

Briefing 48

Geoengineering

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Summary

- *The issue of global warming has led to the development of geoengineering techniques in an attempt to modify the climate.*
- *Solar radiation management typically involves injecting aerosols into the stratosphere. Uncertainties remain about these methods, and they have been criticised for their impacts and risks.*
- *Carbon dioxide (CO₂) capture and storage techniques present interesting opportunities but they are not all fully developed and affordable yet.*
- *These techniques are the subject of research that should be controlled in view of their inherent risks.*

Maxime Laisney, Member of the National Assembly

Stéphane Piednoir, Senator

Since the 20th century, the Earth has been experiencing major climate change that threatens ecosystems and human societies.¹ The average global temperature has risen by more than 1°C since the pre-industrial era, and all the evidence suggests that this trend will continue.²

The signatory countries of the 2015 Paris Climate Accords agreed to keep the increase in average temperature “well below 2°C” and try to limit it to 1.5°C above pre-industrial levels. The current scientific consensus is that the 1.5°C threshold will very probably be reached or exceeded soon.³

The causes of climate change are mainly anthropogenic. The main cause is actually the emission of greenhouse gases (GHGs) such as carbon dioxide and methane, which are produced by human activities (energy production, transport, industry, housing, agriculture, etc.).⁴ The principal method for mitigating climate change is to reduce these emissions.⁵ The amount of GHGs emitted in the coming years will be key to determining whether the commitments of the Paris Accords can be achieved or not.

Geoengineering⁶ is an umbrella term that encompasses a number of techniques said to complement efforts to reduce GHG emissions and slow the process of climate change.

According to one prevailing definition of geoengineering, it is the “deliberate large-scale intervention in the Earth’s climate system, in order to thwart anthropogenic global warming”.⁷ Our societies have unintentionally⁸ modified the climate and should take action to limit the consequences. Geoengineering proposes an alternative approach to climate change mitigation besides reduction, restraint and moderation. It aims to produce large-scale impacts and therefore does not include localised

techniques. Lastly, although weather-modification techniques have long been the subject of dreams and experiments,⁹ their main aim is not to mitigate climate change and therefore they are not within the scope of this briefing.

The growth of geoengineering within the scientific field has been made possible by massive investments from multinational organisations in the fossil fuel, technology and finance sectors.¹⁰

Geoengineering techniques are generally grouped into two categories: firstly, those aiming to reduce the amount of solar energy absorbed by the Earth system in order to adjust the balance of the earth’s radiation budget, which is referred to as “solar radiation management” (SRM); secondly, those aiming to capture the GHGs present in the Earth’s atmosphere and reduce the greenhouse effect, known as “carbon dioxide removal” (CDR).¹¹

■ **Solar radiation management: an example of maladaptation?**

Solar radiation management (SRM)¹² refers to all techniques that aim to adjust the radiation budget¹³ of the Earth system by using alternative methods to those that aim to reduce the concentration of greenhouse gases in the atmosphere. SRM techniques are the most controversial because they do not address the causes of climate change and do not aim to restore levels to those of the early 20th century. Instead, they aim to create a new physical state of the Earth that is governed by different parameters. However, the Earth is a complex system in which modifications to a single parameter can have unexpected side-effects.¹⁴ Hence why SRM proponents are sometimes accused of “playing god”¹⁵ with the climate by their opponents.

It is important to note that SRM techniques do not reduce atmospheric CO₂ concentration,¹⁶ but their advocates defend them as being last-resort methods. The bigger the discrepancies between the recorded temperatures and the desired pathways, the stronger this argument will seem, particularly in countries that are most affected by global warming.

SRM methods are numerous and the possibilities are limited only by researchers' imaginations. Some techniques, such as space mirrors, seem to belong more to science fiction than to reality but have sometimes enjoyed media attention and been the object of a few isolated research programmes. The present briefing lays out the two most commonly proposed techniques.¹⁷

➤ Stratospheric aerosol injection

Stratospheric aerosol injection (SAI) is an oft-endorsed SRM technique that involves dispersing aerosols in the atmosphere at an altitude of between 15 and 25 km. In a similar way to the phenomena observed during volcanic eruptions,¹⁸ the dispersed particles are expected to reflect solar radiation and produce a cooling effect. The standard method proposes to use sulphates, whose chemical characteristics are relatively well understood.

The lifespan of the sulphates in the stratosphere would be no more than two to three years, so the process must be repeated in order to maintain a constant cooling effect. This would require large fleets of stratospheric aircraft capable of regularly carrying several tonnes of sulphate to the desired altitude. SAI advocates highlight the technique's relative ease of deployment and affordability compared with other methods. However, these arguments have been challenged by the latest estimations, which tend to show that the cost of this technique has been underestimated and that it would more likely cost between several dozen and some one hundred billion dollars per year and per degree of cooling.¹⁹

There are also several major issues with SAI. Firstly, the prolonged use of sulphates may cause acid rain²⁰ and damage the ozone layer. Secondly, the aerosols may have an uneven effect on global warming across the Earth's surface and deregulate the planet's hydrological system, with serious impacts on the Asian monsoon, for example. This technique therefore carries risks for food supply.²¹

➤ Marine cloud brightening

Another SRM technique involves diffusing seawater into tropospheric clouds from boats to increase the clouds' reflectiveness and thereby impede part of the incoming solar radiation. This method is based on markedly less-well-developed scientific foundations than with SAI but several experiments have already been carried out, particularly at the Great Barrier Reef.²² The potential impacts following large-scale deployment of marine cloud brightening are similar to those of SAI,²³ and its effectiveness is far from proven. Notably, its effect would

be limited to no more than a few days and would be relatively localised, unless even more substantial resources were employed than those required for SAI.

➤ Risks outweighing the potential benefits

If these technologies were to see large-scale deployment, they threaten to place human societies in a socio-technical impasse that requires their constant use because, after venturing along the SRM path, it is difficult to turn back quickly without causing a terminal shock. Since CO₂ has a much longer lifespan in the atmosphere than the aerosols used to counter its effects, the sudden stoppage²⁴ of SRM could lead to a rapid and record-breaking rise in global temperature.

In the light of these arguments, SRM seems to be an example of maladaptation to climate change: instead of increasing resilience to the climate crisis, it would weaken the Earth system. By contributing to the creation of a new and unstable global climate in a context of already critical levels of warming, it would serve to accentuate problems rather than resolve them. The fact that the biggest investors in SRM²⁵ are also the countries with the most substantial CO₂ emissions suggests that they may see it as a way to continue using fossil fuels.

These methods are little developed in Europe, particularly in France. In a recent opinion paper, the CNRS Ethics Committee²⁶ concluded that SRM is a high-risk science and recommended focusing research on monitoring and assessing the impacts of SRM rather than on its effective deployment.²⁷

■ Carbon dioxide removal (CDR)

Human activities emit between 50 and 55 Gt of CO₂ equivalent per year.²⁸ These emissions are continuing to rise, albeit at a lesser rate than during previous decades.

Each year, approximately half the CO₂ emitted is captured by natural carbon sinks in the form of oceans, forests and soil.²⁹ The remaining half contributes to the atmospheric concentration of this greenhouse gas. CDR techniques aim to improve or complement natural CO₂ capture.³⁰

➤ The main CO₂ capture and removal techniques

• Forest management

Using **forests** to capture more carbon might seem to be one of the simplest solutions. However, this approach brings up a number of difficulties.³¹

In 2024, 6.7 Mha of primary forest were destroyed, leading to the emission of 4.1 Gt of CO₂.³² The prevention of deforestation is therefore essential to maintaining CO₂ absorption at significant levels. This also applies to forest management in general and its two branches: reforestation, which aims to plant trees in areas where there used to be a forest, and afforestation, which aims to create new forests.³³

The nearly natural³⁴ nature of these techniques stands them in good light. However, to be effective, they require much larger scale deployment than is currently the case,

but this would create competition for land use with agriculture, for example. One study³⁵ aggregated the pledges of 194 countries and demonstrated the need for a change in land use involving an area of 3.7 million km² being dedicated to reforestation between 2020 and 2060.³⁶ Since the CO₂-capture capacity in tropical regions is significantly higher per hectare than in other areas, questions of optimal location and international fairness must be taken into consideration.

At the same time, forests can be negatively impacted by global warming and their capture potential can be reduced.³⁷ The care taken when trees are planted can also have a major impact on their capture potential, a fact that calls for close monitoring of the quantities of CO₂ that are actually absorbed.³⁸

Lastly, forests do not offer unlimited CO₂ capture because their capacity for CO₂ removal diminishes with age, meaning that they reach a point of equilibrium at which the quantities of CO₂ that are emitted and captured balance out, despite having stored a net amount of carbon during their life cycle.³⁹ While forest management can contribute to climate change mitigation, forests alone cannot absorb the totality of anthropogenic emissions.⁴⁰

- *Hybrid or technological capture and storage*

Today, one of the main avenues explored for industrial decarbonisation is direct CO₂ capture and storage (CCS) at industrial plants,⁴¹ which may offer a solution for decarbonising unavoidable emissions. However, ADEME (the French Agency for Ecological Transition) stresses that CCS must remain the final option after restrained use, improved efficiency, input modification and recycling, and calls for a "merit order" for solutions.

CCS uses filters and solvents to absorb and capture CO₂ before it leaves factory flues.⁴² It is then taken away for long-term storage – ideally for several millennia – or reuse.⁴³ Current avenues being explored for carbon reuse include the development of e-fuels and chemical processes.⁴⁴ But this is not without cost, particularly in terms of energy. In addition, the rest of the CCS chain must also be considered, namely transport and storage which have a high economic cost and can lead to other risks,⁴⁵ such as CO₂ leakages.⁴⁶ The EVASTOCO2 study⁴⁷ estimated France's underground storage capacity at 4.8 Gt of CO₂.

CCS is still little developed, but a number of stakeholders are starting to position themselves, including in France since the country recently removed an obstacle to exporting CO₂.⁴⁸

Strictly speaking, CCS is not actually a geoengineering technique because it does not produce negative emissions. However, it is the basis of several CDR techniques including **bioenergy with carbon capture and storage** (BECCS), which involves linking biomass-fuelled power plants to a CCS system. Emissions are captured and stored using the decarbonised energy

produced by the plant. BECCS emissions are thus negative overall, on the condition that the CO₂ storage is durable. Although this method seems promising, it carries a downside in the substantial land area required for biomass production.⁴⁹

An alternative technique could avoid these problems: **direct air capture and storage** (DACs). Instead of using photosynthesis to capture carbon, DACs uses chemical processes with similar filters and solvents to those used in flue-exit CCS. However, capture is trickier because it is carried out directly from the atmosphere, where the CO₂ concentration is lower by several orders of magnitude compared with flue exits.

DACS offers two main advantages. Like BECCS, it can produce negative emissions when combined with long-term storage, ideally for several thousand years.⁵⁰ In addition, these facilities do not need to be installed in precise locations (i.e. near forests or industrial areas) and can therefore be built near storage sites, which removes the issue of transport.

The technology for this technique is still underdeveloped.⁵¹ Direct air capture requires substantial facilities and quantities of energy and water. The cost per tonne of CO₂ captured is estimated at several times the current price of the tonne in the carbon market⁵² and will likely be a long time in becoming competitive. An increasing number of start-ups⁵³ are trying to innovate to improve the efficiency of these techniques, especially in the USA, where there is both public- and private-sector funding. In France, this field is just beginning to take shape.⁵⁴ Estimated trajectories for technical developments and price increases on the carbon market suggest that these technologies will not see significant deployment before 2050. The International Energy Agency's net-zero scenario projects DACs at 1 Gt of CO₂ per year in 2050.⁵⁵

- *The place of CDR in climate policies*

The negative emissions allowed by carbon removal are already part of the fight against climate change and the approach features to a greater or lesser extent in almost all IPCC scenarios in which the 2°C threshold is respected. The aim is to use it first during the transition and then to absorb residual emissions.⁵⁶ If the global temperature limits are exceeded, the negative emissions could even bring warming down to an acceptable level.⁵⁷

Forest management and BECCS are the most frequently advanced solutions, sometimes to extremely ambitious levels. On the other hand, DACs is still underrepresented in these strategies. Although it does not present the same challenges as BECCS, it can only really be of use if it is powered by decarbonised energy, and if it would not be more beneficial to use it to replace fossil fuels in another sector. It therefore only truly makes sense in a world that has already been largely decarbonised, where it could serve to reduce residual emissions or allow net negative

emissions. However, this method offers the greatest scale-up potential.⁵⁸

■ International governance is still in its infancy

Geoengineering experiments can have global consequences that are difficult to predict, but international law is very fragmented in this area. Although the use of geoengineering for military purposes has been banned,⁵⁹ there is nothing to prevent civil experiments. Some of these technologies are easily accessible and large-scale deployment by a single state outside of any cooperation agreements is a possibility that must not be excluded.⁶⁰ This makes geoengineering a matter of national defence and it is possible that negatively impacted countries could retaliate with “counter-geoengineering”. In addition, it is difficult to locate the source of SRM experiments. Part of the modelling research aims to remove this obstacle.

The absence of regulation leaves private or academic stakeholders free to carry out geoengineering experiments unchecked,⁶¹ despite the opposition often raised. A few attempts at self-regulation have emerged, but without great success.⁶²

CDR is not exempt from these problems either. Ocean fertilisation⁶³ is one of the rare techniques that is regulated by international law, and is currently the subject of a moratorium.⁶⁴

The impacts of geoengineering research are potentially dangerous and difficult to predict, and establishing the origins of potential damages is equally complicated. The absence of an international legal framework creates a vacuum *vis-à-vis* the general principle of responsibility.

■ Conclusions

As global warming continues, the possibilities opened up by geoengineering may seem appealing. Initiatives have already been launched and initial progress has been made. However, extreme caution is required.⁶⁵

Scientifically, neither SRM nor CDR techniques are free from undesirable consequences or repercussions, particularly for the environment. Their true effectiveness remains to be proven, either because it depends on physical, chemical and biological mechanisms that only operate in the short or medium term, or because the technique must be combined with a process capable of durably isolating the carbon removed from the atmosphere for at least several millennia, without the risk of it being re-released.

Politically, both SRM and CDR present a major moral hazard because they may deter from restraint and reduction in the use of fossil fuels. In addition, SRM carries the risk of leading to a socio-technical impasse, as mentioned above, which is one of the reasons requests are made for experiments to be banned, particularly in Europe.⁶⁶

Nonetheless, CDR offers interesting potential and seems likely to be developed further, but it must be ensured that

it remains a last resort. Moreover, stakeholders in the sector stress the importance maintaining two distinct aims in order to avoid creating any conflict between the two approaches: reducing raw GHG emissions on the one hand and introducing negative emissions on the other hand. CDR innovation must stay on a narrow path: maintaining government control because realistic and feasible CDR is a limited resource and a common good; providing significant resources because many scientific and technical unknowns remain; being yet very selective and agile because some new avenues explored will likely turn out to be dead ends, as with any research; ensuring that all the planetary boundaries are taken into account; constantly assessing the real effectiveness of each technique studied;⁶⁷ ensuring that potential business models are robust, including the potential inclusion of these techniques in carbon markets.

At this stage, it is illusionary to see geoengineering as the perfect remedy to the worldwide problem of global warming. Nevertheless, some techniques may, under certain conditions, serve to complement efforts to achieve “net zero”, which requires, first and foremost, the reduction of raw greenhouse gas emissions.

OPECST websites:

<http://www.assemblee-nationale.fr/commissions/opecest-index.asp>

<http://www.senat.fr/opecest>

People consulted

- A delegation from the French Agency for Ecological Transition (Ademe):
 - Mr. David Marchal, Executive Director of Expertise and Programmes
 - Ms. Solène Bouvier, Engineer in CO₂ capture, storage and reuse in the Decarbonisation of Industry and Hydrogen Department
- A delegation from IFP Energies Nouvelles (IFPEN):
 - Mr. Raphaël Huyghe, Head of the “CO₂ capture and storage” programme
 - Mr. Florent Guillou, Project Manager for Capture and Negative Emissions
- Mr. Philippe Ciais, Member of the Academy of Science, Research Director in the Laboratory for Climate and Environmental Sciences (LSCE-IPSL)
- Mr. Sylvain Delerce, Chief Scientist at the NGO Carbon Gap
- Ms. Alexandra Deprez, Research specialised in climate science at the Sustainable Development and International Relations Institute (IDDR)
- Ms. Elena Gerebizza, Member of the association Recommon, where she deals with energy and infrastructure issues and for which she wrote a report on the Callisto project
- Ms. Aurélie Gonzalez, CEO and co-founder of the start-up Yama
- Ms. Marine de Guglielmo Weber, Researcher in the environment, energy and raw materials at the Strategic Research Institute of the French Ministry of Armed Forces (IRSEM)
- Mr. Pierre Isnard-Dupuy, independent Journalist and radio Reporter, member of the Presse-Papiers collective, co-author of an investigation on the Callisto project for the Multinationals Observatory
- Mr. Eric Lambin, Geographer and a specialist in environmental science; former member of the group of chief scientific advisors of the Scientific Advice Mechanism of the European Commission, co-author of the Scientific Advice Mechanism’s report on solar radiation modification (Solar Radiation Modification, December 2024)
- Ms. Valérie Masson Delmotte, Member of the Academy of Science, Research Director in the Laboratory for Climate and Environmental Sciences (LSCE-IPSL)
- Mr. Johannes Quaas, University Professor for Theoretical Meteorology in the Faculty of Physics and Earth Sciences in Leipzig, Co-President of the group of experts consulted by the Scientific Advice Mechanism of the European Commission for the report on solar radiation modification (Solar Radiation Modification, December 2024)

References

¹ See IPCC GouP 2 report on impacts, adaptation and vulnerability: IPCC, 2022: Summary for Policymakers [H.-O. Pörtner, D.C. Roberts, E.S. Poloczanska, K. Mintenbeck, M. Tignor, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem (eds.)]. In: *Climate Change 2022: Impacts, Adaptation and Vulnerability*. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 3–33, doi:10.1017/9781009325844.001.

² See the summary of the 6th IPCC report: IPCC, 2023: Summary for Policymakers. In: *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, pp. 1-34, doi: 10.59327/IPCC/AR6-9789291691647.001.

³ As shown by a recent study based on data from 2024: Forster, P. M. et al. (2025). Indicators of Global Climate Change 2024: annual update of key indicators of the state of the climate system and human influence. *Earth System Science Data*, 17, 2641-2680. <https://doi.org/10.5194/essd-17-2641-2025>

⁴ More details on the distribution of greenhouse gas emissions per sector can be found in *Key Figures on Climate: France, Europe and Worldwide*, 2024 edition. French Ministries for Territories, Ecology and Housing. <https://www.statistiques.developpement-durable.gouv.fr/chiffres-cles-du-climat-france-europe-et-monde-edition-2024>.

⁵ This is the aim of France’s national low-carbon strategy (SNBC, March 2020, Ministry for the Ecological and Solidarity Transition).

⁶ Others prefer to use the expression “climate engineering”, particularly in order to avoid the prefix “geo-”, which may lead to confusion or fears over the scale of climate manipulation. In French, the plural is also used to represent the multiplicity of approaches (Xavier Landes, *La Géoingénierie*. Que sais-je ?, October 2024).

⁷ This definition was proposed by the Royal Society in 2009 (J. Shepherd et al, *Geoengineering the Climate: Science, Governance and Uncertainty*) and has been widely adopted. It is very similar to the one produced by the REAGIR forward-looking reflection panel at the ANR in 2014 (O. Boucher et al, *Réflexion systémique sur les enjeux et méthodes de la géo-ingénierie de l’environnement*): “environmental geoengineering means all techniques and practices that are implemented or planned with the aim of large-scale correction of the effects of

anthropic pressure on the environment. It is important to properly differentiate geoengineering, which involves mechanisms that have a global impact on the Earth system, from techniques and practices for mitigation or those with only a local impact”.

⁸ Climate change can be described as “unintentional” in the sense that it was and it is not deliberately sought as either an objective or a result of human activities. Nevertheless, it has been known about since the 1970s and its anthropic causes are widely attested to and accepted by the scientific consensus.

⁹ The 2024 floods in Dubai and other countries of the Gulf sparked rumours that blamed them on cloud seeding by the United Arab Emirates. Evidence of the use of wide-scale cloud seeding by China to attempt to prevent drought has triggered serious geopolitical tensions with India. Lastly, the American operation *Popeye* during the Vietnam War, which aimed to intensify the monsoon rains and slow enemy movements, led to the Convention on the prohibition of military of any hostile use of environmental modification techniques, known as the “ENMOD convention” (adopted in 1976 and applicable from 1978).

¹⁰ As shown by Clive Hamilton in *Les apprentis sorciers du climat. Raisons et déraisons de la géo-ingénierie*. Seuil, coll. “Anthropocène”, 2013 (translated from the original: *Earthmasters, The Dawn of the Age of Climate Engineering*), and Marine de Guglielmo Weber and Rémi Noyon in *Le grand retournement. Comment la géoingénierie s’infiltré dans les politiques climatiques*. Les Liens qui libèrent, 2024.

¹¹ Although the challenges presented by these techniques and how they are viewed by society differ, they have the same ultimate aim: mitigate climate change through deliberate actions carried out at global level, which justifies examining them together. Nevertheless, some experts are reluctant to consider CDR and SRM as belonging to the same category. One of the reasons for this reluctance is to avoid tarnishing CDR by the poor reputation of SRM. However, the present briefing uses the conventional categorisation of the subject, which is also used in recent works (Xavier Landes, *la géoingénierie, Que sais-je ?*, October 2024). CDR and SRM are different but have many points in common ontologically and can be studied together while maintaining a nuanced vision of their respective impacts.

¹² This expression, which can also be substituted by “solar radiation modification”, was allegedly coined by the geoengineering advocate Ken Caldeira in order to make it more “bureaucratic” and acceptable than the term “geoengineering” (Clive Hamilton, *Les apprentis sorciers du climat*).

¹³ The Earth’s radiation balance is calculated as the difference in energy exchanges between the Earth system and space. It is structured round a flow of incoming energy, i.e. the Sun’s light, which warms the Earth, and a flow of outgoing energy, which is partly reflected off the Earth and partly re-emitted after being absorbed, mainly as visible light and infrared energy. The adjustment variable that balances out the system is the Earth’s temperature. An increase in the concentration of atmospheric gases such as CO₂ leads to a rise in both the energy stored in the lower atmosphere and the radiation emitted by the latter towards the Earth’s surface; the result is an increase in temperature at the planet’s surface, hence the expression “greenhouse effect”. The radiation balance of the Earth system is controlled by the vertical circulation of atmospheric air masses, which carry the masses of hot air present in the lower layers towards the upper atmosphere; the energy stored in these masses can thus be released into space through radiation.

¹⁴ An obvious example is the famous “butterfly effect”, which describes the purportedly chaotic nature of the Earth system: one small localised change can break the balance and significantly affect the whole system. However, this highly mediated approach fails to take account of the self-regulating capacities of the Earth system, thanks to which truly chaotic phenomena are not legion.

¹⁵ Clive Hamilton, *Earthmasters, The Dawn of the Age of Climate Engineering*.

¹⁶ In particular, they do not mitigate many phenomena that are harmful to ecosystems, such as ocean acidification.

¹⁷ The other methods have been much less studied, but examples include cirrus cloud thinning and surface brightening.

¹⁸ Although this analogy is often mentioned by SAI advocates, probably to give it a “natural” flavour, it should be tempered: unlike SAI techniques which are based on a sustained dispersion of particles in the stratosphere, volcanic eruptions have a single point of injection located in the lower altitudes of the Earth’s atmosphere.

¹⁹ These estimations are presented in chapter 2 (page 38) of a report by the European Commission’s Scientific Advice Mechanism: *SAPEA evidence review report on Solar radiation modification*, December 2024. This same report concludes (page 17) that SAI proves to be potentially more costly and complex to deploy than first imagined.

²⁰ Current research is seeking to identify other particles that may be dispersed in the stratosphere, but the results are still non-conclusive and raise many new problems.

²¹ This would go against the Sustainable Development Goals endorsed by the United Nations Framework Agreement on Climate Change (UNFCCC) and the 2015 Paris Agreement.

²² The Marine Cloud Brightening for the Great Barrier Reef project aims to protect coral reefs weakened by global warming. To this end, relatively limited experiments were carried out to in 2023.

²³ It is likely that large-scale deployment would produce the same type of impacts as with SAI, with changes to precipitation – particularly the Asian monsoon – and an uneven distribution of cooling and even high-latitude warming (Haywood, J. M., Jones, A., Jones, A. C., Halloran, P., & Rasch, P. J. (2023). Climate intervention using marine cloud brightening (MCB) compared with stratospheric aerosol injection (SAI) in the UKESM1 climate model. *Atmospheric Chemistry & Physics*, 23(24), 15305-15324. <https://doi.org/10.5194/acp-23-15305-2023>).

²⁴ Potential stoppage due to conflict, geopolitical tensions or unsupportable aerosol pollution.

²⁵ Primarily the USA, which withdrew from the Paris Agreement in 2025 for the second time.

²⁶ CNRS Ethic Committee (COMETS), opinion no. 2025-47: “Virus manipulation, geoengineering... how can the ‘responsible’ aspect of research be assessed?”, 10 June 2025.

²⁷ The French Academy of Science recently published a report on the subject, in which it called for caution over these technologies (Report by the Academy of Science of 2 October 2025: Climate geoengineering: a call for caution and rigorous supervision).

²⁸ CO₂ equivalent is a metric used to keep account of all greenhouse gas emissions, by weighting the quantities emitted by their global warming potential (for example, methane is emitted in smaller quantities than CO₂, but has a much greater warming effect per kilogramme).

⁵⁰ Storage durability is a crucial factor for the credibility and the pertinence of solutions based on CO₂ removal. The challenge lies in isolating it and preventing it from returning into the atmosphere on a geological timescale, especially if it undergoes no chemical transformation and remains stored in the form of CO₂. Needless to say, CO₂ leaks could be very dangerous for human populations, without mentioning that they would destroy all the efforts made to cleanse the atmosphere and would become a factor of global warming themselves.

⁵¹ ClimeWorks and the first generation of demonstrators are currently still unable to compensate for their own emissions (Jean-Baptiste Fressoz, 21 May 2025, "Les entreprises de capture du CO₂ dans l'air émettent plus de carbone qu'elles n'en éliminent". Le Monde).

⁵² Emissions Trading Schemes (ETS) are trading systems that enable the sale or purchase of carbon emission allowances. EU ETS 1 was set up in the European Union in 2005 and concerns approximately 40% of EU emissions. It established a cap of emissions allowances and made it possible to trade them on the market. Its scope will be extended to other sectors in 2027. The cap decreases each year to oblige industries to decarbonise. The exchange price per tonne of CO₂ is an important indicator. Since 2022, it has fluctuated between €60 and €100. The EU ETS does not currently include the possibility to take account of negative emissions, but discussions in this respect are underway. Voluntary carbon markets have been put in place to allow the growth of private companies, especially in the USA.

⁵³ In France, the start-up Yama intends to develop a demonstrator capable of capturing 5,000 t of CO₂ per year by 2028 and hopes to increase its capture capacities in the following years.

⁵⁴ Particularly within the *Association Française pour les Émissions Négatives* (French Association for Negative Emissions), a professional association created in 2024.

⁵⁵ The International Energy Agency (2022). *Direct Air Capture. A key technology for net zero*.

⁵⁶ Residual, or unavoidable, emissions are those emitted by sectors that cannot be completely decarbonised. In its 2023 summary for policymakers, the IPCC stated that CDR methods will be necessary to remove these emissions (point B.6.2). It also highlights (point B.6.4) that some CDR techniques can have negative socio-economic and environmental impacts. IPCC, 2023: Summary for Policymakers. In: *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, pp. 1-34, doi: 10.59327/IPCC/AR6-9789291691647.001.

⁵⁷ The IPCC provides details on the use of CDR to this end at the end of part B.7 of its 2023 summary for policymakers, but stresses (point B.7.3) that it is still better to avoid overshoot than use CDR for this purpose, given the associated risks (IPCC, 2023: Summary for Policymakers).

⁵⁸ A study by Carbon Gap evaluated the theoretical maximum potential of electrochemical DACCS in France at 549 MtCO₂/year, compared with 66 for BECCS (Carbon Gap, *Deployment potential of carbon dioxide removal methods in France*. March 2024).

⁵⁹ Since the ENMOD convention.

⁶⁰ The USA is by far the biggest investor in these technologies. In doing so, they give themselves option of choosing for large-scale deployment in a few years' time to avoid have to extract fossil fuels, which they are particularly dependent on.

⁶¹ Like the stratospheric aerosol injections carried out by the start-up Make Sunsets in Mexico in 2022.

⁶² In 2013, Steve Rayner and other scientists proposed to apply a list of criteria called "The Oxford Principles" to solar radiation management (S. Rayner, C. Heyward, T. Kruger, N. Pidgeon, C. Redgwell, J. Savulescu, « The Oxford Principles », *Climatic Change*, Springer, vol. 121(3), 2013). They recommend transparency and concertation upstream of any experiments and call for geoengineering to be regulated as a public good. However, these principles have limited scope and are not often respected.

⁶³ This CDR method aims to enhance CO₂ capture potential through the ocean by adding iron to stimulate the growth of phytoplankton, which can capture more CO₂. Since the phytoplankton sink to the bottom of the ocean when they die, the surface layer is not contaminated by acidification by the dissolved CO₂. The method was the subject of 13 experiments starting from the 1990s, mainly in the Southern Ocean (Yoon, J.-E. et al, 2018. Reviews and syntheses: Ocean iron fertilization experiments – past, present, and future looking to a future Korean Iron Fertilization Experiment in the Southern Ocean – KIFES - project, *Biogeosciences*, 15, 5847–5889) but proved ineffective. Above all, it caused several major problems including oxygen and nutrient depletion in certain regions, which were exhausted by the phytoplankton growth, and the appearance of consequences far from the experiment's location.

⁶⁴ More generally, all marine geoengineering methods have been the subject of a moratorium since 2010 for countries that are part of the 1992 Convention on Biological Diversity and also those part of the 1982 United Nations Convention on the Law of the Sea. It is important to note that these moratoria are non-binding.

⁶⁵ A characteristic example is polar geoengineering, of which the different techniques aim to protect the polar regions, which are among the most vulnerable to climate change. However, an article published in *Frontiers in Science* this year shows that many of the techniques envisaged and defended by their advocates as necessary, such as aerosol injection and albedo modification at the poles using reflective beads, are in fact unlikely to protect the poles in the long term: Siegert, M., et al (2025). Safeguarding the polar regions from dangerous geoengineering: a critical assessment of proposed concepts and future prospects. *Frontiers in Science*, 3(1527393). <https://doi.org/10.3389/fsci.2025.1527393>.

⁶⁶ This was the case of the report on SRM published in 2025 by the Scientific Advice Mechanism of the European Commission, which calls for a moratorium on experiments as well as heightened research on modelling the adverse effects of SRM techniques and questions of international governance.

⁶⁷ Negative-emissions monitoring must be developed in the framework of international climate governance to better measure each country's efforts. One possibility would be to improve monitoring of the increase or decrease of capture linked with forest management through satellite measurements.