acceptable use of the technologies. This should help to deter rogue actors from embarking on clandestine R&D, as coordinated research efforts could stay ahead of individual development efforts – making these useless. It would also prevent research from

[4] The entire map of arguments has been presented by Rickels, W.; Klepper, G.; Dovern, J.; Betz, G.; Brachatzek, N.; Cacean, S.; Güssow, K.; Heintzenberg, J.; Hiller, S.; Hoose, C.; Leisner, T.; Oschlies, A.; Platt, U.; Proelß, A.; Renn, O.; Schäfer, S.; Zürn M. (2011):. Large-Scale Intentional Interventions into the Climate System? Assessing the Climate Engineering Debate, Kiel

taking on a life of its own, as the vested interests would be closely watched. This should make it possible to stop development in the case of new risks becoming apparent. An assessment of how to shield research from particular interests could be based on studies of more established technologies, like nuclear power or fossil fuel industries.

An argument that clearly cuts both ways is not to impose any irreversible changes on coming generations. This could mean not to impose an ongoing CE regime on future generations, but could just as well be seen as an obligation to explore any chance of reducing the severity of climate change for coming generations.

The widening gap between actual emission reductions and the ones required for the 2°C limit and the resulting possibility of a dramatic increase of extreme events could result in political pressure for a quick fix. In view of these developments more and more researchers favor researching CE – not least to avoid being surprised by unilateral deployment. Due to the described risks emission reduction efforts need to be kept up and the issues of CE governance have to be addressed from the beginning. The mitigation discourse should therefore be cautiously expanded to include CE, with a specific focus on adequate framing of the issue in the media to allow a balanced opinion to develop in the general public.

Research design

Credible economic cost-benefit estimates as well as risk assessments require a strong foundation of research on the physical effects of different technologies. The CE research challenge will be – even more so than with previous climate research – to link efforts from the human and the environmental side: atmospheric modeling, atmospheric chemistry, oceanography, plant biology and ecology are among the disciplines on the environmental side. Political science, ethics, history, sociology, psychology, media sciences, agricultural science, forest science, economics, national security studies, engineering and more are concerned with the human side. Results from all such disciplines will be needed to advance understanding in other disciplines: this calls for an internationally coordinated and balanced effort.

Extensive atmospheric modeling of primary effects caused by specific CE interferences will be required for a comprehensive assessment of the spatial and temporal distribution of the physical effects. Based on such modeling results the impacts on terrestrial and aquatic ecosystems should be assessed as well as the impacts on agriculture, forestry and other sectors of the economy as well as human health and infrastructure. From such assessments, economic estimates could quantify the damages and benefits caused by any CE scheme in comparison to likely climate change impacts without the scheme.

Aside from such an effect-based cost-benefit approach, special focus should be placed on the range of possible damages – the risks. From a political science perspective, the possibility of societal failure in maintaining a SRM scheme needs to be addressed. Such an unplanned termination, due to an act of terror, international conflicts and governance failure or a major economic breakdown, would cause the nightmare scenario of abrupt warming by several degrees. It is crucial to determine how the termination risk could be reduced, e.g. by building spare installations and thus introducing redundancies in the scheme. Concerning moral hazard the framing of CE in public media should be closely monitored through a dedicated media science research project: It is vital to avoid misrepresentation of SRM as equal to emission reduction or CDR, as this could adversely affect efforts aimed at emissions reduction. The independence of public research and the absence of biases introduced by specific interest groups should be monitored, including the possibility of halting research if a technology should represent unacceptable threats. A preliminary assessment of those risks could be done in a comparative way looking at the lobbying power of more established technologies, such as nuclear power or fossil fuel industries.

Monitoring for CE development and potential deployment will be necessary at some point. Such monitoring will require in-depth knowledge of the technologies – a further argument for solid research.

In the end, the various engineering challenges must be addressed; current estimates of costs, infrastructure and material requirements seem inadequate. Technologies with termination risk require a special focus on reliability and long-term effectiveness.

In view of the many challenges regarding CE research and testing, a panel of experts[5] has

[5] US Government Accountability Office (2010): Climate Change - A Coordinated Strategy Could Focus Federal

estimated the time required for developing and evaluating a CE scheme to be at least two decades. This may even be optimistic, as co-ordinated international research efforts, especially in the atmospheric sciences, have tended to take longer than expected. Major politically motivated disputes fuelling the already limited public acceptance of such technologies might possibly block CE research – an early instance is the UK engineering research project SPICE.[6]

Governance: Next steps

Climate engineering is not well represented in existing international norms: Whereas the 1996 London Protocol of the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter prohibits CO_2 storage in the ocean, no other international treaty addresses CE directly. However, the 1976 Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques (ENMOD) might provide a starting point for regulation of CE interventions. In 2010 the Conference of the Parties to the Convention on Biological Diversity provided the non-binding guidance that no '[…] climate-related geoengineering activeties that may affect biodiversity take place, until there is an adequate scientific basis on which to justify such activities and appropriate consideration of the associated risks for the environment and biodiversity.' Codes of conduct have been suggested concerning research the Oxford Principles of 2010 include the following points:

- CE needs regulation as a public good.
- Public participation is a must in CE decision-making.
- Research plans should be fully disclosed and all research results made publicly available.
- Impacts are to be independently assessed.
- Robust governance needs to be in place before CE deployment.

Geoengineering Research and Inform Governance Efforts, Washington

[6] The SPICE project – a collaboration of the Universities of Bristol, Cambridge, Edinburgh and Oxford as well as the Marshall Aerospace institute – was intended in September 2011 as a small-scale field test of a hose supported by a helium balloon. It was meant to offer insights into the technological requirements for atmospheric distribution of aerosol particles.. Due to a number of protests the test was put on hold.

Rather than governance through an outright ban or continued neglect of the topic,[7] we recommend adequate decisions under the UNFCCC or a dedicated international treaty on CE, as a protocol to the UNFCCC. Further, developing sound norms requires a solid basis of information that can be delivered only through a coordinated research effort, in accordance with a set of principles like those mentioned above. Ideally, the IPCC would write a Special Report on CE as soon as the bulk of work on the 5th Assessment Report has been completed in 2013. This would trigger more academic research, as the taboo within the scientific community would finally be broken. In addition a Special Report could provide a shared terminology and a framework of criteria to assess the various aspects of CE technologies. Both are necessary in order to develop adequate norms.

As mentioned, a general ban would be counterproductive or even dangerous, as it would continue to put off a major share of research activities, without deterring other entities from clandestinely engaging in CE activities. Such entities – be it single nations or even companies – might be acting in their best interests. For example a small island state like Tuvalu might want to save its territorial integrity. Unilateral deployment would be highly problematic from the perspective of national security and international relations, as high-risk CE might benefit a few but create grave threats to other nations, perhaps provoking the latter to retaliation. The international community will thus have to develop mechanisms to monitor for unilateral development or deployment, similar to the monitoring of nuclear technology or terrorist activities. Such monitoring could be based on an international regime for CE that would require parties to control activities within their jurisdiction, and would clarify jurisdiction over activities outside of national territory, as on the high seas or in outer space.

The military will have an interest in turning CE into a classified matter of national security. Most armies could – if they were to engage – offer significant means to develop CE technologies. In fact, the US agency DARPA already assessed CE in a non-classified meeting in 2009 involving leading CE researchers. Capture of CE by the military or other interest groups could be the worst start imaginable,

[7] Bodansky, D. (2011): Governing Climate Engineering: Scenarios for Analysis", Harvard Project on Climate Agreements Discussion Paper 2011-47, Cambridge Mass.

'tainting' the issue before the public could form any kind of unbiased opinion. Transparency and clear disclosure of conflicts of interest – similar to current practice in medical research – are crucial, to prevent such loss of credibility and the potential for a new type of arms race.

Dedicated public participation in developing norms on the use of CE technology is a necessary condition to create the long-term support and stability essential to successful governance of such an intergenerational effort.

As a key element of governance, research on the design of policy instruments to include CE in ongoing mitigation schemes will need special attention. For example, integrating CE into carbon markets will require the definition of a common trading unit for emissions reductions, CDR and SRM activities. This unit might be based on the contribution of the mitigation option to the reduction of radiative forcing and it could for practical reasons represent the equivalent forcing of 1 metric ton of CO_2 (roughly $5x10^{-13}W/m^2$). The design of such a novel 'climate currency' will have to account for the various risk components and the side-effects, as well as temporal aspects in attributing monetary value of the effects of each specific technology. Given our interest in designing efficient mitigation policy instruments, we will look into design options both for market and non-market policy instruments addressing CE in detail in forthcoming publications.

Conclusion

Despite two decades of international climate policy, emissions of greenhouse gases have continued to rise. Emission reduction efforts are increasingly seen as inadequate to stay below the 2°C threshold agreed internationally, but countries shy away from shouldering the burden of emissions abatement. Therefore, in the next decades an increase in meteorological extreme events is increasingly likely to trigger public pressure to find quick solutions to halt climate change. Climate engineering, especially the apparently cheap and high-leverage Solar Radiation Management proposals, will be attractive in this context. But SRM could turn into a Pandora's Box if not managed carefully. A sudden political demand for implementing CE could end in disaster if pressure leads to premature deployment. It is vital to establish a solid understanding of CE with all its indirect effects as well as significant acceptance and thus legitimacy. Since for many CE options, the risks seem negatively correlated to costs, a global research coordination effort is needed that is fully transparent and avoids biases introduced by interest groups. The IPCC would be the right forum to harness this research. Research should go hand in hand with the development of new norms and international approaches in monitoring, similar to the case of nuclear weapons or terrorism. It is time for climate engineering to enter the discourse on climate change mitigation – in a research-led, transparent and conscientiously governed manner.

About the author(s)

Matthias Honegger *holds a degree in environmental science from ETH Zurich. His studies in Switzerland, Norway, the UK and the US join economic and natural science outlooks on climate change. At Perspectives his work deals with the various implications of climate engineering proposals.*

Axel Michaelowa *is senior founding partner of Perspectives and researcher at the University of Zurich. He has 18 years of experience in climate policy.*

Sonja Butzengeiger-Geyer *has worked on climate policies since 1999. She started her professional career at the Hamburg Institute of International Economics, and worked for the German Environment Ministry for one year. In 2003, she cofounded Perspectives GmbH and is one of the Managing Directors of the company.*

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