

PLANETARY SUNSHADE
INSTITUTE

STATE OF
SPACE BASED
SOLAR RADIATION
MODIFICATION

OCTOBER, 2023

www.planetarysunshade.org



INTRODUCTION

This report is an introduction to how the concept of space based geoengineering, or a Planetary Sunshade, could complement existing efforts to mitigate the climate crisis. It is intended for policy makers who are discussing climate overshoot scenarios.

The Planetary Sunshade Foundation was founded in 2021 because current decarbonization strategies are insufficient for a liveable planet. We develop and advance the concept of space-based solar radiation modification.

The Planetary Sunshade Foundation believes that solar radiation modification will be a necessary part of the global warming solution, safeguarding and complementing the transition away from fossil fuels and the removal of excess greenhouse gases from the atmosphere.

This version of the report was co-developed with Fuglesang Space Center of Sweden.





REPORT RECOMMENDATIONS

- Solar Radiation Modification (SRM) discussions should consider space based SRM alongside other options so the world can make the most informed decision about when, how, or if to deploy.
- The ethical, legal and socio-economic impacts of every SRM option needs to be understood and a regulatory framework defined.
- Climate modelers and scientists studying SRM should also study space based SRM.
- Space based SRM should be part of space research programs, with
 - Space based SRM technology development integrated into existing space roadmaps
 - Dedicated ground and flight demonstrator missions for selected Space based SRM technologies defined and implemented
 - A Digital Twin of Space based SRM mission scenarios being linked to the Digital Twin Earth to understand expected climate impacts and schedule needs
- Encouraging research into SRM methods as a complement to carbon emission elimination should be a high priority of IPCCs 7th Assessment Cycle.
- International workshops and conferences should be organised on a yearly basis to discuss the state-of-the-art and detailed needs for space based SRM, similar to the Global Space Conference on Climate Change (GLOC 2023) - bringing together space researchers, politics, climate researchers, climate activists and space industry.
- Investment in sunshade research should be considered both a climate and space policy investment, and therefore be additional to existing programs in both arenas. This funding would be a global 'insurance policy' against failures to limit warming to 1.5°C .

PREAMBLE

THE CLIMATE CRISIS IS HERE, AND IT IS GETTING WORSE FAST.

Earth will most probably exceed the threshold for 1.5°C of warming during the 2030s, and there are credible scenarios for catastrophic warming of 4.5°C by the end of the century. While transitioning away from fossil fuel use is imperative, net-zero emissions will not solve the problem of elevated carbon levels already present in the atmosphere. As the effects of global warming worsen, world leaders are more seriously considering solar radiation modification (SRM) as part of the climate toolkit.

The Earth is a thermodynamic system. Greenhouse gas emissions have caused the Earth to retain more energy than it emits, which results in global warming. SRM proposals focus on correcting that energy imbalance.

There are two main types of geoengineering. The first is removing carbon from the environment to restore pre-Industrial levels. Carbon removal is necessary, and it will require natural carbon sinks and a massive industrial project, which should be powered by clean energy.^[1] The second type is SRM, which reduces the amount of solar energy that impacts Earth.

The most well-known SRM technology is stratospheric aerosol injection (SAI). SAI involves dispersing millions of tons of tiny particles, called aerosols, into the stratosphere each year to reflect a small percentage of incoming solar energy.

SAI could probably be deployed relatively cheaply and would be rapidly effective at cooling the Earth. However, it has significant drawbacks, such as increased pollution, damage to the ozone layer, and a milky appearance to the sky. SAI also builds increasing risk for sudden, devastating climate shock, if it were discontinued due to unforeseen side effects or policy changes.

Given that it is most probably impossible to limit Earth to a 1.5°C temperature rise without geoengineering, the eventual deployment of SRM is increasingly discussed. Any credible discussion of SRM should include space based options, since these less intrusive solutions are quickly becoming financially and technologically viable.

Placing a physical structure, a Planetary Sunshade, between the Sun and the Earth would reduce solar energy and provide a long-term, sustainable solution until pre-industrial levels of atmospheric greenhouse gases have been reached. Developing the technological road map, doing the climate modelling work, and aligning on a legal framework for a sunshade would be a very inexpensive insurance policy for possible use of this technology.

For more detailed analysis of the relevant aspects of the greenhouse effect, see [Appendix A](#).
For a more detailed overview of geoengineering and SAI, see [Appendix B](#).

¹ [CO2 air-capture costs](#), John Tanner Physics Today 76 (2), 12 (2023)



REPORT ORGANISATION

PREAMBLE

Current efforts to mitigate catastrophic climate change are insufficient. Solar Radiation Modification (SRM) could be deployed to buy time to restore Earth's atmosphere. Stratospheric aerosol injection (SAI), now being researched, might become fast and cheap but has side effects and considerable risks. A Planetary Sunshade could be a clean, sustainable, long-term alternative to terrestrial SRM. Active research on this would be a relatively inexpensive insurance against large temperature increases.

THE PLANETARY SUNSHADE

A structure in space that blocks enough solar radiation to offset all or part of anthropogenic global warming.

ECONOMIC BENEFITS OF SOLAR RADIATION MODIFICATION / MANAGEMENT

Planetary Sunshade Research is an urgent and inexpensive insurance policy against huge costs from uncapped climate change. It may also contribute to and benefit from economies from off-planet mining development.

POLICY RECOMMENDATIONS

Space technology and climate mastery, hand in hand with insurance thinking on Planetary Sunshade research, can ensure that climate targets are met sooner, with reduced hardships and costs of disasters.

SUMMARY

The Sunshade should be considered a key part of a comprehensive response to the climate crisis, focusing emerging space capabilities on the defining issue of our time.

SPACE BASED SOLAR RADIATION MODIFICATION

THE CONCEPT OF A PLANETARY SUNSHADE IS RELATIVELY SIMPLE.

Like an umbrella on a sunny day, an object placed between the Earth and the Sun will reduce the amount of incoming solar energy and, therefore, the temperature of Earth.

A Planetary Sunshade is a scalable intervention: larger Sunshades would be able to block more solar energy. Preliminary calculations show that, to counteract about 1°C of anthropogenic warming, a Sunshade would need to block approximately 0.5% of incoming solar energy^[2].



² Fix, S. (2021). [Feasibility study of a Sunshade in the vicinity of the Sun Earth L1 Lagrange Point](#) (Issue February). University of Stuttgart.

A real-world example of this concept was the transit of Venus between the Earth and the Sun in June of 2012.

Although the transit was much too short to have a measurable effect on Earth's temperature, the transit reduced incoming solar radiation by 0.35 W/m^2 .^[3] Figure 1 shows how a transit of Venus appears from Earth. A Planetary Sunshade would be made from many smaller elements, achieving similar radiation blocking while being far less visible than Venus or even the sunspots in this image. Since Venus is much farther away from Earth than the Sunshade would be, the cross-sectional area of Venus is many times larger than the Planetary Sunshade.

Because the distance from the Earth is great, and the relative size of the Sunshade elements is tiny in comparison, a Sunshade would cast a diffuse but not an acute shadow on the Earth. The 'umbra', or acute part of the shadow, does not reach Earth, and therefore no part of the Earth would experience direct shading. Instead, the Sunshade's penumbra, or diffuse shadow, is what covers the entire Earth (see Figure 2). The penumbra's diffuse shading ensures that the cooling is spread evenly across the globe, minimising regional impacts.

Figure 1: The sun during the 2012 transit of Venus (large spot), as observed from Tempe, Arizona (smaller dots are sunspots)^[4]



³[Observations of the Venus Transit – Total Irradiance \(2012\)](#). Laboratory for Atmospheric and Space Physics, University of Colorado at Boulder.

⁴[Wikipedia. 2012 transit of Venus](#). Stephen Rector. https://en.wikipedia.org/wiki/2012_transit_of_Venus.

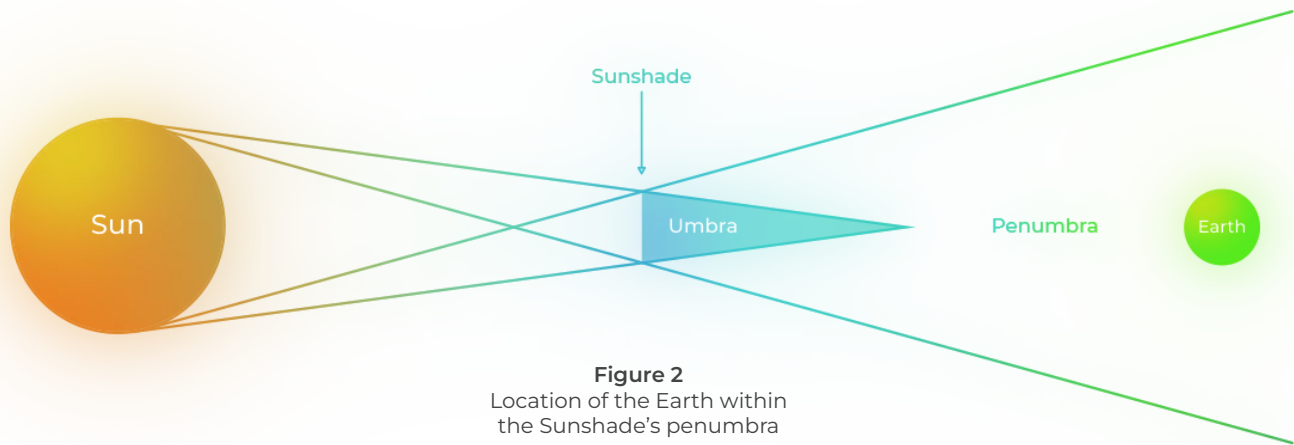


Figure 2
Location of the Earth within the Sunshade's penumbra

Due to the realities of gravitational physics, the most feasible location for a Planetary Sunshade is near the Sun-Earth Lagrange point 1 (L_1)^[5] (see Figure 3). Lagrange points are equilibrium points where the gravity of two large bodies (in this case, the Sun and the Earth) and the centrifugal orbital forces balance. Objects located at L_1 remain on the line between the Earth and the Sun and require relatively minor station keeping to maintain their orbital location. Without orbital maintenance in the long term, objects will naturally drift away slowly from the shading position. The Sunshade's optimal location is about 2.4 million km from Earth, or about 5 times further away than our Moon's^[6] orbit.

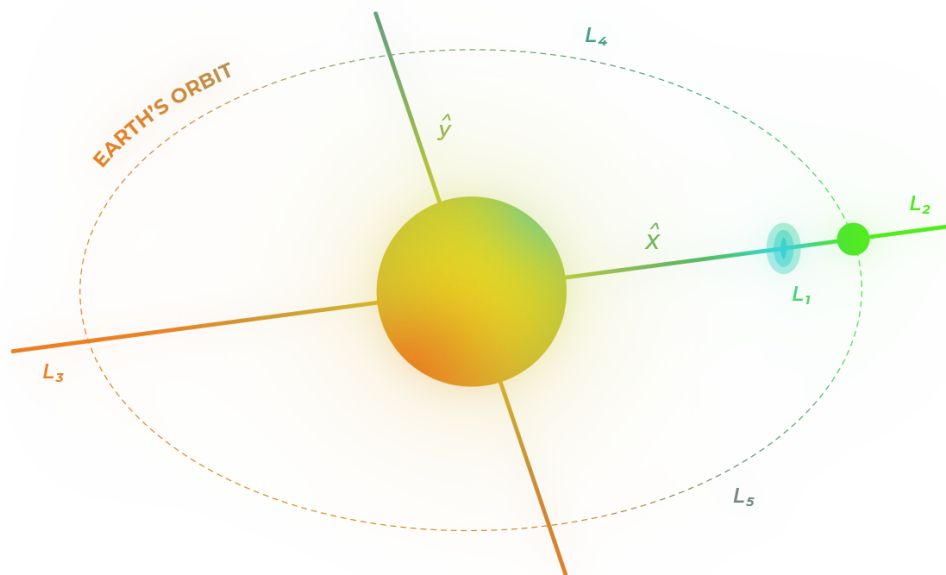


Figure 3
Planetary Sunshade location at Sun-Earth Lagrange point 1.^[7]

⁵ Jehle, A., Scott, E., Centers, R. (2020) [A Planetary Sunshade Built from Space Resources](#). AIAA ASCEND Conference, November 16-18, 2020, Virtual

⁶ The length of the umbra of an object in sunlight near Earth is some 100 times its size. Elements of the Sunshade will be a few 10's meters to about a square mile in size. The umbra even of large elements would extend much less than a thousandth of the distance from the Sunshade to the Earth. It will not extend to the Moon or satellites.

⁷ Sánchez, J. P., McInnes, C. R., & Marchis, F. (2015). [Optimal Sunshade configurations for space-based geoengineering near the Sun-Earth \$L_1\$ point](#). PLoS ONE, 10(8), 1-25.

A larger Sunshade results in more cooling, while a smaller Sunshade causes less.

For reference purposes, achieving 1°C of cooling would require blocking 0.5% of the Sun's energy. 1.7 million km² of Sunshade would achieve this result. This size corresponds to 75 million tons of material, mostly very thin aluminum foil

To construct such a Sunshade, a variety of methods could be used to maximise surface area while minimising mass and without needing to deploy a monolithic structure. Thousands of medium-sized elements, or tens-of-thousands of small elements would work, as long as sufficient shading is achieved.

Planetary Sunshades might be built and manufactured from materials mined outside of Earth from the Moon or Asteroids, reducing the number of launches from Earth and corresponding launch and re-entry emissions.

PLANETARY SUNSHADE KEY POINTS

Planetary Sunshade concept was first proposed as early as 1989^[8] and researchers have revisited the concept with increasing frequency. Recently, the Planetary Sunshade Foundation has undertaken to organise, assess and communicate this research. Based on this assessment, the key characteristics of a sunshade would be:

- A Planetary Sunshade would orbit near Sun Earth Lagrange Point 1, and cast a diffuse but not acute shadow evenly across the globe.
- A sunshade would be scalable and reversible, with the possibility to add or remove elements to adjust the size.
- The cost of launch has decreased substantially in recent years, allowing the sunshade concept to become feasible

The Planetary Sunshade is a large project, but achievable with commitment from the world's nations. Construction of the Sunshade would afford its creators significant prestige and economic opportunities, in addition to climate stability.

ANALOGIES

Civil engineering projects of comparable scale have been undertaken successfully before:

- The International Space Station, built by a coalition of partnering nations at the end of the cold war, was developed independently, but with agreed interfaces and a common Concept of Operations (CONOPS). It has been in continuous operation for over 20 years, despite many crises and even wars.
- In the 1860s the United States embarked on constructing a transcontinental railroad. While the federal government's payments to construct the railroad were seen as very substantial at the time, they pale in hindsight compared to the benefit to the country's well-being and financial growth.
- In the 1960s, just 60 years after the first flight of an airplane, humans walked on the Moon. NASA's budget grew to over 4% of the US government's spending to achieve this feat.
- Denmark is currently building an 18 km immersed tunnel under the Baltic Sea to connect Denmark and Germany. Once completed, it will be the longest road and rail tunnel in the world.
- Japan's first bullet train line was 514 km, a major civil engineering achievement.
- The world builds about 85 million automobiles per year. The average weight of a car is more than 1,5 tons. This amounts to the mass of almost 2 Planetary Sunshades a year. If the steel or aluminium of these were rolled out to 40 g/m² (half the weight of office paper) it would also cover the area of about 1.5 Sunshades per year.

⁸J. T. Early (1989). "Space-Based Solar Shield To Offset Greenhouse Effect". Journal of the British Interplanetary Society. Vol. 42. pp. 567–569.

CLIMATE INSURANCE POLICY: SUNSHADE RESEARCH TO AVOID FUTURE COSTS

We have more and more droughts, wildfires, storms and floods all over the world, which according to current climate research are indications of climate warming. Arctic ice is melting and oceans are warming faster than forecasted, and climate variability is increasing. The Paris Agreement to cap the temperature increase from pre-industrial levels to well below 2°C and close to 1.5 °C seems less and less probable.

Calculations by a Deloitte study of 2022 show that compared to keeping the Paris goal, moving to a 3°C hotter world in 2070 would result in a loss for the global economy of USD 178 trillion from 2021 to 2070, and after that USD 25 trillion per year.



Figure 4: Deloitte study - Economic losses 2021-2070⁹, Copyright 2022 Deloitte.

We are facing a global crisis and Planetary Sunshade Research is an urgent "insurance policy" for a situation where sufficient greenhouse gas reduction to cap climate change cannot be reached with voluntary, corporate image protection and CO2 tax/trade barrier means.

Depending on current cost assumptions (these vary from USD 3-50 trillion) for the complete construction of a Sunshade capping average temperature at 2°C, rather than at 3°C, the payback time for the entire Sunshade would, compared to the Deloitte calculation, vary from a few months to a year or two.

The insurance policy parallel, is that all relevant technologies can be fully developed at very low cost if the decision is made early. The substantial effort of deployment can, however, await a decision point of clear and immediate danger.

SUNSHADE RESEARCH AND PRACTICAL TESTS SEEN AS AN "INSURANCE FEE"

Even assuming an exaggerated research & test cost of totally USD 5 billion spent as an "insurance fee" over the next 10 years, would mean that the "fee" is almost negligible compared to the 5,000 times higher "insurance payout" every year from 2070 envisaged by Deloitte as the alternative cost.

Further, if/when deployment of the Planetary Sunshade begins, the increasing reduction of the adverse effects of climate change frees up resources that would be increasingly bound by disaster management. As the Sunshade in deployment achieves even modest cooling, the intensity of climate disasters would start being reduced immediately. Globally, even slight reductions in the destructiveness of natural disasters could save vast amounts of money, freeing up resources to deal with the causes instead of the symptoms.

⁹ [Deloitte study 2022: The turning point A Global Summary](https://www.deloitte.com/global/en/issues/climate-environment/sunshade-research-and-practical-tests-seen-as-an-insurance-fee.html) (deloitte.com)

ECONOMIC BENEFITS OF PLANETARY SUNSHADE RESEARCH

A driving force in the rapid expansion of space activity is the plummeting cost of launch (see Figure 5). It was only as recently as 2015 that SpaceX first succeeded in landing a Falcon 9 rocket for reuse, transforming the launch industry. In the years since, ‘flight-proven’ rockets have become the norm, with individual boosters flying over 15 times and counting. The next generation of heavy lift launch vehicles will push this trend much further. China has scrapped plans to develop any new rockets which are not reusable, choosing to focus entirely on re-use. The cost savings of reusing rockets are enormous, and the space industry is responding quickly to the new opportunities these lower costs make possible.

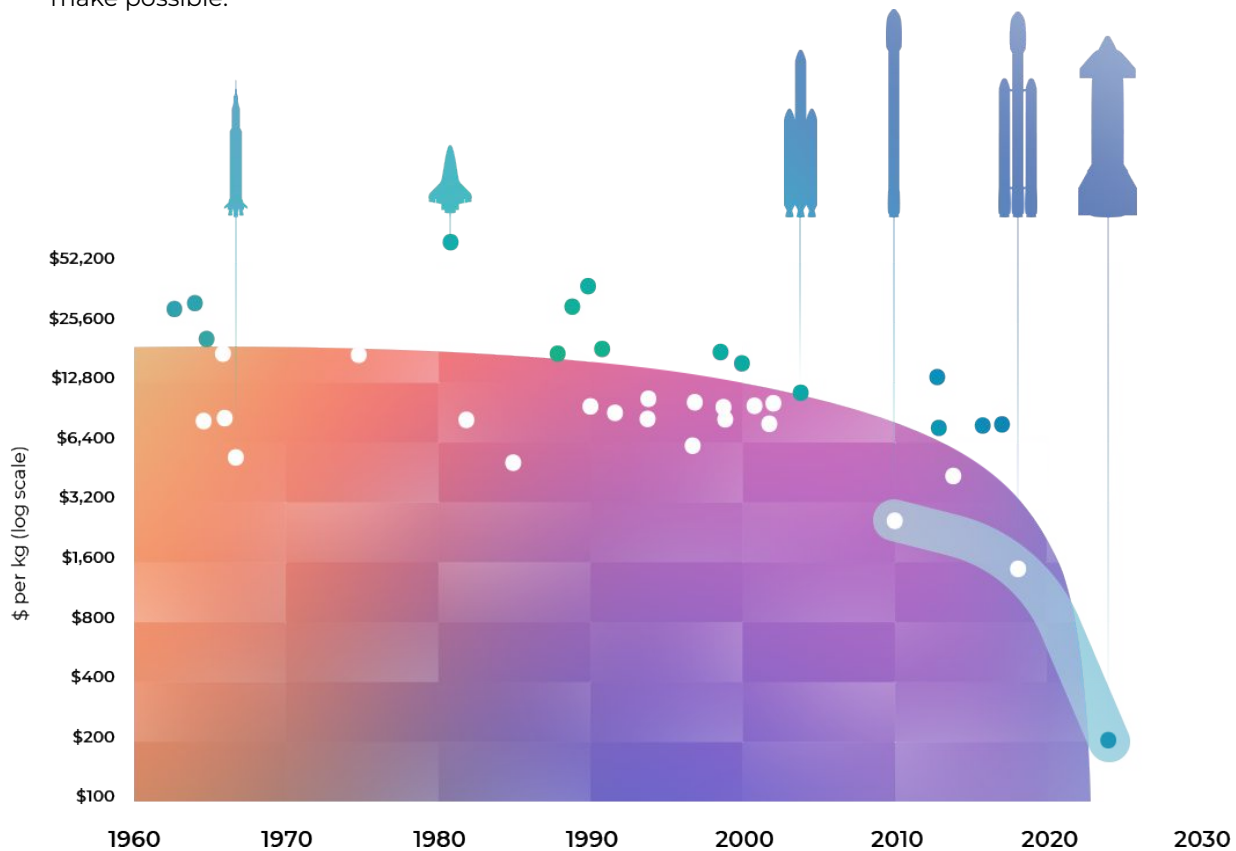


Figure 5: The cost of launch is falling rapidly. Note the exponential scale of this chart ^[10]

Concurrently, miniaturisation has advanced greatly in space. The majority of spacecraft launched in the past decade are small spacecraft. Only the combination of reusable launch vehicles and small spacecraft platforms has enabled access to affordable communication also in the most remote areas of the world via networks like StarLink. A vibrant NewSpace economy has launched over 2,200 nanosatellites such as cubesats, most of them in the last 10 years and by commercial operators providing services to Earth.

Space industries around the world have positive impacts on their national economies. Space technology often leads to new uses for consumers and industry. If the use of space resources becomes feasible, there will be opportunities to develop new arenas for industrial activity which have the advantage of being outside the Earth’s biosphere. These industrial operations offer the potential for greatly expanded human economic activity.

¹⁰ Olson, J., et al. Edited by Peter Garretson, 2021. [State of the Space Industrial Base 2021](#)

SUMMARY

The Planetary Sunshade should be considered a key part of a comprehensive response to the climate crisis. The Sunshade concept complements greenhouse gas reduction efforts such as the phasing out of fossil fuels, and buys Earth time to remove the extra carbon from the atmosphere by natural and technical means. It is a viable alternative to stratospheric aerosol injection, and a possible replacement if such has been implemented. While the Sunshade concept does not address all the impacts of climate change, it greatly increases our ability to manage a wide array of impacts associated with rising temperatures.

Construction of a Planetary Sunshade is possible. The fundamental physics and engineering are understood, initial solar sail technology missions have been flown, and more are coming. Civil engineering projects of this magnitude have been built before and have proven to be transformative. The rapid technological progress of space launch systems has resulted in the cost of sending materials and people into space dropping fast, changing the scope of what is possible.

Climate change is here, and each additional bit of warming has a horrific human cost. The Earth will most probably cross 1.5°C in the next decade, a threshold that looms large among climate leaders. Every year, the destruction caused by extreme weather, sea level rise, and fires will increase, as will political pressure to respond to the crisis. Melted ice caps and methane released from permafrost cannot be undone.

The foundation of our civilization is at stake, and the Planetary Sunshade could become a really strong mitigating tool to ensure a livable climate by managing without big risks for the environment. Putting serious research efforts into this today is an inexpensive “insurance policy”, that also prepares the ground for an extremely high return on investment should temperatures risk crossing 2 °C during this century.



APPENDIX A

The Earth as a Thermodynamic System



Climate change is here, and it is getting worse fast. Despite decades of international climate talks, the trajectory of emissions under best-case scenarios still points toward unacceptable warming.

In order to limit global warming to 1.5°C, the Intergovernmental Panel on Climate Change (IPCC) estimates that the remaining carbon emissions budget is around 500 million tons of carbon dioxide.^[11] The cumulative net CO₂ emissions between 2010 and 2019 was 410 million tons which means, on the current emissions trajectory, we will exceed the threshold for 1.5°C of warming sometime in the early 2030s. There are credible scenarios, driven by continued greenhouse gas emissions and exacerbated by feedbacks in the climate cycle and potential ecological tipping points, for warming of 4.5°C or more by 2100; warming at that level would have catastrophic consequences for the environment and human health and society.^[12]

Transitioning away from fossil fuel use is imperative and must be accomplished as quickly as possible. Although progress has been made on international commitments to reduce greenhouse gas (GHG) emissions, proposed emissions cuts are insufficient to reach the goal of limiting global warming to 1.5°C (see Figure 6).

2030 EMISSIONS GAPS

CAT projections and resulting emissions gaps in meeting the 1.5°C Paris Agreement goal

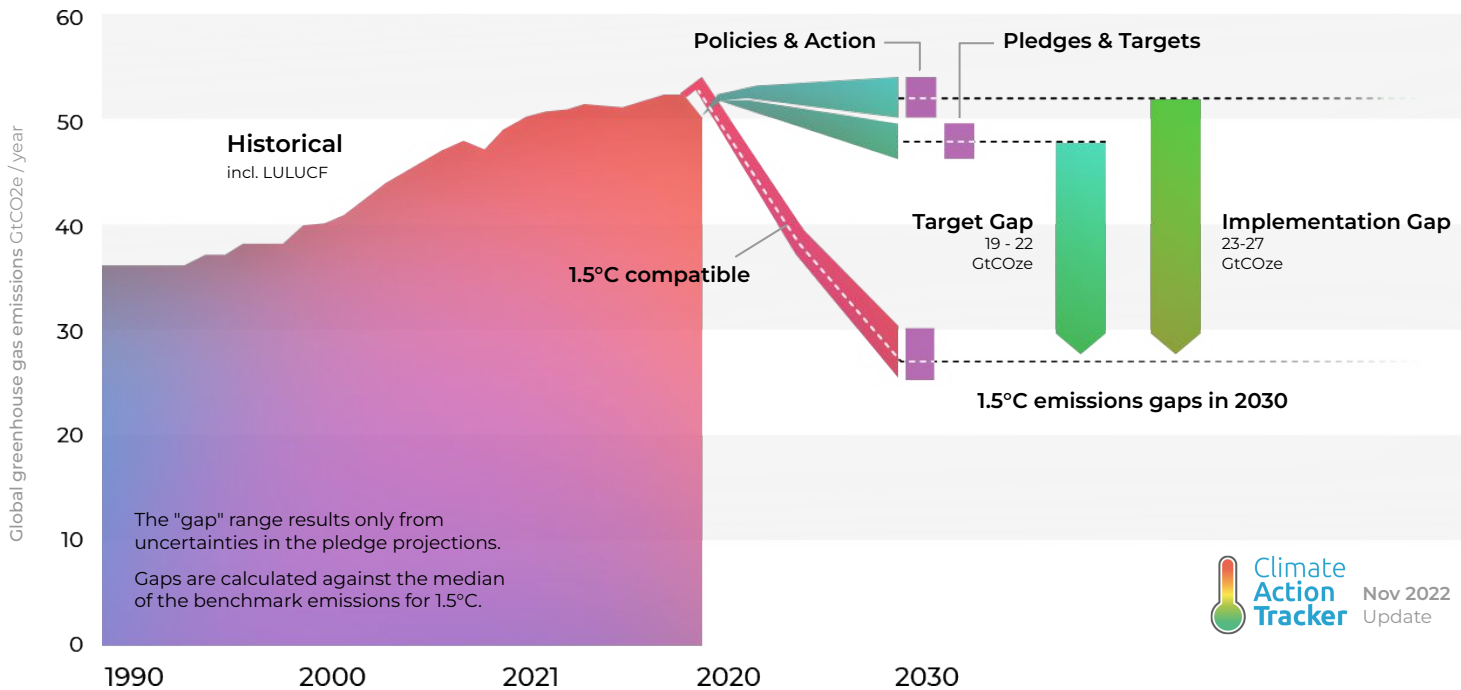


Figure 6 2030 emissions gap, showing the difference between international emissions reduction pledges and targets and the emissions trajectory required to limit global warming to 1.5°C. (LULUCF: land use, land use change, and forestry).^[13]

¹¹ IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., et al. (eds)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 2391 pp. doi: 10.1017/9781009157896.

¹² Kemp, L, et al. (2022) [Climate Endgame: Exploring catastrophic climate change scenarios](#). PNAS Vol 119, No, 34.

¹³ [Climate Action Tracker](#)

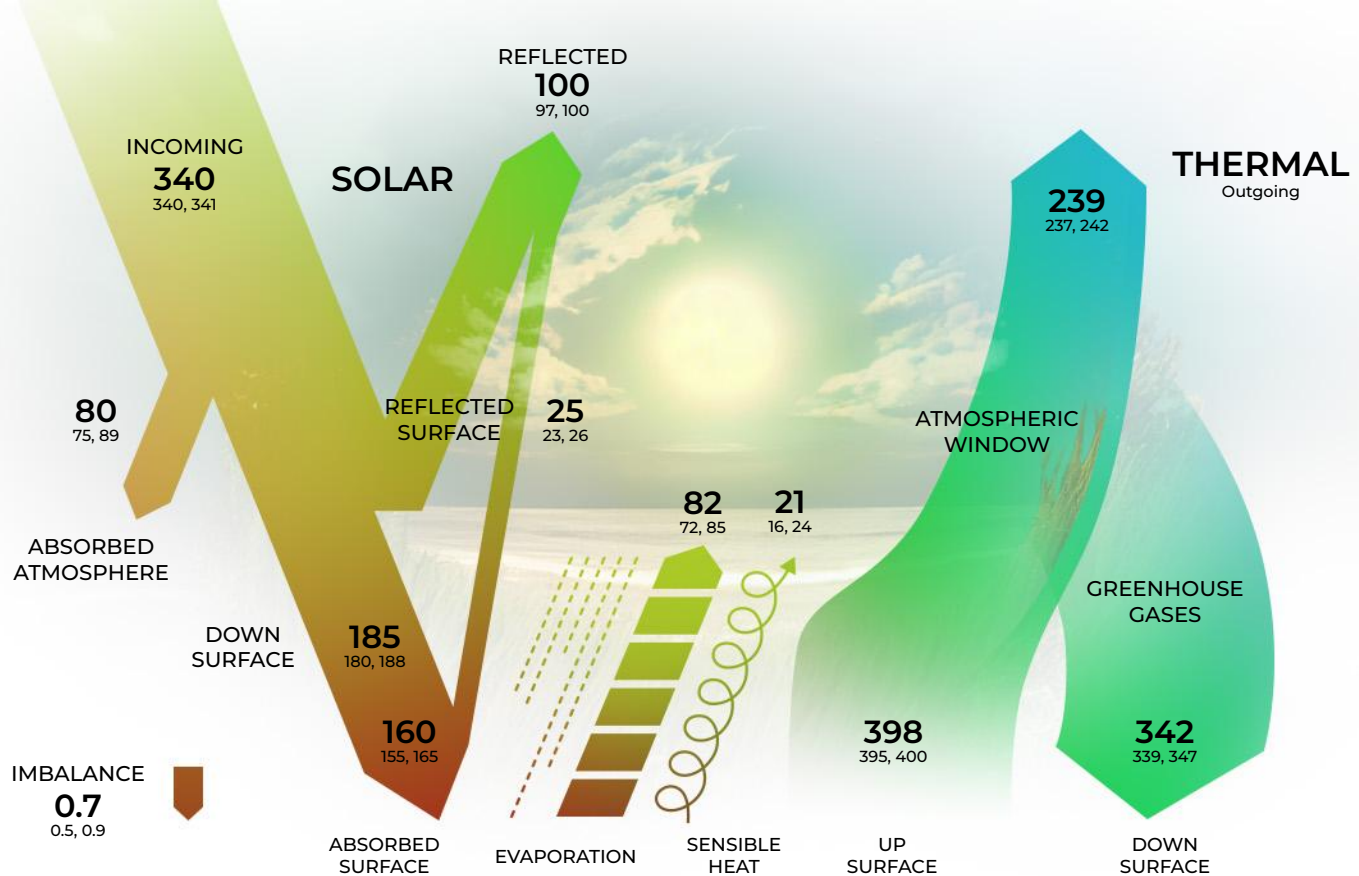


Figure 7

Global mean energy budget of the Earth according to the IPCC's 2022 report (values expressed in W/m^2 , uncertainty ranges shown in parentheses).

However, achieving net-zero emissions will not solve the problem of the high carbon concentration already present in the atmosphere. Carbon dioxide can last for a very long time in the atmosphere, and buffer reservoirs in exchange with it such as oceans. Even if we reached net-zero emissions today, global temperatures could continue to rise for decades before stabilising.^[14] Every bit of warming causes more destruction and reduces the capability of ecosystems to remove carbon. Because of increases the risk for tipping points, world leaders are more seriously considering active climate interventions, known as geoengineering.

Geoengineering proposals all focus on correcting the energy imbalance of the greenhouse effect. When the system is in equilibrium, global temperatures are relatively stable. However, carbon dioxide and other greenhouse gases (GHG) have accumulated in the atmosphere, causing it to absorb thermal energy that would have otherwise radiated back into space. This energy imbalance is approximately 0.7 W/m^2 (see figure 7), and results in global warming.

¹⁴ IPCC, 2022: Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Pörtner, H.O., et al (eds.)] Cambridge University Press, Cambridge, UK and New York, NY, USA, 3056 pp., doi:10.1017/9781009325844.



APPENDIX B

Geoengineering



“Geoengineering is the deliberate large-scale intervention in the Earth’s natural systems to counteract climate change.”

Oxford Geoengineering Programme

Geoengineering, also known as climate intervention, is being discussed by many decision makers to address the imbalance in the Earth’s energy budget. Here we briefly review the two most discussed methods: Carbon Dioxide Removal and Solar Radiation Modification.

Carbon Dioxide Removal (CDR)

Carbon Dioxide Removal focuses on increasing the amount of energy Earth emits out to space by restoring the atmosphere towards pre-industrial conditions through removal of heat trapping Greenhouse Gases (GHG) already present in the environment. There are many forms of CDR in various stages of readiness, but they all remove and sequester carbon from the atmosphere.

CDR is necessary to fully undo the effects of climate change. It is the only solution that will address global warming as well as other side effects, such as ocean acidification and altered weather patterns. However, removing hundreds of billions of tons of excess carbon from the atmosphere will be slow and expensive, whether by natural or technical means, or both.

Technical CDR cannot begin at scale until enough excess clean energy is available to power direct air capture systems, and requires very large amounts of energy^[15]. Carbon removal directly embedded in industrial processes that involve high concentration or density of CO₂ flows could be implemented more quickly or at less energy expense. It limits new CO₂ being added to the atmosphere, but is not a geo-engineering effort to remove already existing CO₂.

There is a significant potential to enable and increase natural carbon removal, and sometimes it can be done quickly or/and at a local scale e.g. by wetlands recovery, or by re-directing plant-based materials into permanent use (e.g. construction wood) rather than using them as biofuels. But natural carbon removal capacity, although vast, is naturally limited. Even after net-zero emissions are reached, removing excess carbon from the atmosphere will be a generational effort, unlikely to be profitable and requiring substantial public subsidy.

¹⁵ [CO₂ air-capture costs](#), John Tanner, Physics Today 76 (2), 12 (2023)



Solar Radiation Modification (SRM)

The other way to restore the balance between energy entering and energy leaving the Earth system is to block incoming solar energy. This set of proposals is referred to as Solar Radiation Modification. Unlike CDR, SRM does not solve the underlying imbalance of the atmosphere's chemistry (too much carbon in the atmosphere). Instead, SRM addresses one of climate change's most severe consequences - global warming - to buy time for emissions reductions and carbon removal while minimising the ecological, economic, and human impacts of climate change. The cost of climate change impact, disaster management and adaptation can in this way be reduced and make it easier to address the cause rather than the symptoms of climate change.

If SRM is deployed, we are committed to maintaining it until excess carbon can be removed from the atmosphere. The alternative, known as 'termination shock', involves the full brunt of climate change suddenly surging back in the absence of SRM.

Many regional forms of SRM have been proposed and studied in models, including modifying land to increase its reflectivity, preserving highly reflective ice sheets, brightening marine clouds by seeding them with saltwater, and thinning cirrus clouds, which trap heat in the atmosphere. The SRM method that has garnered the most attention so far is Stratospheric Aerosol Injection (SAI).

Stratospheric Aerosol Injection (SAI)

In stratospheric aerosol injection, sulphur dioxide (SO²) gas is injected into the stratosphere, creating particles that reflect a small percentage of incoming solar energy. The stratosphere is high in the atmosphere, where the air is thin and relatively stable. It begins at altitudes 11 km (polar regions) - 17 km (near the equator) above sea level, and extends up to about 50 km altitude. Aerosols injected at these altitudes can last for around two years before migrating to the poles and falling back to the surface. The motion of currents in the stratosphere is primarily horizontally layered (hence "strato-") and latitudinal (i.e., east-west), so injections made at one longitude will distribute relatively evenly around the globe at that latitude and then gradually begin to drift and fall out. To cool the Earth enough to offset 0.5-1.0°C of global warming, several million metric tons of aerosols must be injected into the atmosphere continuously each year to maintain the necessary concentration in balance with the natural loss^[16].

Various aerosols have been proposed, but SO² has received the most study. In addition to being plentiful and cheap, sulphur dioxide is naturally present in the stratosphere as a result of volcanic activity. Powerful volcanic eruptions such as Mount Pinatubo's in 1991, send millions of tons of sulphur dioxide into the stratosphere and have marked impacts on Earth's temperature. Mount Pinatubo's eruption reduced temperatures by 0.5°C^[17] with effects lasting one to two years, but the best known event may be 1816, the "year without summer" following the much larger eruption of Mount Tambora in 1815. Powerful volcanic events are a natural proof of concept for SAI.

¹⁶ Keith, D. (2013) [A Case for Climate Engineering](#). MIT Press

¹⁷ Parker, D. E, et al. (1996). The Impact of Mount Pinatubo on World-Wide Temperatures. *International Journal of Climatology*. 16 (5): 487-497. Bibcode:1996IJCl..16..487P. doi:10.1002/(SICI)1097-0088(199605)16:5<487::AID-JOC39>3.0.CO;2-J



SAI may be regarded as an attractive “quick-fix” solution, for primarily three reasons:

1. When implemented, it is effective very rapidly. As demonstrated by volcanoes, injecting aerosols into the stratosphere can result in dramatic temperature reductions within a year or two.
2. SAI provides flexibility in desired temperature. More aerosol injection could fully return Earth to pre-Industrial temperatures; less SAI could shave a few tenths of a degree off global temperatures to avoid the worst temperature-related outcomes of climate change.
3. The cost of implementation appears to be relatively low. The technical capabilities to deploy SAI at scale are not available today but could probably be developed with existing technology if a decision was made to pursue SAI^[19]. A fleet of one hundred purpose-built high-altitude aircraft, plus the infrastructure to support deployment, could cost several tens of billions of USD: vastly less than the cost for CDR or to cope with unmitigated climate change.

¹⁸ [Dave Harlow, USGS](#).

¹⁹ Smith, Wake. Pandora's Toolbox: The Hopes and Hazards of Climate Intervention. Cambridge University Press, 2022.

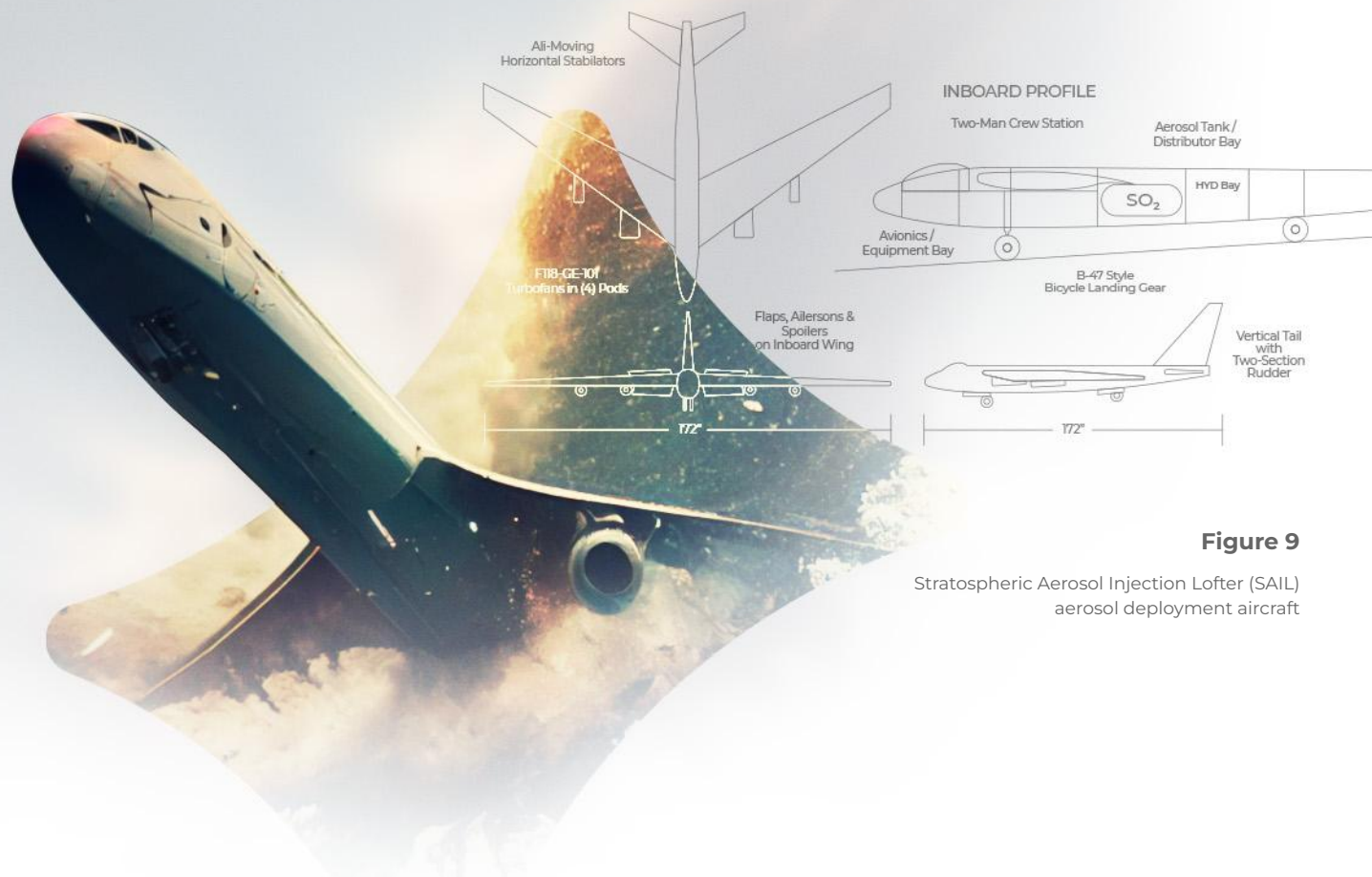


Figure 9

Stratospheric Aerosol Injection Lofter (SAIL) aerosol deployment aircraft

SAI has however serious drawbacks:

Sulphur dioxide is a precursor to sulfuric acid, which causes acid rain. SAI would be an order of magnitude less than the SO_2 currently emitted by the world's industry, but would still have a measurable impact as it ultimately falls out to the troposphere and enters the precipitation system.

Deployment at the level needed to significantly mitigate global warming will result in a cloudy or milky appearance of the sky (also considerably limiting the opportunity to view a starry sky from anywhere).

SAI may also have undesirable impacts on the hydrological cycle, where more modelling is needed.

Injecting sulphur into the stratosphere will also cause some damage to Earth's ozone layer, as sulphur reacts with ozone to become sulfuric acid. The highly localized formation of the polar ozone holes has shown that global pollution can have out-of-proportion local effects.

SAI, like all SRM, sets up the conditions for termination shock, where the full effects of global warming would return over the course of 1-2 years. The speed of this rapid snap-back would be more damaging than gradual global warming. SAI must be consistently maintained at some level and this requires considerable continuous funding, sensitive to political changes.



Optimistic estimates for removing hundreds of gigatons of carbon from the atmosphere guess at over 100 years^[20] of expensive ‘waste removal’ style work, funded by governments with little room for economic upside.

GEOENGINEERING

MORE RESEARCH NEEDED

Impacts of geoengineering require a greater level of understanding, but unfortunately the research is woefully underfunded. SRM, and geoengineering in general, have long been the third rail of climate discussions, although this is changing fast.

The opposition to geoengineering research centres on two key arguments:

1. The moral hazard

and

2. The unintended consequences.

The moral hazard argument says that geoengineering interventions will reduce our commitment to decarbonization. The Planetary Sunshade Foundation supports the urgent phase-out of all fossil fuel use and does not accept money from the fossil fuel industry. Furthermore, we believe that current efforts to decarbonize are already far too weak, and thus more effort fighting the climate crisis generally is far better than a purist argument around only one ‘right’ way.

The unintended consequences will always be a concern, as are the unintended consequences of burning all available fossil fuels. We should study this as much as we can and weigh our best knowledge against the catastrophic consequences of unmitigated warming.

²⁰ UNEP (2017). [The Emissions Gap Report 2017](#). United Nations Environment Programme (UNEP), Nairobi.



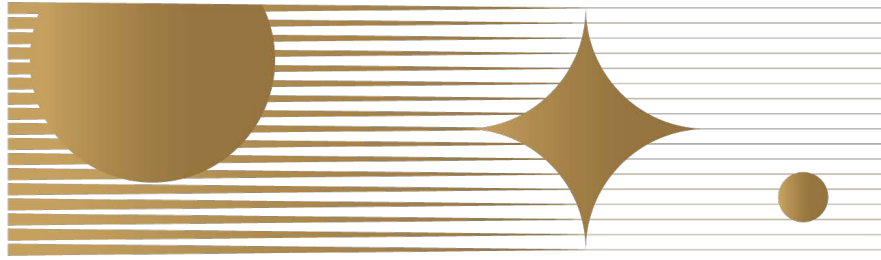
Decision makers will need to weigh these factors against climate change impacts when making a decision to implement this technology. Any discussion of stratospheric aerosol injection should therefore also include the only other global method of solar radiation modification / management: **the Planetary Sunshade.**

Space Based Solar Radiation Modification

Placing a physical structure, a Planetary Sunshade, between the Sun and the Earth can reduce solar energy and provide a long-term, sustainable SRM.

SAI and space based SRM may complement each other. While SAI can probably be deployed more quickly and less expensively, it must be replenished constantly and maintained until carbon is removed from the atmosphere.

Deploying the Sunshade will probably take longer and could initially cost more during the deployment phase, but it is a cleaner, more sustainable proposal. If SAI is implemented on a large scale, the Planetary Sunshade should be considered its wind-down strategy. The Sunshade also has many positive benefits beyond addressing climate change that should be understood by policy makers.



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