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Scientific Advice Mechanism

Solar Radiation Modification

Group of Chief Scientific Advisors

Independent Expert Report

Scientific Opinion No. 17

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Research and Innovation

Solar Radiation Modification

Group of Chief Scientific Advisors

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(Supported by SAPEA Evidence Review Report)

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Brussels, 9 December 2024

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Group of Chief Scientific Advisors

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EXECUTIVE SUMMARY

Climate change caused by human activities is becoming increasingly evident and severe in its adverse effects (IPCC, 2023b). Extreme weather events such as heatwaves, droughts and floods now occur with increasing frequency and intensity, with adverse effects on lives, health, food, water, energy, settlements, infrastructure, and more. The Paris Agreement limits temperature increase to 2o C and if possible to 1.5o C above pre-industrial levels, to avoid adverse climate change. Global emissions would need to be reduced rapidly towards net zero by the middle of the century to achieve the ambitious targets of the Paris Agreement. They will be exceeded with every delay in achieving net-zero emissions, resulting in a temperature 'overshoot'. Net-negative emissions, namely removal of the carbon dioxide from the atmosphere, would be required to reduce the overshoot.

For decades now, the use of technological interventions to reduce incoming solar radiation, termed solar radiation modification (SRM) have been suggested as a possible means to compensate for such an 'overshoot' of global-mean temperature. SRM is a group of technologies designed for large-scale climate interventions that aim to cool the planet by enhancing the reflection of sunlight back into space directly or as infrared radiation. They include stratospheric aerosol injection (SAI), cloud brightening (targeting low-latitude clouds), cirrus cloud thinning (high-altitude clouds), surface brightening and space mirrors. These interventions would result in masking some of the global warming that results from climate change.

The benefits and risks of these SRM technologies are highly uncertain. They address the symptoms rather than the root causes of climate change. At best, they would reduce warming from solar radiation on a temporary and local scale, while greenhouse gas concentrations and ocean acidification continue to increase. Climate stabilization would require that net-zero emissions are reached. SRM deployment would be likely to bring substantial negative ecological and economic effects, including changing patterns of rainfall, impacts on ecosystems, a decrease in the security of food production, and a decrease in the potential of solar energy.

As the effects of SRM are global, any large-scale deployment would fall under international law and regulations of the Earth and outer space. While there are substantial international agreements and laws in place to govern climate interventions and activities affecting the atmosphere and the seas, there is not yet an international framework to govern SRM research or deployment.

Given that the potential benefits and risks of SRM are highly uncertain, the College of Commissioners has asked the Group of Chief Scientific Advisors to the European Commission – which, together with the Science Advice for Policy by European Academies and a Commission secretariat, constitutes the Scientific Advice Mechanism – to provide a scientific opinion on SRM, with policy recommendations on research and potential deployment, and options for governance. The opinion that follows is informed by an evidence review report by experts of the Science Advice for Policy by European Academies consortium, extensive literature reviews, and targeted workshops.

There are **five main policy recommendations**:

Recommendation 1

Prioritise reducing GHG emissions as the main solution to avoid dangerous levels of climate change.

1.1 Continue to treat emissions reduction and adaptation to climate change as the highest priority in reaching net zero by mid-century and minimising 'overshoot' and its adverse effects.

1.2 Continue to actively and vigorously invest in research on and deployment of climate mitigation and adaptation.

Recommendation 2

Agree on an EU-wide moratorium on the use of SRM as a measure for offsetting climate warming.

2.1 Acknowledge that there is currently insufficient scientific evidence that SRM would effectively help to avoid dangerous climate change by reducing some of the resulting global warming.

2.2 Recognise that the deep uncertainties associated with possible SRM deployment are inconsistent with the precautionary and 'do no harm' principles.

Recommendation 3

Proactively negotiate a global governance system for deployment of SRM by means of a multilateral process with international legitimacy. Given the current state of knowledge, the EU position in these

negotiations should be for the non-deployment of SRM in the foreseeable future.

3.1 Base the EU negotiating position on relevant international and EU law.

3.2 Carry out a broad and inclusive public consultation, to inform the negotiation of the international agreement.

3.3 Include an exemption in the international treaty, with a clear permitting process that specifies conditions under which to authorise some limited outdoor SRM research, with appropriate consideration of the risks this research poses to the environment and associated social, economic and cultural impacts.

3.4 Ensure that the global governance system addresses the risk of militarisation of SRM technologies in an international treaty.

3.5 Invest in operational Earth observation satellite and other technologies to improve the EU's capability to detect and quantify any undeclared deployment of SRM by public or private actors, anywhere in the world.

3.6 Oppose the use of 'cooling credits' derived from SRM technologies in future negotiations on the implementation of multilateral climate agreements.

Recommendation 4

Ensure that research on SRM is conducted responsibly, with scientific rigour and in accordance with EU ethical principles in research. This should include research into the full range of direct and indirect effects and unintended impacts of SRM on the climate system, the biosphere and humankind, including governance and justice issues.

4.1 Create clear ethical requirements for research projects on SRM, whether they are funded publicly or privately.

4.2 Develop guidelines for outdoor research projects on SRM..

4.3 Ensure that any public funding for SRM research is additional to and not instead of public funding for research on climate change mitigation and adaptation.

4.4 Impose a moratorium on large-scale outdoor SRM experiments.

Recommendation 5

Reassess the scientific evidence on risks and opportunities of SRM research and deployment periodically, every 5-10 years.

5.1 Consider supporting the participation of the scientific community in intergovernmental assessments.

5.2 Set up citizens' assemblies to initiate a debate on SRM, promote transparency and develop fair governance.

5.3 Support the development or adaptation and operationalisation of detection-attribution modelling tools, which could cover the range of time horizons and deployment scenarios under consideration.

1. INTRODUCTION

Global warming is caused by greenhouse gas (GHG) emissions due to human activities (IPCC, 2023b). This warming is exacerbated by major feedback mechanisms like loss of ice cover, which reduces the Earth's reflectivity (albedo). The Paris Agreement limits temperature increase to 2° C and if possible to 1.5° C above pre-industrial levels to avoid adverse climate change. Global emissions would need to be reduced rapidly towards net zero by the middle of the century to achieve the ambitious targets of the Paris Agreement. They will be exceeded with every delay in achieving net-zero emissions, resulting in a temperature 'overshoot'. Net-negative emissions, namely removal of the carbon dioxide from the atmosphere, would be required to reduce the overshoot.[1]

The use of technological interventions to reduce incoming solar radiation, solar radiation modification (SRM), and in particular stratospheric aerosol injection, has been suggested as a possibility to compensate for an 'overshoot' in global mean temperature. Theoretically, this might result in 'peak shaving', where SRM is deployed to maintain a temperature target during the overshoot, or provide protection of specific regions (Crutzen, 2006). SRM is a deliberate and large-scale intervention in the Earth's climatic system to reduce the impacts of global warming (SAPEA, 2024). At face value, this seems an attractive option, as some estimates have given the impression that the costs of SRM are lower than those associated with the required deep reduction in anthropogenic GHG emissions (Smith, 2020). In reality, the benefits and risks of SRM technologies are highly uncertain.

Scenarios and climate projections reveal many technological challenges with SRM and considerable physical and biological risks – e.g. related to rainfall, ecosystems and ozone – and, in consequence, also social and economic risks (IPCC, 2023b; SAPEA, 2024; UNEP, 2023). Given the nature of SRM technologies, political, institutional and governance constraints limit the feasibility of controlled use. Private funding, lobbying activity, and possible military applications (such as dual use of delivery aircraft for stratospheric aerosol injection or space mirrors) represent serious challenges to such control. Moreover, any disruption or discontinuation of SRM deployment can result in a 'termination shock' and sudden temperature changes.

[1] Paris Agreement: https://unfccc.int/process-and-meetings/the-paris-agreement.

Some visual representations and metaphors used to describe SRM technologies suggest viability, controllability and even necessity. Such optimism about the perceived potential of SRM to address adverse climate change can potentially undermine political and economic incentives to negotiate international climate-change mitigation agreements and reduce emissions, and therefore constitutes a moral hazard for people, industries and governments (SAPEA, 2024) (Chapter 6).

Fifty years of scientific research indicate that reducing GHG emissions would help us avoid dangerous climate change while also bringing multiple additional benefits for the people and the planet. SRM technologies, by contrast, address the symptoms but not the source of the climate problem. At best, they would temporarily reduce warming from solar radiation (possibly on a regional basis), while GHG concentrations and ocean acidification continue to increase until net-zero GHG emissions are reached. Moreover, deployment would be likely to have substantial negative ecological and economic effects due to changing patterns of rainfall, impacts on ecosystems, a decrease in the security of food production, and reduced potential of solar energy.

Against this background, the College of Commissioners has asked the Group of Chief Scientific Advisors (GCSA) to the European Commission – which, together with the Science Advice for Policy by European Academies (SAPEA) and a Commission secretariat, constitutes the Scientific Advice Mechanism (SAM)[2] – to provide a scientific opinion on Solar Radiation Modification, with policy recommendations, on the basis of the following questions set out in the scoping paper, which constitute the terms of reference for the SAM.

1. How to address the risks and opportunities associated with research on Solar Radiation
Modification and with its potential deployment?
2. What are the options for a governance system for research and potential deployment taking into account different SRM technologies and their scale?

[2] SAM: https://scientificadvice.eu/.

2. POLICY LANDSCAPE

While the idea of SRM has been around for more than half a century, policy development around the topic is still in its early stages. This section provides an overview of existing SRM policies, assessment reports and research funding at European and global levels.

EU policies related to SRM

EU climate policy is strongly focused on: (i) achieving climate neutrality by 2050[3]; (ii) reducing GHG emissions by 55% by 2030[4] and 90% by 2040; and (iii) adapting to climate change[5]. The European Commission does not currently consider SRM to be a solution to climate change, as it masks warming but does not address the root cause of climate change – i.e. the increase in global GHG concentrations in the atmosphere. No wide-ranging EU position on SRM has therefore been developed thus far.

In their Joint Communication on the Climate-Security Nexus[6], the European Commission and the High Representative of the Union for Foreign Affairs and Security Policy identified SRM technologies as a risk. They concluded that these technologies introduce new risks to people and ecosystems, and could also increase power imbalances between and within nations, sparking conflicts and raising a myriad of ethical, legal, governance and political issues. Guided by the precautionary principle, the EU supports international initiatives to make a comprehensive assessment of the risks and uncertainties of climate interventions, including SRM, and promotes discussions on a potential international framework for SRM governance, including research-related aspects.

International policies on SRM

According to the 1976 Convention on the Prohibition of Military or any other Hostile Use of Environmental Modification Techniques (ENMOD)[7]: 'States parties undertake not to engage in military or any other hostile use of environmental modification techniques having widespread, long-lasting or

[3] Climate Law: https://climate.ec.europa.eu/eu-action/european-climate-law_en.
[4] 'Fit for 55' legislative package: https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55/.
[5] EU Adaptation Strategy: https://climate.ec.europa.eu/eu-action/adaptation-climate-change/eu-adaptation-strategy_en.
[6] https://www.eeas.europa.eu/eeas/joint-communication-climate-security-nexus_en
[7] https://disarmament.unoda.org/enmod/

severe effects as the means of destruction, damage or injury to another State party'. The definition of 'environmental modification technique' explicitly mentions the manipulation of the atmosphere, thus of the climate system, which would include the use of SRM for military or other hostile purposes.

In 2010, at its 10th meeting, the governing body of the Convention on Biological Diversity (CBD) adopted restrictions on the deployment of both carbon dioxide removal (CDR) and SRM, but not on carbon capture and storage (CCS), until there is a sufficient evidence base (Decision X/33)[8]. CCS and CDR act on carbon dioxide emissions, the main anthropogenic source of climate change, whereas SRM only acts on temperature, masking climate change to some degree.

Box 1: Definitions:

Carbon capture and storage (CCS) refers to the decarbonisation of fossil and biomass energy sources and industrial processes, such as steel and concrete production, to avoid the release of carbon dioxide into the atmosphere.

Carbon dioxide removal (CDR) refers to the carbon removal from the atmosphere, either through technological means of direct air capture (DAC) of carbon dioxide, or by strengthening nature--based solutions such as afforestation and other Earth-system sinks.

Solar radiation modification (SRM) is a deliberate and large-scale intervention in the Earth's climatic system to reduce global warming.

Decision X/33 exempts 'small scale scientific research … studies subject to a thorough prior assessment of the potential impacts on the environment' in order to develop an adequate knowledge base on the topic. The CBD called for a better understanding of the impacts of these interventions on biodiversity and ecosystem functions and services, socio-economic, cultural and ethical issues, and regulatory options. The Mexican government referred to Decision X/33 when Mexico became the first country to ban SRM experiments on its

[8] CBD Decision X/33: https://www.cbd.int/decision/cop?id=12299.

territories in response to Make Sunsets, a US start-up, carrying out technical experiments in Baja California Sur[9].

Three years later, the CBD added that more transdisciplinary research and sharing of knowledge among appropriate institutions is needed for further understanding about the impacts of SRM interventions on biodiversity and ecosystem functions and services, socio-economic, cultural and ethical issues and regulatory options (Decision XIII/14)[10]. This 2013 Decision recognises the importance of taking into account life sciences and the knowledge, experience and perspectives of indigenous peoples and local communities when addressing climate-related geoengineering and protecting biodiversity. It also emphasises that climate change should primarily be addressed by reducing anthropogenic emissions from all sources, and by increasing removals by GHG sinks under the United Nations Framework Convention on Climate Change.

Resolution 76/112 adopted by the UN General Assembly on 9 December 2021 on the protection of the atmosphere considers the atmosphere as a natural resource and recognises that the interest of future generations in its conservation should be fully taken into account[11]. It provides guidelines for international practices, including international large-scale modification of the atmosphere, which 'should only be conducted with prudence and caution'.

In 2020, the UK government published its view on carbon capture and solar radiation management technologies stating that 'The government is not deploying SRM, and has no plans to do so.'[12] Nevertheless, the policy paper emphasises the need to cover knowledge gaps in the field and outlines the research carried out in the area, while also listing some of the UK's recent support to GHG removal technologies.

Countries such as Switzerland have started a debate on whether climate interventions including SRM should be researched. Switzerland proposed setting up an advisory board to analyse these aspects and inform

[9] https://www.gob.mx/semarnat/prensa/la-experimentacion-con-geoingenieria-solar-no-sera-permitida-en-mexico

[10] CBD Decision XIII/14: https://www.cbd.int/decision/cop/default.shtml?id=13496.

[11] https://documents.un.org/doc/undoc/gen/n21/389/40/pdf/n2138940.pdf?token=v55LaobhuUfu5sCaNe&fe=true

[12] https://www.gov.uk/government/publications/geo-engineering-research-the-government-s-view/uk-governments-view-on-greenhouse-gas-removal-technologies-and-solar-radiation-management

governments and stakeholders about the options. The suggestion was discussed at the UN Environmental Assembly in Nairobi in early 2024, before being withdrawn in the absence of consensus on a draft resolution[13].

In contrast to this growing research interest, many environmental organisations oppose the development and deployment of any SRM technology. Friends of the Earth[14], the Climate Action Network[15] and the Environmental Defense Fund[16], among others, have published statements opposing deployment due to serious ecological, moral and geopolitical concerns, and to the risk that activities would divert resources from emission reduction. More than 500 scientists have signed a call for an international non-use agreement on solar geoengineering,[17] urging national governments to prohibit the development of SRM technologies and outdoor experiments, to refrain from granting patent rights and from deploying third-party SRM technologies, and to object to any future institutionalisation at global level.

A separate group of scientists has called for responsible research to continue, to objectively evaluate the potential for SRM,[18] and another has published an open letter calling for balance in research and assessment of SRM[19].

To sum up, while there are a limited number of international agreements in place that oppose the deployment of SRM technologies, SRM research is exempted from these agreements. No government or international organisation currently promotes large-scale SRM deployment or has any stated intention of deploying SRM technologies on a large scale. Some organisations are calling for more research to further our understanding of SRM, while others oppose SRM research on the grounds that it may redirect resources away from reducing GHG emissions or reduce the motivation for such reductions.

Reports on the impact of SRM

The potential impacts of SRM are touched on in a number of reports from various sources.

[13] https://www.climatechangenews.com/2024/02/29/nations-fail-to-agree-ban-or-research-on-solar-geoengineering-regulations/
[14] https://foe.org/news/2015-02-geoengineering-unjust-unproven-and-risky/
[15] https://climatenetwork.org/wp-content/uploads/2019/09/CAN-SRM-position.pdf
[16] https://www.edf.org/climate/our-position-geoengineering
[17] https://www.solargeoeng.org/non-use-agreement/signatories/
[18] https://climate-intervention-research-letter.org/
[19] https://www.call-for-balance.com/

In June 2023, after a 2021 report of the National Academies of Sciences, Engineering, and Medicine[20], the US Congress requested a research plan for solar and other rapid climate interventions, and a research governance framework related to SRM[21]. The report emphasised that the plan should not only promote scientific research in this area but also investigate the societal implications of climate interventions, and that the research should focus on quantifying uncertainties and closing knowledge gaps.

Although the Intergovernmental Panel on Climate Change (IPCC) focuses on the physical science basis of climate change, mitigation and adaptation,[22] its Sixth Assessment Report also includes a brief assessment of SRM[23]. The report states that 'SRM has the potential to offset warming … but would not restore climate to a previous state'. It highlights the risks that SRM would pose to natural and human systems, emphasises the gaps in the knowledge base, and highlights termination shock and international tension as potential risks.

In February 2023, the UN Environment Programme (UNEP) carried out a rapid review of the state of scientific research on SRM[24]. The review aimed to improve understanding of the potential risks of SRM, especially as regards climate, stratospheric ozone, environmental, human health and social aspects. The review outlined a range of informed views, and included issues of governance of small-scale outdoor experiments, technology development, and financing and governance of operational deployment. It found little information on the risks of SRM, and limited literature on the environmental and social impacts of these technologies, and concluded that even as a temporary response option, large-scale SRM deployment is fraught with scientific uncertainties and ethical issues. It finished by calling for: (i) a robust scientific review process; (ii) a governance framework for possible small-scale outdoor SRM experiments and SRM deployment; (iii) a broader framework for the governance of the stratosphere; and (iv) a globally inclusive conversation around SRM.

[20] *Reflecting Sunlight: Recommendations for Solar Geoengineering Research and Research Governance*, 2021 (https://doi.org/10.17226/25762).
[21] https://www.whitehouse.gov/wp-content/uploads/2023/06/Congressionally-Mandated-Report-on-Solar-Radiation-Modification.pdf
[22] https://www.ipcc.ch/site/assets/uploads/2023/03/Doc5_Adopted_AR6_SYR_Longer_Report.pdf
[23] https://www.ipcc.ch/report/ar6/wg3/
[24] https://www.unep.org/resources/report/Solar-Radiation-Modification-research-deployment

In a 2023 report[25], the Climate Overshoot Commission highlights that more research is needed, including in developing countries, to help decide whether to proceed with this technology, and if so, how. It stresses that governance discussions about SRM are in their infancy and recommends that inclusive international dialogues should begin as soon as possible. It points out that the present lack of governance poses its own risks, including the possibility of premature deployment. It recommends a moratorium on the deployment of SRM and large-scale outdoor experiments with any risk of significant transboundary harm, and also calls for expanding research and pursuing international governance dialogues.

Lastly, a 2023 report by the UN Human Rights Council Advisory Committee on the impact of new technologies intended for climate protection on the enjoyment of human rights[26] assesses SRM among other new technologies. The report lists the human rights at risk in the event of unilateral deployment, including the right to a clean, healthy and sustainable environment and the right to information and public participation. The report calls for restrictive regulations, outlines a human rights-based approach, and calls for a protective framework and international governance to be put in place.

Funding for SRM research

Funding programmes for SRM do exist in various forms around the world.

In the EU, limited targeted support has already been provided for SRM research. In 2023, a 'Solar Radiation Modification: governance of research' call was launched under Horizon Europe, and Co-CREATE[27], the coordination and support action selected, is investigating the conditions and governance arrangements necessary for responsible research in this area. The project aims to develop principles and guidelines by which to facilitate decision-making on the basis of scientific grounds, risk assessment, and an analysis of the political and societal issues involved. Horizon Europe also has thematic calls for research projects that can help explore various aspects of SRM.

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25 https://www.overshootcommission.org/_files/ugd/0c3b70_bab3b3c1cd394745b387a594c9a68e2b.pdf

26 https://documents.un.org/doc/undoc/gen/g23/141/86/pdf/g2314186.pdf?token=1HfUuuK1EEe7CxbEA7&fe=true

27 https://cordis.europa.eu/project/id/101137642

In 2021, the World Climate Research Programme (WCRP) launched its 'Lighthouse Activity on Climate Intervention Research'[28]. The activity covers CDR and SRM and draws on the WCRP's capabilities and strategic partnerships. It will explore future scenarios and provide an objective overview of expected risks and opportunities, remaining key uncertainties, and associated knowledge gaps.

In Germany, China, Australia and the USA, national programmes have been developed to help understand the risks and opportunities of SRM (Horton et al., 2023). The USA National Oceanic and Atmospheric Administration has run the Earth's Radiation Budget research programme since 2020[29]. Australia invests a significant amount of money in protecting the Great Barrier Reef, some of which goes to research on and even the pilot testing of marine cloud brightening (Horton et al., 2023). Germany commissioned two larger studies on SRM, which built up competence in the country (Horton et al., 2023). China also runs small-scale research projects on SRM (Horton et al., 2023), although this research is motivated by a desire to improve local weather engineering rather than global climate modification (Chien et al., 2017). And lastly, the UK's Natural Environment Research Council recently announced a 5-year programme of GBP 10.5 million to model the impacts of SRM[30].

Despite these countries directly funding research into SRM, none of them currently intend to deploy it at scale.

Real-world deployment

There have been limited attempts at outdoor experiments with SRM. In 2021, after pushback from environmental groups and indigenous communities, Harvard University's SCoPEx project had to withdraw plans for a large-scale outdoor experiment in the Arctic[31]. In April 2024, the University of Washington conducted an outdoor experiment on atmospheric particle behaviour in Alameda, California. The organisers did not consult local communities before the start, nor did they announce the experiment widely. The City Council stopped the project, due to safety concerns[32].

[28] https://www.wcrp-climate.org/ci-overview
[29] https://csl.noaa.gov/research/erb/
[30] https://www.ukri.org/what-we-do/browse-our-areas-of-investment-and-support/modelling-environmental-responses-to-solar-radiation-management/
[31] https://www.nature.com/articles/d41586-024-00876-1
[32] https://www.scientificamerican.com/article/geoengineering-test-quietly-launches-salt-crystals-into-atmosphere/

3. SAPEA EVIDENCE REVIEW REPORT

The policy recommendations of this Opinion have their scientific foundation in a SAPEA Evidence Review Report (SAPEA, 2024), produced by an interdisciplinary working group of independent experts from the EU, Switzerland, the UK and the USA. The report provides a detailed overview of the current scientific knowledge on SRM and assesses its institutional, governance, ethical and other human dimensions. The report has two parts. Part One covers the definition of SRM, clarifying the distinction between SRM and other types of climate interventions such as CDR or inadvertent interventions such as GHG emissions, and includes an overview of the main technological options and the conditions for technological development, while also assessing impacts and adverse effects. Part Two identifies the main SRM stakeholders and reviews public and expert perceptions of this technology, with a specific look at feasibility and potential governance frameworks, while also covering legal issues and policy design.

In brief, the review describes how SRM is a class of technological approaches that aim to increase the reflection of sunlight back into space, either directly or as infrared radiation. These interventions would result in masking some of the global warming that results from climate change. SRM technological approaches include stratospheric aerosol injection, cloud brightening, cirrus cloud thinning, surface brightening, and space mirrors. The most prominent technology currently being researched in this area is stratospheric aerosol injection. Although these technologies might reduce the incoming sunlight, a high degree of uncertainty surrounds their potential deployment, and it is difficult to predict the beneficial and adverse effects of SRM on climate variables with any degree of precision. The uncertainties are much higher when it comes to cloud brightening, cirrus cloud thinning, mixed-phase cloud thinning, surface brightening, and space mirrors.

Research literature on SRM and its governance looks at how and why SRM might be employed as a climate intervention option, and by whom. A consensus shows that any resulting temperature reduction would be temporary, it would vary across the world, and would not address other consequences of climate change, such as ocean acidification. This temperature reduction could also have unexpected, and likely adverse, impacts. Almost all of this research is based on climate modelling, and narrowly focused on the reflection of sunlight and the resulting temperature reduction, although some laboratory work has been done to test specific mechanisms. The scientific assessment of broader side effects and risks must be part of these scenarios and rationales, and modelling can be used for this purpose too.

While these models indicate that deployment of SRM may have a potential benefit in masking global temperature increase, they also show that new risks may emerge from any deployment of SRM, such as exacerbation or overcompensation of climate changes at regional level and other parameters including precipitation (e.g. rainfall) and food production. Characterising SRM as an option for tackling climate change may also lead to misunderstandings and misuse, resulting in reduced action to cut emissions ('moral hazard'). Moreover, funding SRM research risks drawing investment and grants away from mitigation options, whilst experiments may lead to a higher probability of SRM deployment ('slippery slope'). At the same time, modelling approaches show substantial uncertainties in predicting the overall cooling potential of SRM technology. The societal implications – which might be severe or even prohibitive – are not currently taken into account in climate models or are only acknowledged as boundary conditions. Outdoor research, such as small-scale tests, has been controversial. This underlines the fundamental importance of developing governance for research at an early stage, to ensure that the differing perspectives across society can all be addressed.

We refer to the SAPEA Evidence Review Report (SAPEA, 2024) for a comprehensive and detailed review of scientific knowledge on SRM.

Box 2: The SAPEA Evidence Review Report (ERR, SAPEA, 2024) provides a comprehensive overview of the five main SRM technology options based on the scientific literature. This is a brief extract from the ERR technology overview (ERR. Page 5, and chapter 2)

- *Stratospheric Aerosol Injection (SAI)* is the most widely considered SRM technology. Climate models are the only tools that can assess the impact of SAI on climate and atmospheric composition, including ozone. Although the results vary considerably, models show that global cooling is in principle possible with SAI. This is similar to the observed surface cooling after a large volcanic eruption. However, there are still considerable uncertainties about the quantities required and deployment strategies. The technology for using aerosols is not yet mature (see also Box 3 below). Uneven interhemispheric injection can lead to large climate impacts, as can the abrupt onset or cessation of SAI. SAI is reversible on a timescale of a few years, but any masked warming from SAI would reappear after a few years.

- *Cloud brightening (CB)* would increase the reflectivity of shallow low-level liquid clouds, mainly in marine environments (MCB). Even more than for SAI, there are significant uncertainties in the understanding of aerosol-cloud-radiation interactions, mixed assessments of efficacy and impacts from observational analogues and modelling studies all limit the credibility of MCB. Significant methodological and technological challenges need to be overcome before CB could be deployed operationally. The short lifetime of the injected particles could, in principle, allow the use of CB for limited periods and regions.
- *Cirrus cloud thinning (CCT)* is much less robust due to even greater uncertainties than for CB; even more uncertain is the feasibility of mixed-phase cloud thinning (MCT). CCT and MCT operate in the terrestrial rather than the solar radiation spectrum and could in principle better counteract some aspects of greenhouse gas forcing. However, the technology for application is not yet mature and the seeding not well controlled.
- *Space Mirrors (SM)* for solar dimming have been extensively studied in climate models, confirming the potential cooling effect. Concepts for the possible design of sunshades range from dust derived from moon rocks or asteroids to a swarm of reflective disks or mirrors. Studies to date conclude that the technology is far from available, and that SM would be very expensive.
- CCT and MCT are reversible on timescales of days to weeks and could in principle be deployed on a regional and temporary basis.
- *Surface brightening (SB)* would increase the surface albedo, similar to CB. This would mainly involve surface brightening. According to modelling studies, it is unlikely to be able to counteract global warming on a large scale. At local scales, however, deployment techniques are relatively straightforward.

4. POLICY RECOMMENDATIONS

Recommendation 1:
Prioritise reducing GHG emissions as the main solution to avoid dangerous climate change

The European Green Deal[33], 'Fit for 55'[34] and 90% emissions reduction by 2040[35] provide the best goals for the EU to reduce carbon emissions to net zero by the middle of the century and become climate-neutral. These very ambitious goals will require Herculean efforts, but they are still the best options for the EU in helping stabilise climate change at 2° C and if possible 1.5° C above the pre-industrial average global temperature and achieve the targets of the Paris Agreement[36]. These goals are intended to protect people and the planet from dangerous climate change. There is now strong evidence that 1.5° C and even 2° C targets are likely to be exceeded by mid-century because of the insufficient reduction of global emissions. This would result in a need to remove carbon dioxide from the atmosphere to compensate for emissions overshoot, preferably through nature-based solutions such as afforestation, support of other planetary sinks, and possibly also through technological means, together with carbon storage. Emissions reduction must therefore remain the top priority, together with adaptation to the adverse impacts of climate change. There is widespread agreement among climate scientists that SRM cannot be the only response to climate change, because at best it can marginally supplement and complement the achievement of sustained net-zero or net-negative GHG emission levels. While it may temporarily reduce temperatures, it will have no effect on other adverse impacts such as ocean acidification (SAPEA, 2024) (Chapter 3.1).

1.1 Continue to treat emissions reduction and adaptation to climate change as the highest priority in reaching net zero by mid-century and minimising 'overshoot' and its adverse effects.

The EU should prioritise the reduction of emissions to net zero, alongside adaptation to climate change. Mitigation options (such as efficiency improvements and the substitution of fossil fuels with carbon-emission-free

[33] Climate Law: https://climate.ec.europa.eu/eu-action/european-climate-law_en.
[34] 'Fit for 55' legislative package: https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55/.
[35] Proposal: https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2040-climate-target_en.
[36] https://unfccc.int/sites/default/files/resource/parisagreement_publication.pdf

energy sources, carbon capture and storage (CCS) from fossil fuels, reduction of land-use emissions, and enhancing and preserving carbon sinks of the Earth system (biosphere and oceans remove about half of the anthropogenic carbon dioxide emissions), and carbon dioxide removal from the atmosphere) all have lower inherent risks and uncertainties than SRM, and thus are the main solutions by which to avoid dangerous climate change and achieve climate neutrality by mid-century. Model-based scenarios indicate that net-zero emissions could be achieved through a combination of social, behavioural, technological and economic transformations, and that this would help avoid a large overshoot in temperatures beyond Paris Agreement levels (Grubler et al., 2018; IPCC, 2023b) (Chapter 3.3.4). Moreover, the duration and extent of a possible overshoot could be substantially reduced by achieving net-negative emissions through decarbonisation of sustainable biomass use, carbon dioxide removal (CDR) from the atmosphere, and other approaches (IPCC, 2023b) (Chapter 3.3.4).

1.2 Continue to actively and vigorously invest in research on and deployment of climate mitigation and adaptation.

The EU should actively invest in further research and deployment of climate mitigation and adaptation strategies, including CCS and CDR, as they are less risky and further developed than SRM. This will minimise the risk that governments or private parties might be tempted to deploy SRM technologies in the future. These other technologies are better understood, have already been deployed at scale and have lower risk compared to SRM (IPCC, 2023a) (Chapters 12 and 14.4.5.2). Furthermore, enhancing their deployment at scale would bring multiple co-benefits for people and the environment, while boosting the advance of EU technological and economic capacities and gaining increasing competitiveness in a changing world.

Some scientific literature on SRM argues that the risks of deploying this technology are likely to be lower than the risk of climate change itself (Clark et al., 2023; Ji et al., 2018; Kravitz et al., 2015; Lee et al., 2020; Niemeier et al., 2013; Tew et al., 2023; Tilmes et al., 2013), and that the risks and benefits of SRM should therefore be weighed against the gravest potential impacts of climate change – i.e. a 'risk-risk analysis'. However, this reasoning assumes only weak mitigation action against climate change. This first recommendation guards against such reasoning. In reality, the potential of SRM should be weighed up against a backdrop of increasingly robust and vigorous climate change mitigation and adaptation measures, which have already gained broad support and commitment, and not against unabated climate change. Some mitigation measures, such as a drastic reduction in methane emissions, could slow the rate of climate warming in a matter of one or two decades, with much less uncertainty than SRM.

Recommendation 2:
Agree on an EU-wide moratorium on the use of SRM as a measure for offsetting climate warming

2.1 Acknowledge that there is currently insufficient scientific evidence that SRM would effectively help to avoid dangerous climate change by reducing some of the resulting global warming.

All impact estimates rely on models or are based on small-scale experiments or observations of imperfect analogues such as volcanic eruptions (SAPEA, 2024) (Chapters 2.1.3, 2.2.3 and 2.3.3). The Earth system is strongly non-linear, however, so there is a high level of uncertainty when attempting to predict the cooling effect and other impacts of SRM deployment. Importantly, SRM would not reduce the increasing accumulation of GHG in the atmosphere or the acidification of oceans, nor would it reduce their negative effects on life as we know it (SAPEA, 2024) (Chapter 3.1).

It is evident from model simulations, observations and theoretical considerations that SRM would not prevent the impacts of dangerous climate change in ways that are comparable to deep cuts in GHG emissions. At best, SRM deployment would temporarily (i.e. during the period of deployment) reduce only some of the global warming effects of climate change. As SRM deployment would be a direct intervention in the climate system, rainfall would be affected, especially if deployment involved injecting aerosols into the stratosphere. If SRM is deployed in one hemisphere only, it may nonetheless cause changes in monsoon patterns (SAPEA, 2024) (Chapter 3.2.2). In some cases, there is no scientific consensus on the magnitude of these impacts. Sometimes there is not even a consensus on their direction (i.e. whether they are positive or negative). These broader side effects and their risks to geopolitical stability preclude actual deployment of SRM technologies (SAPEA, 2024) (Chapter 3.1).

Box 3: Cost estimates for stratospheric aerosol injection deployment

Development and deployment of SRM technologies at scale would require considerable resources, including the delivery mechanisms for aerosols in the stratosphere. Although stratospheric aerosol injection might cost significantly less than other SRM interventions (such as marine cloud brightening techniques or space mirrors), there are various estimates published in the literature indicating large uncertainties, in the range of USD 18 to 107 billion per year to offset 1 °C of warming (Niemeier & Tilmes, 2017; Robock, 2020; SAPEA, 2024; Smith, 2020) (Chapter 2.1.4). The real cost of delivery at scale could potentially be substantially higher. This introduces an additional source of uncertainty on the viability of SRM. While using aircraft to deliver sulphur aerosols to the stratosphere may appear to be an effective solution (SAPEA, 2024) (Chapter 2.1.4), they would have to fly at altitudes of around 25 km for the most efficient injection. Even Concorde cruised at only 18,300 metres. The aircraft that would be required do not yet exist and would need to be developed in the coming decades (SAPEA, 2024) (Chapter 2.01.4). The only known comparable examples are the Lockheed U-2 'Dragon Lady' spy plane, which could cruise at 21 km, and the Global Hawk drone (up to 18,000 metres), which has a payload of some 1.35 tonnes. The payload capacity required would be at least 10 to 100 times larger. The Lockheed SR-71 'Blackbird' spy plane did fly at a comparable altitude, but it had no payload. A possible solution might be to fly at lower altitudes compromising injection efficiency, with a lower capacity to lift and distribute up to 15 tonnes of aerosols (Bingaman et al., 2020; SAPEA, 2024; Smith, 2020; Smith & Wagner, 2018) (Chapter 2.1.4). The estimated amount of sulphur needed to offset 1°C of global warming generally ranges between 5 and 10 million tonnes per year. Robock et al. (2008) estimated it at about 5 million tonnes per year, Budyko (1977) estimated that it could range from 5 to 8 million tonnes per year, and Kravitz et al. (2017) estimated it at about 10 million tonnes per year, all associated with significant uncertainties. Assuming one flight can deliver 15 tonnes, this translates to some 900 to 1,800 flights per day, which requires a fleet of aircraft comparable to twice to four times that of Federal Express (Smith, 2020; Smith et al., 2022). Smith (2020 and 2022) estimates that an initial fleet of fewer than 10 aircraft with a payload capacity of 15.7 tonnes could start deployment in 2035, ramping up to a fleet of two dozen to several hundred aircraft with a payload capacity of 25.4 tonnes by mid-century. In short, the development and production of a fleet of delivery aircraft that do not yet exist would likely take decades. Once initiated, sulphur injection into the stratosphere or upper troposphere would need to continue 24/7 for many years, until emissions are reduced to at least net zero, to avoid a termination shock.

2.2 Recognise that the deep uncertainties associated with possible SRM deployment are inconsistent with the precautionary and 'do no harm' principles.

The many climate, ecological, geopolitical and social risks and uncertainties of SRM deployment remain high and insufficiently understood, and are also inherently not fully predictable. Consequently, these risks and uncertainties imply that it would not be possible to comply with the precautionary and 'do no harm' principles, as is customary in international law, in view of obligations to cooperate on impact assessment and observe international treaties (SAPEA, 2024) (Chapter 7.3).

Currently there are no effective governance approaches to regulating the deployment of SRM at global or international levels to ensure that values of justice, equity and cooperation would be central to any large-scale deployment of SRM (SAPEA, 2024) (Chapters 6 and 7.2). Moreover, it is unlikely that this might be achieved in time to complement current measures to halve global emissions by 2030 and reduce to net zero by 2050, in accordance with the Paris Agreement (IPCC, 2023a) (Cross-Working Group Box 4).

An EU-wide moratorium should be re-evaluated periodically, for example every 5 to 10 years or so (see recommendation 5), with the expectation that only a widespread scientific and political consensus based on strong scientific evidence could lead to an evaluation of whether lifting the ban is justified. The timeframe for reconsideration could be related to the current EU targets for GHG net reduction – i.e. 55% reduction by 2030[37], 90% by 2040[38] and 100% by 2050[39] – and to the projected timeframe for research to make sufficient progress in offering robust scientific evidence on SRM. A safe and equitable deployment of SRM technologies in the EU should only be considered once the following criteria are met: (i) there is an international governance system in place that includes monitoring and verification of compliance; (ii) the scientific evidence convincingly demonstrates that the benefits outweigh the risks; and (iii) the governance is based on an inclusive process, including key stakeholders, and on rigorous evidence of compliance with the 'do no harm' principle.

[37] 'Fit for 55' legislative package: https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55/.
[38] Proposal: https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2040-climate-target_en.
[39] Climate Law: https://climate.ec.europa.eu/eu-action/european-climate-law_en.

Recommendation 3:
Proactively negotiate a global governance system for deployment of SRM by means of a multilateral process with international legitimacy. Given the current state of knowledge, the EU position in these negotiations should be for the non-deployment of SRM in the foreseeable future**.**

Given the risk of transboundary spill-over effects of SRM, there is a need for a global governance system, e.g. under the aegis of United Nations organisations such as UNFCCC[40], UNEP[41], WMO[42] and UNCBD[43]. Any non-deployment agreement should concern all countries, private stakeholders, and any other entities, and prevent unauthorised deployment of SRM both by individual states and within states. SRM with a local or regional scope and negligible spill-over effects outside the deployment area – e.g. a city deciding to paint its streets or buildings in white – should not fall under a non-deployment agreement. However, some regional SRM interventions, such as marine cloud brightening, have recently been shown, through model simulations, to generate substantial responses well outside the target region through climate teleconnections, and should therefore be covered by the non-deployment agreement (Wan et al., 2024).

The negotiation of a multilateral agreement should be globally inclusive. It should fully involve the perspectives of the Global South, which includes people and countries most vulnerable both to climate change and to possible side effects of SRM deployment (SAPEA, 2024) (Chapter 5.2). Aspects to be negotiated include whether this agreement should be binding (i.e. treaty versus declaration) and whether enforceable sanctions and penalties should be associated with it. This agreement should also mandate full transparency and information exchange on SRM research and its results, conducted anywhere in the world. The nuclear test-ban treaty and genetic engineering ban could serve as past examples (SAPEA, 2024) (Chapter 7.3).

Impacts on international security and peace, especially in the case of poorly designed, unilateral or rogue deployment of SRM, should be a central motivation for this multilateral agreement. The agreement should prohibit deployment in the foreseeable future, not only by nation states but also by private and public organisations.

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[40] https://unfccc.int/
[41] https://www.unep.org/
[42] https://wmo.int/
[43] https://www.cbd.int/

3.1 Base the EU negotiating position on relevant international and EU law.

The EU negotiating position for an international treaty on SRM should always be informed by, and aligned with, the EU's legal commitments under public international law and EU law (SAPEA, 2024) (Chapter 7.3). These include the law of the sea, protection of the atmosphere, environmental law, and human rights law. Governance of non-deployment should fully comply with international law, commitments and practices, in line with other activities with similar risk profiles. In particular, governance should consider EU environmental commitments such as multilateralism (SAPEA, 2024) (Chapter 7.3). Relevant legal obligations include the 'do no harm' principle under customary international law; the obligation to cooperate on impact assessment; international treaties such as the Convention on Biological Diversity[44], the UN Convention on the Law of the Sea[45], the Convention on Long-range Transboundary Air Pollution[46], and the Aarhus Convention[47]; human rights safeguards, such as the rights of the child; the principle of intergenerational equity and human rights obligations owed to future generations; and the precautionary principle (SAPEA, 2024) (Chapter 7.3).

3.2 Carry out a broad and inclusive public consultation, to inform the negotiation of the international agreement.

An effective international governance system to prohibit any unilateral deployment of SRM has to be based on a shared understanding among all parties, including civil society, of: (i) acceptable future world development scenarios, in this case the Paris Agreement and the 2030 Agenda[48]; (ii) risk and benefit perceptions associated with climate change by different cultures and societies; and (iii) valid and evidence--based sources of knowledge about the future, such as ERRs of the SAM[49] or the IPCC[50]. The acceptability of SRM is in part based on moral choices (SAPEA, 2024) (Chapter 7.3). We refer here to the related EGE (European Group on Ethics, an independent advisory body

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[44] https://www.cbd.int/
[45] Full text of UNCLOS: https://www.un.org/depts/los/convention_agreements/texts/unclos/unclos_e.pdf.
[46] Full text of LRTAP: https://unece.org/sites/default/files/2021-05/1979%20CLRTAP.e.pdf.
[47] The Aarhus Convention is the UNECE Convention on Access to Information, Public Participation in Decision-making and Access to Justice in Environmental Matters. Full text: https://unece.org/DAM/env/pp/documents/cep43e.pdf.
[48] UN 2030 Agenda for sustainable development: https://sdgs.un.org/2030agenda
[49] Evidence review reports are part of the SAM's work https://scientificadvice.eu/.
[50] https://www.ipcc.ch/

of the President of the European Commission) Opinion, which develops this point (EGE, 2024)

3.3 Include an exemption in the international treaty, with a clear permitting process that specifies conditions under which to authorise some limited outdoor SRM research, with appropriate consideration of the risks this research poses to the environment and associated social, economic and cultural impacts.

This exemption would specify the processes that would: (i) permit outdoor SRM research; and (ii) demonstrate that this research does not pose risks of local and transboundary environmental or social harm. Permit allocation should be limited to experiments of high scientific and policy relevance and with low environmental and (geo)political risks (SAPEA, 2024) (Chapter 7.2). The exemption on research should follow the principles outlined in recommendation 4. The negotiation of the text of this exemption could take CBD Decisions X/33[51] and XI/20[52] as a basis.

3.4 Ensure that the global governance system addresses the risk of militarisation of SRM technologies in an international treaty.

There is a risk of military use of some SRM technologies and technologies developed for SRM deployment (SAPEA, 2024; Sovacool et al., 2023) (Chapter 6.4). SRM falls under the definition of environmental modification techniques under the Convention on the Prohibition of Military or any other Hostile Use of Environmental Modification Techniques (ENMOD)[53]. Article II of the ENMOD Convention explicitly bans the use of environmental modification techniques for military or hostile use (SAPEA, 2024) (Chapter 7.3). This ban should be reiterated and strengthened in a multilateral agreement on SRM.

3.5 Invest in operational Earth observation satellite and other technologies to improve the EU's capability to detect and quantify any undeclared deployment of SRM by public or private actors, anywhere in the world.

This monitoring system could use operational satellites handled by the EU or its Member States or organisations (e.g. the European Space Agency and the European Organisation for the Exploitation of Meteorological Satellites) and

[51] CBD Decision X/33: https://www.cbd.int/decision/cop?id=12299.
[52] CBD Decision XI/20: https://www.cbd.int/decision/cop/default.shtml?id=13181.
[53] ENMOD: https://disarmament.unoda.org/enmod/.

might extend to collaborations with similar agencies in allied countries (SAPEA, 2024) (Chapters 6.4 and 7.2). An option beyond current capabilities, to detect smaller volumes of substances deployed in the stratosphere, would be a polar-orbiting Earth radiation budget instrument to identify relevant radiative forcings and/or an instrument capable of identifying and monitoring stratospheric aerosol (e.g. a lidar) (SAPEA, 2024) (Chapter 8.3).

Putting in place an international agreement on the non-deployment of or a moratorium on SRM should be the goal, but rogue deployment may occur before any agreement is in place. The EU needs to have the capabilities to independently monitor undeclared deployment and to prepare reaction scenarios in the event of rogue deployment. These scenarios should set out appropriate responses, depending on the size of deployment and the parties involved (SAPEA, 2024) (Chapter 6.4).

3.6 Oppose the use of 'cooling credits' derived from SRM technologies in future negotiations on the implementation of multilateral climate agreements.

Cooling credits generated through SRM deployment at any scale risk diverting efforts away from emissions reduction and climate change mitigation and could potentially create financial gain for actors who are big contributors to global GHG emissions.

Recommendation 4:

Ensure that research on SRM is conducted responsibly, with scientific rigour and in accordance with EU ethical principles in research. This should include research into the full range of direct and indirect effects and unintended impacts of SRM on the climate system, the biosphere and humankind, including governance and justice issues.

The high uncertainties in the potential benefits and risks of SRM can only be addressed by further research (as in any other field), ideally supported by public funding. There are many knowledge gaps, but those that deserve priority funding concern the need to: (i) understand better the basic physics of SRM, including aerosol-cloud interactions (SAPEA, 2024) (Chapter 2.2.5) and the impacts of SRM on atmospheric chemistry; (ii) simulate better the spread of aerosols in climate models (SAPEA, 2024) (Chapter 2.1.3); (iii) analyse comprehensively the potential direct and indirect effects and risks of SRM, its possible delivery mechanisms and technologies; and (iv) develop a greater ability to detect deployment by other nations or private stakeholders and attribute side and other effects to this deployment. Even if the EU has no plans to ever deploy SRM, gaining a deeper understanding of this technology is still important for negotiating an international agreement and to detect and respond to possible deployment by other parties. Another argument for research is that it builds the expertise needed to assess SRM and provide up-to-date science advice to policymakers (SAPEA, 2024) (Chapter 7.1).

At the same time, researching SRM also entails some inherent risks, including unintended environmental impacts of outdoor experiments or implicitly creating the impression that controlling climate change through SRM might become a feasible option (SAPEA, 2024) (Chapter 6.1). The EU therefore needs to ensure that any research funding directed towards SRM is: (i) clearly targeted to support the EU's position in international negotiations; and (ii) fully addresses all direct and indirect potential risks to and unintended impacts on the climate system, the biosphere and humankind, including governance and justice issues.

Private-sector research is already taking place. It should be transparent, with appropriate disclosure of projects, intentions and results, and should comply with the same principles as publicly funded research, namely that it must be conducted responsibly and in accordance with ethical principles (see EGE, 2024).

4.1 Create clear ethical requirements for research projects on SRM, regardless of whether they are funded publicly or privately.

Research on SRM should be subject to: (i) a determination of whether pre-approval by an ethics board is needed, and (ii) an obligation of full transparency on data, methods and results. To minimise the administrative burden, SRM-related research projects could be subject to some form of triage, to decide whether pre-approval by an ethics board is needed. There are clearly different risks associated with indoor versus outdoor, and small-scale versus large-scale experiments. However, scientists involved in modelling or indoor experimentation should also be aware of the broader consequences of their work and should feel accountable for the social implications of their research. Evaluation of the ethical implications of SRM research projects should include interdisciplinary scientific expertise.

SRM research and deployment involve a number of ethical and justice concerns, which have also been examined in scholarly research (SAPEA, 2024) (Chapter 6.1). Among these are mitigation deterrence (SRM undermining commitment to mitigation) and outdoor experiments impacting local communities without their prior consent. Specific research protocols should be developed using interdisciplinary scholarly expertise on these issues, as for any research involving human subjects. Ethical guidelines should be developed for indoor and small-scale outdoor research, with full transparency on data, methods and results, in line with the advice of the European Group on Ethics (EGE, 2024). Adherence to these guidelines should be assessed in proposals for public funding and promoted among private research organisations.

As policymakers look to scientific research to inform their decisions about SRM, transparency of research results is crucial (SAPEA, 2024) (Chapter 7.1). The funding source, advisory boards, methods and all research data should be disclosed for independent assessment of the project. This is one of the four substantive Oxford Principles (Rayner et al., 2013) which enable independent assessment of research. Experts have proposed an international registry of SRM research to increase transparency about research, patent applications and technology developments (SAPEA, 2024) (Chapter 8.1).

4.2 Develop guidelines for outdoor research projects on SRM.

Outdoor experiments may have long-term consequences for local climates and ecosystems (SAPEA, 2024) (Chapters 3 and 6.1). Therefore, in order to receive funding for small-scale outdoor SRM experiments, researchers should be required to: (i) demonstrate that the experiments do no significant economic, social, cultural, ecological or geopolitical harm; (ii) carry out a public consultation among potentially affected populations; and (iii) take into account a broad range of possible impacts beyond temperature reduction. Any research funding for outdoor SRM experiments should be conditional on a clear case made on the basis of prior indoor research, which demonstrates that the potential scientific and other benefits have sufficient potential to outweigh the costs and risks. Interdisciplinary panels of experts covering a broad spectrum of disciplines, from climate science to ethics, should be responsible for developing guidelines and evaluating projects. The process should include the development of criteria for distinguishing small- from large-scale outdoor experiments. More specifically, it should be clarified what constitutes a large-scale experiment and what constitutes a small--scale experiment.

Any research programme on SRM should commit not to be used to catalyse or promote a 'slippery slope' from research to deployment. This would be consistent with the precautionary and 'do no harm' principles.

4.3 Ensure that any public funding for SRM research is additional to and not instead of public funding for research on climate change mitigation and adaptation.

Mitigation and adaptation should remain the top priority, and SRM funding should not divert funds and intellectual effort away from climate change mitigation or other related research activities. While research funding for SRM is relatively small compared to more general climate change research, it is important not to downgrade the primary priority of climate change mitigation and adaptation research. The promise of a cheaper and seemingly less disruptive technological solution risks undermining mitigation action by the public, private actors and policymakers (SAPEA, 2024) (Chapter 6.1). This 'mitigation deterrence' can also result in lowering ambitions, delaying action or redirecting funding. It should be noted that some climate research and modelling may also provide advances in the understanding of SRM, as well as of mitigation and adaptation.

4.4 Impose a moratorium on large-scale outdoor SRM experiments.

An experiment should be considered largescale if it is associated with a risk of significant transboundary effects and harm beyond the place of the intervention. Large-scale experiments pose partly unpredictable risks of creating significant long-term climate disturbances at local to global scales. As mentioned in recommendation 4.2, a process should be put in place to define precisely the differences between small- and large-scale outdoor SRM experiments. The moratorium should cover both publicly and privately funded research projects.

Recommendation 5:
Reassess the scientific evidence on risks and opportunities of SRM research and deployment periodically, every 5 to 10 years.

Research on Earth-system processes and dynamics and on governance related to SRM could evolve quickly. This requires periodic updates on the current recommendations, based on scientific progress. These updates could go both ways, i.e. either revealing a greater potential for and lower risk of SRM or identifying dangerous risks that could lead to a permanent ban of this technology. Given the potential risks and possible opportunities of SRM deployment, a comprehensive and policy-relevant scientific assessment could provide further clarity and knowledge to EU decision-makers. It could involve the regular evaluation of a possible moratorium and/or non-deployment agreement on SRM, for example every 5 to 10 years, or so (see recommendation 2.2). This requires internationally coordinated scientific action to improve our knowledge about the opportunities, risks and technical and financial resources associated with SRM.

Such an assessment could be carried out by the Intergovernmental Panel on Climate Change (IPCC)[54] and Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES)[55], and possibly a new European intergovernmental panel on climate change, which would also cover SRM. This way, SRM could be integrated into a systemic assessment of all options, policies and measures for Europe to become climate-neutral in the sense of a 90% emission reduction by 2040 and net zero by 2050. The assessment should include: (i) experts in climate change from a range of disciplines, from climate physics and atmospheric chemistry to social sciences, economics and engineering; (ii) experts on the ethical and governance dimensions of such technologies; and (iii) relevant stakeholders with diverse backgrounds beyond scientists. The reviews could lead to periodic updates of policies on SRM research and deployment at both EU and global level.

5.1 Consider supporting the participation of the scientific community in intergovernmental assessments.

It is important to support scientists' participation in intergovernmental and international assessments. These assessments can include the IPCC, the IPBES, the WCRP or a peer-reviewed scientific assessment like the Global Energy Assessment (Banerjee et al., 2012) (GEA, 2012). Information procedures should also be put in place to ensure decision-makers involved in international and domestic decisions are appropriately informed about the latest scientific evidence related to SRM activities (including largescale field campaigns).

5.2 Establish citizens' assemblies to initiate a debate on SRM, promote transparency and develop fair governance.

The inclusion of representatives from various societal sectors is key to a just decision-making process. The debate on SRM in citizens' assemblies should be supported by groups of interdisciplinary scientists and other experts working on technologies, climate science and policy, alongside decision-makers and experts in ethics (SAPEA, 2024)(Chapter 8.2). The

[54] https://www.ipcc.ch/
[55] https://www.ipbes.net/

geographical scale at which assemblies would be organised could be regional, national or continental, and there could be assemblies at several scales at the same time. They should cover all 27 Member States, and other European countries. Representatives from countries and various civil society and indigenous communities around the world should be invited to join.

Box 4: The GeoMIP project[56]

Findings indicate that SRM could potentially reduce global temperatures and counteract some climate impacts, but there are substantial uncertainties and regional differences in climate response. Further research should include social, moral and ethical studies of SRM, and should cover all potential adverse effects of such interferences in the climate system, from local to global and from short-term (for 'peak shaving') to permanent effects. This work could incorporate and build on already existing international scientific collaborations like CMIP6 which, using climate models, assessed scenarios of potential temperature reductions and the need for comprehensive risk assessments, and the IPCC Special Report on 1.5 C and AR6, which concluded that SRM could potentially provide temporary and partial temperature-raise relief, but would come with significant uncertainties and risks.

5.3 Support the development or adaptation and operationalisation of detection-attribution modelling tools, which could cover the range of time horizons and deployment scenarios under consideration.

This would make it possible to identify the effects and impacts of SRM based on field experiments, regional/intermittent or global deployment using known or identified SRM action, and a counterfactual situation without SRM (SAPEA, 2024) (Chapter 8.3). In addition to funding the corresponding research and development within the EU, collaboration on such tools at international level should also be supported, including as part of the World Climate Research Programme (WCRP)[57]. The WCRP initiated the 'Lighthouse Activity on Climate Intervention Research', which includes CDR and sequestration technologies as well as SRM. Such scientific programmes are critical for: (i) evaluating the literature; (ii) identifying key scenarios, environmental consequences,

[56] https://www.wcrp-climate.org/modelling-wgcm-mip-catalogue/cmip6-endorsed-mips-article/1054-modelling-cmip6-geomip
[57] https://www.wcrp-climate.org/ci-overview

uncertainties, and knowledge gaps; and (iii) guiding the research necessary to serve as a foundation for governance and decision-making.

Possibilities include mandating SAPEA to organise and coordinate such an assessment or requesting it directly through a Horizon call. Considerations would range from supporting and funding European authors of IPCC reports and various national assessments listed above, to a simpler scenario in which national assessments in all Member States would be supported and used as a basis for an EU-wide assessment in the form of a policymakers' summary followed by concise national assessments.

Box 5: National climate assessments

Climate assessments carried out across Member States include the following:

- The Austrian Panel on Climate Change[58] is currently drafting its second assessment report, initiated in 2022. The first one was published in 2014 and involved contributions from hundreds of scientists, stakeholders and government agencies.
- The Finnish Climate Change Panel[59] is an independent, interdisciplinary group of experts that provides scientific advice on climate policy to the Finnish government with its National Climate Change Adaptation Plan 2022[60] and Finland's National Climate and Energy Strategy[61], which is updated regularly to achieve carbon neutrality by 2035 and is aligned with EU climate policies.
- Germany has conducted extensive climate assessments through institutions such as the German Environment Agency (Umweltbundesamt)[62] and the Potsdam Institute for Climate Impact Research (PIK)[63]. Reports like *Climate Futures* and *Climate Impact and Vulnerability Assessment* provide detailed analysis similar to the IPCC assessments.

[58] https://ccca.ac.at/en/climate-knowledge/apcc
[59] https://ilmastopaneeli.fi/en/etusivu-en/
[60] https://mmm.fi/documents/1410837/0/Finland_s_National_climate_Change_Adaptation_Plan_2022+%281%29.pdf
[61] https://tem.fi/documents/1410877/2769658/Carbon+neutral+Finland+2035+-+national+climate+and+energy+strategy.pdf/7d9d4a71-81c7-c11f-ec7e-df3eee446e81/Carbon+neutral+Finland+2035+-+national+climate+and+energy+strategy.pdf?t=1715858224013
[62] https://www.umweltbundesamt.de/en
[63] https://www.pik-potsdam.de/en

- Sweden conducts climate assessments through the Swedish Meteorological and Hydrological Institute[64]. Documents like the Swedish National Strategy for Climate Change Adaptation[65] provide comprehensive analysis of climate impacts and adaptation strategies
- The French National Observatory for the Effects of Global Warming[66] produces assessments like the French National Climate Change Adaptation Plan[67], which includes detailed analysis akin to the IPCC's approach.
- Two European countries that are not EU Member States – Norway and the United Kingdom – have also produced assessment reports. For example, the Norwegian Climate Adaptation Strategy[68] was published by the Norwegian Environment Agency[69]; the UK Climate Change Committee[70] regularly publishes detailed reports on climate risks and adaptation, and the UK Climate Change Risk Assessment[71], which is comparable in depth to IPCC reports, is published every 5 years.
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[64] https://www.smhi.se/en/about-smhi
[65] https://www.smhi.se/polopoly_fs/1.168045!/National%20Strategy%20for%20Climate%20Change%20Adaptation.pdf
[66] https://www.ecologie.gouv.fr/politiques-publiques/observatoire-national-effets-du-rechauffement-climatique-onerc
[67] https://climate-laws.org/document/national-climate-change-adaptation-plan-2018-2022_248a
[68] https://publikasjoner.nve.no/diverse/2017/nves.strategy.for.climate.change.adaption2017.pdf
[69] https://www.environmentagency.no/
[70] https://www.theccc.org.uk/
[71] https://www.gov.uk/government/publications/uk-climate-change-risk-assessment-2022

ANNEX 1 – METHODOLOGY

The Group of Chief Scientific Advisors (GCSA) provides independent scientific advice to the to the European Commission (EC) to inform policy making. The advisors work closely with the Scientific Advice for Policy by European Academies (SAPEA) consortium, which brings together expertise in natural, biomedical, and social sciences, humanities, and engineering from a network of more than 100 academies and societies across Europe. The GCSA is supported by an administrative/scientific group in the EC's Research and Innovation Directorate General (DG RTD). GCSA, the DG RTD group and SAPEA constitute collectively the Scientific Advice Mechanism (SAM).

In this framework, the GCSA has been asked to provide a Scientific Opinion on Solar Radiation Modification (SRM) as a climate intervention. Specifically, the question was on how to address the risks and opportunities associated with research on SRM and with its potential deployment. What the options are for a governance system for research and potential deployment, considering different SRM technologies and their scale. The background to this request and the above-mentioned specific question to be addressed by the GSCA is presented in the 'Scoping Paper' (Annex 2). The recommendations presented in this Opinion build upon the Evidence Review Report (ERR) carried out by SAPEA (ERR, 2024), additional literature, and expert and stakeholder consultation (Annex 3).

The scoping of the question was based almost entirely on peer-reviewed literature and occasionally grey literature such as reports of international organisations, and scientific experts. Based on this a Scoping Paper (Annex 2) was prepared. The Scoping Paper was the result of consultation with Directorates-General responsible for climate policies. The request originated from former EVP Timmermans. The scientific advisors Nebojsa Nakicenovic, Eric Lambin, and Naomi Ellemers have worked on the ScientificOpinion on behalf of the GCSA.

The work of the scientific advisors was supported by SAPEA, which provided the scientific evidence in a state-of-the-art report underpinning the scientific opinion. SAPEA established a working group of experts to write the ERR. Two sub-groups addressed different pillars of the topic. One group carried out the work on the scientific and technological evidence, whereas the other explored the societal and ethical dimension of the issue. The results were consolidated and written up into a single report. The evidence was discussed in meetings of academic experts, policy experts and practitioners (Annex 3). SAPEA also organised an expert workshop with independent scientific experts.

The SAM Secretariat helped the GCSA in organising a discussion with EC policy experts on the scientific evidence based on the ERR, the related policy considerations, and in organizing an expert 'sounding board meeting' on the draft scientific opinion.

A stakeholder meeting was organised by the SAM Secretariat. In this meeting the SAPEA Working Groups members and the Scientific Advisor presented the output of the SAPEA ERR and the specific topics addressed in the scientific opinion.

In summary, the current scientific opinion was informed by the:

- Scoping paper: 'Solar Radiation Modification', (SAM 2023).
- Evidence Review Report of the scientific literature on Solar Radiation Modification carried out by SAPEA 2024
- SAPEA Expert Workshop May 2024
- Sounding board meeting June 2024
- Stakeholders meeting September 2024.

Meeting reports are published online.

ANNEX 2 – SCOPING PAPER

Scientific Advice Mechanism

European Commission's Group of Chief Scientific Advisors

Scoping paper:
Solar Radiation Modification

August 3 2023

Research and Innovation

1. ISSUE AT STAKE

Solar radiation modification (SRM) is a deliberate and large-scale intervention in the Earth's climatic system, with the aim of reducing global warming. It attempts to offset the effects of greenhouse gases by causing the Earth to absorb less solar radiation.

The idea that the climate could be artificially cooled emerged in the 1960's at the same time as the potential risks of climate change were first being taken seriously. SRM is an umbrella term for proposed technologies that would reflect more sunlight back into space, or allow more infrared radiation to escape into space, thereby creating a net cooling effect on the earth's climate. SRM technology options include stratospheric aerosol interventions (SAI - the most studied option), marine cloud brightening (MCB), ground-based albedo modifications (GBAM), ocean albedo change (OAC) and cirrus cloud thinning (CCT). Modelling studies have shown SRM could potentially offset some climate change risks, including the increase in frequency and intensity of extremes of temperature and precipitation. However, it could also introduce a range of new risks related to the change of global weather patterns.

SRM could be relatively cost-effective[72] and several countries could develop a capacity for its deployment. SRM does not reverse climate change and it could cause unintended climate changes (warming or excessive cooling), regional precipitation changes, harm the ozone layer[73], and impact human health and well-being. Sudden and sustained termination of SRM (in particular SAI) would cause rapid climate change. There is also a worry that SRM could be used for military purposes. Furthermore, there is the "moral hazard" suggesting that SRM's recognition as option may divert governments and companies from necessary GHGs emission reductions. In addition to physical risks of SRM, the response of political and social systems is decisive.

According to the IPCC most recent, Sixth Assessment report[74], the current speed and scale of global emissions reductions is insufficient for meeting the Paris Agreement temperature goal of holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-

[72] One Atmosphere: An independent expert review on Solar Radiation Modification research and deployment
[73] See also National Academies of Sciences, Engineering, and Medicine. 20 21. ReflectingSunlight: Recommendations for Solar Geoengineering Research and Research Governance. Washington, DC: The National Academies Press. https://doi.org/10.17226/25762
[74] AR6 Synthesis Report: Climate Change 2023

industrial levels. To reach the Paris Agreement temperature targets, global climate action needs to be accelerated and there are multiple, feasible and effective options available today to reduce GHG emissions and adapt to anthropogenic climate change. However, in most of the scenarios and modelled pathways considered in the IPCC, it is now more likely than not that global warming will exceed 1.5 °C, at least temporarily by the end of this century.

Therefore, additional climate responses such as SRM are gaining more attention. Nevertheless, keeping global warming at a specific temperature level using SRM does not have the same impact on the climate system as limiting warming through GHG emissions reduction, and with SRM multiple impacts on important elements of the climate system remain (e.g. ocean acidification). Moreover, SRM could exacerbate or overcompensate climate changes, and create multiple novel risks. The IPCC emphasises that in order to limit temperature increase to 1.5°C with no or limited overshoot, net-zero CO2 emissions at global level needs to be achieved around 2050[75]. On this basis, the European Green Deal sets out the objective for climate neutrality to be reached in the EU by 2050.

The IPCC indicates that while some SRM techniques may be theoretically effective in reducing some climate hazards, the risks or benefits they pose are poorly understood and relevant rules, procedures and institutions (often referred to as "governance") are weak or missing.

In addition to the IPCC, other UN bodies (including the UN Human Rights Council and UNESCO) are addressing SRM and its governance. The UNEP has published the Report "One Atmosphere: An independent expert review on Solar Radiation Modification research and deployment" on 28 February 2023 calling for: global scientific assessment process for SRM; exploration of prospects for a multilateral SRM governance; a framework for the governance of the stratosphere, and inclusivity in the evolution of SRM governance and research.

A number of academics signed the call for an International Non-Use Agreement on Solar Geoengineering. On the other hand, one group of scientists published a call for proceeding with responsible research to

[75] Synthesis Report of the Sixth Assessment Report of the Intergovernmental Panel on Climate Change: Synthesis Report — IPCC

objectively evaluate the potential for SRM and another one an open letter calling for balance in research and assessment of SRM.

Currently, there is no dedicated, formal international SRM governance for research, development, demonstration or deployment. There are restrictions on deployment of SRM stemming from the UN Convention on Biological Diversity (CBD) decision 2010 X/33 and Resolution adopted by the General Assembly on 9 December 2021 (76/112 on Protection of the atmosphere).

2. EU POLICY BACKGROUND

The EU does not consider SRM as a solution, as it does not address the root cause of the problem, which is the increase in greenhouse gases in the atmosphere. Even if technically feasible and proven safe, it would provide only a temporary relief, not a cure. In the current state of development, SRM deployment represents an unacceptable risk for humans and the environment. Only massive climate change mitigation together with climate change adaptation leads to fulfilment of the Paris Agreement objectives.

The EU strongly focus on its objective to achieve climate neutrality by 2050 (Climate Law), reduction of GHG emissions by 55% by 2030 (Fit for 55 legislative package) and adaptation to the climate change (Adaptation Strategy).

The Commission and the Member States are united in the scepticism about SRM and the EU supported restrictions on geoengineering (including solar radiation modification) in framework of the CBD. Nevertheless, a wide-ranging EU position on SRM is not developed.

SRM research in the EU is limited. Some projects focusing on the implications and risks of engineering solar radiation have been supported by EU funds (focusing on the modelling of implications and risks of engineering solar radiation[76]; Geoengineering and Negative Emissions Pathways[77]). One project focusing on governance of research on the SRM will be funded by Horizon Europe. Number of projects are also supported in the US and Australia (including Marine Cloud Brightening field tests). Some stratospheric aerosol injection-related experiments planned in the past were cancelled following objections from indigenous people and environmental groups.

[76] https://cordis.europa.eu/project/id/226567
[77] GENIE: GeoEngineering and NegatIve Emissions pathways in Europe | GENIE Project | Fact Sheet | H2020 | CORDIS | European Commission (europa.eu)

According to IPCC review, the public has a little knowledge about SRM. Some surveys indicate that the public prefers Carbon Dioxide Removal (CDR) to SRM, is very cautious about SRM deployment because of potential environmental side effects and governance concerns, and mostly rejects deployment for the foreseeable future.

It can be expected that interest in some forms of SRM is likely to grow in the future in case of temperature overshoot due to insufficient mitigation or the risk of climate tipping points being reached.

3. REQUEST TO THE GROUP OF CHIEF SCIENTIFIC ADVISORS

Given the complexity of the issues related to SRM, the EU needs to carefully assess its position taking into account all risks and potential benefits. There are wide-ranging risks, including potential harm to the environment, climate, security, social, occupational, political, economic impacts as well as ethical, moral, legal and justice issues. On other hand, SRM could potentially provide a temporary support in case of the catastrophic impacts of increasing global warming or/and high risk of reaching climate tipping points.

The EU needs to address risks and potential benefits connected to SRM. It should also be ready to engage actively in discussions on international level to address governance issues related to SRM regarding its research, small tests and potential deployment. At the same time, the EU needs to define how to regulate SRM research in the EU. The potential application of any SRM method, including for research, would have to be fully aligned with the broader EU policies, including with climate policy objectives.

There is a good basis for the comprehensive assessment of SRM technology stemming from a number of reports including the IPCC report[3], UNEP report, the 2021 report of the National Academies of Science[2], the 2023 OSTP report[78] as well as EuTRACE Horizon 2020 project.

Consequently, the request to the Group of Chief Scientific Advisors is:

How to address the risks and opportunities associated with research on Solar Radiation Modification and with its potential deployment? What are the options for a governance system for research and

[78] Congressionally-Mandated Report on Solar Radiation Modification | OSTP | The White House

potential deployment taking into account different SRM technologies and their scale?

This scoping question should be analysed by reviewing scientific evidence, including from social sciences, and taking a systemic approach which considers the complexity of all aspects of the issue.

The scientific advice requested here should be delivered by Q3 2024. It will contribute to the definition of EU position in international discussions on SRM governance and for planning of EU research programmes. decisions on implementation of EU financing instruments.

ANNEX 3 – LIST OF EXPERTS AND STAKEHOLDER REPRESENTATIVES CONSULTED

Sounding Board Meeting Participants

Name	**Current Institution**
Nicholas Pidgeon	Cardiff University
Sebastian Oberthúr	Brussels School of Governance
Wake Smith	Harvard Kennedy School Wake Smith
Peter Irvine	UCL
Takis Vladis	International Hellenic University of Thessaloniki

Stakeholder Meeting Participants

Name	**Current Institution**
Hindumathi K PALANISAMY	World Climate Research Programme Secretariat - World Meteorological Organization
Daniele Visioni	World Climate Research Program - Lighthouse Activity on Climate Intervention Research
Jesse Reynolds	The Degrees Initiative

Guillaume Morauw	Environmental Defense Fund Europe
Claire Bulger	European Climate Foundation
Matthias Honegger	International Center for Future Generations (ICFG)

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‘Solar radiation modification’ is an umbrella term for proposed technologies that would reflect more sunlight back into space, or allow more infrared radiation to escape into space, thereby creating a net cooling effect on the Earth’s climate.

This scientific opinion by the Group of Chief Scientific Advisors (GCSA) examines how the EU can address the risks and opportunities associated with research on solar radiation modification and with its potential deployment. It also presents the possible options for a governance system for research and potential deployment, considering different solar radiation modification technologies and their scale.

This opinion is published in the context of the Scientific Advice Mechanism (SAM) which provides independent scientific evidence and policy recommendations to the European institutions by request of the College of Commissioners.

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