EEJOURNALS OPEN ACCESS

EURASIAN EXPERIMENT JOURNAL OF ENGINEERING

(EEJE) ISSN: 2992-409X

@EEJE PUBLICATIONS Volume 5 Issue 1 2025

The Science of Climate Engineering: Risks and Benefits

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ABSTRACT

As the global community struggles to curb greenhouse gas emissions and mitigate the impacts of climate change, climate engineering also known as geoengineering has emerged as a controversial yet potentially powerful strategy. This paper examines the science of climate engineering by examining its historical evolution, technological mechanisms, perceived benefits, and inherent risks. It differentiates between the two primary branches of climate engineering: Solar Radiation Management (SRM), which aims to reflect sunlight to cool the planet, and Carbon Dioxide Removal (CDR), which targets the extraction of greenhouse gases from the atmosphere. While SRM techniques such as stratospheric aerosol injection promise rapid climate effects at relatively low financial costs, they also pose significant environmental, geopolitical, and ethical risks. Conversely, CDR methods are perceived as more natural and less hazardous but are slower, more expensive, and less scalable in the short term. Public perception and international legal frameworks further complicate the deployment of these technologies. The paper emphasizes the need for robust governance mechanisms, transparent research agendas, and interdisciplinary collaboration to ensure that any future applications of climate engineering prioritize safety, equity, and sustainability. In the face of escalating climate threats, geoengineering may become a necessary complement to mitigation and adaptation strategies but only under strict regulatory and ethical safeguards.

Keywords: Climate Engineering, Geoengineering, Solar Radiation Management (SRM), Carbon Dioxide Removal (CDR), Stratospheric Aerosol Injection, Marine Cloud Brightening, Climate Risk, Global Warming.

INTRODUCTION

Climate engineering, also known as geoengineering, encompasses a variety of techniques aimed at large-scale interventions within the climate system with the primary goal of moderating the effects of global warming. Since the establishment of the 1992 United Nations Framework Convention on Climate Change, there has been a noticeable lack of success in stabilizing greenhouse gas emissions, which has fueled the exploration of alternative approaches to tackle climate change. One such approach involves the potential injection of sulfur aerosols into the stratosphere, a process intended to reflect a portion of solar radiation back into space, thereby reducing the amount of solar energy that penetrates the troposphere and influences climate patterns. While the idea of globally implementing climate engineering seems improbable due to the enormous commitment and resources required, it is conceivable that smaller nations or coalitions may consider adopting such measures unilaterally, driven by the urgency of the climate crisis. The continuing rise in greenhouse gas emissions points to a scenario where an emergency response could become necessary, particularly in light of the fact that many climate engineering techniques can be deployed much more swiftly than traditional methods of emission reduction or carbon capture and storage technologies. For this reason, geoengineering is frequently regarded as the only feasible option available for achieving rapid cooling of the Earth's atmosphere. It should be noted, however, that while the potential costs associated with deploying a climate engineering program may appear manageable, the spectrum of possible negative consequences remains extensive and fraught with uncertainty. These consequences could vary significantly, impacting ecosystems, weather patterns, and even international relations, making the discussion around the use of geoengineering both vital and complex. As the urgency of climate concerns intensifies, the debate over these measures continues to evolve, underscoring the need for careful consideration and rigorous scientific evaluation of all possible techniques before implementation [1, 2].

Historical Context of Climate Engineering

The concept of climate engineering, which began in the nineteenth century, became credible only in the late twentieth century. Early projects were impractical and dangerous, while recent approaches, although more credible, remain controversial. Climate engineering is classified into Solar Radiation Management (SRM) and Carbon Dioxide Removal (CDR). SRM aims to counteract warming by reflecting solar radiation back into space, with stratospheric aerosols being the most researched method due to their swift deployment and relatively quick atmospheric removal. Conversely, CDR seeks to lower greenhouse-gas levels, utilizing strategies like afforestation, enhanced rock weathering, and ocean fertilization, each with significant drawbacks. Public acceptance leans more toward agricultural intervention than skepticism towards climate engineering, highlighting a discrepancy in attitudes toward deliberate versus accidental modifications to nature. Critics warn that this could prompt a slippery slope toward global climatic control, as the availability of technology may spur misuse. Historical challenges emphasize feasibility, governance, and risk management issues. Future solutions are likely to emerge from collaborative development rather than isolated efforts [3, 4].

Types of Climate Engineering

Climate engineering is an intricate and multifaceted field that has been divided into two primary categories: solar radiation management (SRM) and carbon dioxide removal (CDR). SRM encompasses a wide array of methods and techniques that aim to reflect a small fraction of the incoming solar radiation back into space, which could potentially assist in cooling the Earth's surface and alleviating some of the adverse effects associated with climate change. This technique involves several innovative approaches, including stratospheric aerosol injection, marine cloud brightening, and other geoengineering strategies that seek to modify the sunlight reaching the planet. Conversely, CDR includes a variety of strategies and processes designed specifically to remove carbon dioxide from the atmosphere and securely store it in various types of reservoirs, such as underground geological formations or within natural ecosystems like forests and soils. Each of these methods has its unique set of challenges, benefits, and potential risks. Both strategies represent critical and innovative responses to the urgent and pressing challenge of global warming and its associated impacts, seeking to mitigate changes that threaten both natural and human systems around the world. As researchers and policymakers explore these complex approaches, they continue to seek a balance between technological advancement and ecological preservation [5, 6].

Mechanisms of Solar Radiation Management

Solar radiation management (SRM) encompasses methods designed to reflect a fraction of incoming sunlight back into space, thereby lessening global warming. By contrast, carbon dioxide removal (CDR) approaches address the root problem of climate change by extracting greenhouse gases from the atmosphere, and are generally regarded as safer but slower and more costly. The sluggish progress of international climate negotiations, accompanied by concerns that current mitigation policies may not effectuate the emissions cuts needed to avert dangerous climate change, has stimulated interest in SRM. Among the principal SRM proposals are stratospheric aerosol injection (SAI) the dispersal of reflective particles in the stratosphere and marine cloud brightening (MCB), which involves artificially increasing the reflectivity of clouds. These techniques are characterized as "fast, cheap, and imperfect": they could produce significant cooling within months of deployment and might cost approximately 5 to 20 billion dollars annually, markedly less than the expense of comprehensive emissions cuts. Nonetheless, SRM cannot restore the planet to preindustrial conditions and does not obviate the necessity of reducing greenhouse gas emissions. The risks linked to SRM vary with the method applied and the scale of deployment, and the very advisability of pursuing SRM compounded by concerns that it might detract from mitigation and adaptation efforts remains a subject of debate. Governing institutions thus face the formidable task of establishing regulations that account for these risks and ensure protection for the most vulnerable populations [7, 8].

Mechanisms of Carbon Dioxide Removal

Rising levels of carbon dioxide (CO2) in the atmosphere have already led to a noticeable and detectable warming of Earth's climate that, in turn, is significantly altering the dynamics of the global carbon cycle. Atmospheric CO2 has now crossed an alarming threshold of 400 parts per million (ppm), which represents a striking increase of nearly 50% since preindustrial times, correlating with the highest levels experienced on our planet in at least 800,000 years. As CO2 continues to accumulate at a concerning rate, the associated risks of severe and potentially irreversible impacts on our climate, our ecosystems, and biodiversity will only increase even further. Current international commitments to emission reduction are, unfortunately, widely regarded as insufficient to return global temperatures to those preindustrial levels that we once knew and relied upon for our stability and safety. Given the remarkable longevity and persistence of CO2 in the atmosphere, the option of actively taking carbon back out becomes not just attractive but essential for the future of our planet. The urgent need for effective carbon dioxide removal (CDR) methods and strategies is increasing significantly as time progresses, making it crucial that we explore innovative solutions to tackle this pressing issue of climate change [9, 10].

Potential Benefits of Climate Engineering

Increasing temperatures and the lack of success in stabilizing greenhouse gases have motivated the exploration of strategies beyond conventional mitigation. Climate engineering aims to manipulate the atmosphere or land surface to reflect or divert a portion of incoming solar radiation, thereby reducing global temperatures. The injection of sulfur aerosols by Mount Pinatubo in 1991 serves as a natural experiment illustrating the potential effectiveness of this approach. The costs of limiting emissions are substantial, providing a strong incentive to investigate engineering solutions. Climate engineering is more likely to be implemented than emission reductions because it can be undertaken independently by a small coalition of countries or even a single nation, circumventing the need for broad consensus. Furthermore, deployment can occur swiftly, enabling a rapid emergency response to sudden climate change. Even a mild temperature increase of 1.5°C would have dramatic and lasting consequences for ecosystems, communities, food production, and human health. The speed at which temperatures may rise compounds these challenges. Because some warming is inevitable and the continued emission of greenhouse gases will exacerbate the trend, adaptation will be necessary even with aggressive mitigation. Therefore, it is important to assess the potential benefits of climate engineering alongside the risks. Climate engineering has received considerable attention from scientific bodies (National Academy of Sciences, Royal Society, International Council for Science) and influential scientists and economists (Teller, Crutzen, Cicerone, Barrett, Nordhaus, Schelling). It is perceived as a promising research subject and a potential backstop should mitigation and adaptation prove inadequate [11, 12].

Risks Associated With Climate Engineering

The potential risks linked with climate engineering have received less attention compared to its benefits. Concerns include direct impacts on the hydrological cycle and stratospheric ozone, risks that could escalate if a carbon dioxide removal program were suddenly halted. In the event of an abrupt cessation of climate engineering, temperature changes might reach up to 0.7C annually, resulting in rapid warming over two decades. As a result, ongoing research efforts aim to explore the implications of climate engineering, with a particular focus on the feasibility of governing such technologies at an international level. Economic analyses indicate that, despite general cost-effectiveness, climate engineering introduces a suite of risks that merit careful consideration. While incidental environmental interference such as the release of greenhouse gases from fossil fuel burning is broadly accepted, the notion of deliberate intervention5such as depositing sulfate aerosols into the stratosphere 5 is viewed with skepticism by the public, which often associates it with experimental tampering in the Sahel region. Among scientists, a prevalent concern is that climate engineering could precipitate a 'slippery slope' toward global climate management, thereby legitimizing further large-scale environmental manipulations once the necessary technologies become feasible. Furthermore, the interplay between climate engineering and natural climate variability may engender regional disparities in climatic impacts; some areas could experience benefits, whereas others might suffer severe consequences. These asymmetrical effects could precipitate political and ethical dilemmas, prompting calls for the establishment of an international governance framework designed to navigate potential conflicts arising from regional divergences [13, 14].

Public Perception of Climate Engineering

Since the term geoengineering was introduced, the public perception of the approach has been the focus of studies on academia and science communication. They have generally organized around a few themes of perceptions of risks, benefits, and costs. Some of the earliest research investigated public views of the science, politics, and ethics of research on the topic. Since a recent review by, some of the main themes emerge from the studies that explored these questions, in these words: “general unfamiliarity” with the issue, when introduced; a “perception of high risks”; a “last-resort framing” (related to the “moral hazard” hypothesis); and a “preference for other climate policies” instead. “Clinical awareness” of climate engineering e.g., a technical familiarity with a concept such as space mirrors remains limited. According to a survey conducted in 2010, only approximately 8% of respondents could provide a meaningful definition of the term; furthermore, a majority of people feel uneasy about research and application of a “technology that attempts to control the climate”. People also perceive geoengineering as a “high risk” option, which can be expected since unknown or uncontrollable consequences tend to increase perceived risks. Climate engineering policies commonly associated with fears of loss of human control and uncontrollable, unpredictable, or dangerous consequences. Perceived risks of climate engineering tend to depend on the specific approach under consideration individual applications are not regarded with equal concern. Carbon dioxide removal tends to be viewed more favorably than any solar radiation management approach on the grounds that the former is a more “natural” form of climate intervention [15, 16].

Regulatory Framework for Climate Engineering

International law regulating climate engineering is still in its initial stages and continues to develop. Scientific and political debates surrounding the topic remain active and ongoing, with meaningful dialogue occurring among various stakeholders. A comprehensive framework for the deployment of climate engineering technologies has yet to be clearly defined or established. Nevertheless, certain principles have the potential to inform the formulation of relevant and effective laws in this area. For instance, during the negotiations of the United Nations Framework Convention on Climate Change, which were initiated in 1992, climate engineering technologies were explicitly excluded from consideration, as they were not seen as a significant threat in that context at the time. However, as our understanding of climate science has progressed, perspectives on such technologies have shifted. In 2008, the Convention on Biological Diversity took significant action by adopting a de facto moratorium on geoengineering activities that may potentially impact biodiversity, unless those activities are conducted under specific and carefully defined conditions. Given that many of the climate engineering technologies under consideration carry substantial environmental risks, it becomes increasingly important for an established framework that regulates both research and deployment to address such concerns effectively; ensuring that risks are mitigated and the benefits are maximized in a responsible manner [17, 18].

Case Studies of Climate Engineering Projects

Well-documented case studies of climate engineering are scarce. Large scale projects underway in Australia, Canada, and The Netherlands lack thorough documentation. Current projects explore various techniques, including ocean fertilisation enhancement, terrestrial carbon sink increases, and land surface reflectivity improvements. Ocean fertilisation, aimed at boosting fish stocks and algal growth for aquaculture and biofuels, began with the 1993 Meyer's Feather experiment, where trace elements stimulated algal growth. Martin (1990) popularised this, proposing iron as a limiting nutrient for phytoplankton in vast ocean regions. This marked the start of studies mainly by private companies on ocean fertilisation's carbon sequestration potential. While iron fertilisation can sequester organics and enhance carbon drawdown, its impact on ocean systems post-fertilisation remains uncertain, with potential issues like nutrient limitation and seabed damage, as well as harmful algal blooms. Nonetheless, Australian Trustees of The Great Barrier Reef have sanctioned fertilisation trials. Terrestrial carbon sequestration aims to increase the carbon pool by enhancing carbon input, minimising losses, or increasing inert carbon pools. Methods include reforestation, soil carbon enhancement, and land management changes. Innovative strategies involve engineering crops for non-degradable by-products, potentially serving as long-term carbon stores. However, this approach is controversial as it adds to inert carbon but disrupts active carbon cycling due to reduced biomass decay [19, 20].

Future Directions in Climate Engineering Research

Active support and research initiatives in the area of climate engineering are currently on the decline. However, it is worth noting that policy interest in these solutions remains notably high. The apparent collapse of the research-to-policy pipeline in geoengineering does not call into question the ongoing validity of active climate intervention strategies or the importance of large-scale field trials. It is clear that there exists a substantive and fundamental interest, alongside a significant policy rationale, for the deployment of stratospheric aerosols as an emergency measure to counteract climate change. The recent attention directed toward proposals concerning the rapid melting of Arctic sea ice serves to backwardly explain the sustained enthusiasm for stratospheric aerosol deployment measures. In order to effectively address the warming induced by CO2 and stabilize temperatures, it is crucial that climate-engineering-scale reductions in the energy absorbed by the Earth-and-ocean system must not only accompany but also persist continuously. Without such efforts, the stabilization of temperatures across the globe becomes an impossible task. The transient loss of Arctic sea ice, coupled with correlated feedbacks from permafrost thawing and rising sea levels, necessitates immediate and proactive responses to avert potentially profound disruptions to the planet's overall system [21, 22].

Economic Implications of Climate Engineering

The economic dimensions of climate engineering encompass cost-benefit analyses as well as political and governance considerations. A cost-benefit analysis using a simple global economic-climate model indicates that the cost of postponing climate engineering is relatively low, allowing time for the resolution of physical and technical uncertainties. While climate engineering passes established cost-benefit tests, political approval remains elusive because the public tends to reject any tampering with nature. This opposition constrains deployment even in authoritarian regimes. Both emission reductions and climate engineering require international governance, meriting further investigation. The influence of small-scale effects on the feasibility and desirability of large-scale interventions emerges as an important area for future work. A global climate engineering solution should be viewed as a global public good that requires decentralized implementation and local governance. In addition to cost-benefit analysis, there is increasing focus on governance, ethical aspects, and public engagement to facilitate informed debate on research and potential deployment [23, 24].

Ethical Framework for Climate Engineering

Decision makers evaluating the desirability of different strategies must integrate scientific and ethical considerations into their analyses. Analytical frameworks cannot by themselves dictate what choices should be made, which are ultimately political and ethical decisions. Widely accepted ethical principles including producing benefits, avoiding, reducing, and remedying harms; protecting the public's right to know; informing decision makers openly and honestly; and respecting compliance with the rule of law remain applicable to climate engineering interventions. Interventions should exhibit predictable physical and social consequences, operate in accordance with established ethical principles, and demonstrate a high degree of safety before deployment. Safety requirements, however, vary and have not been universally defined. Most proposed climate engineering techniques generate substantial social and environmental risks, especially under conditions of uncertainty, amplifying the ethical challenges already present. Issues concerning the fair distribution of social costs, while complex, tend to be less fraught than potential ecological and technical risks. Low-risk approaches that enhance natural carbon storage, such as reforestation and soil management, align well with accepted ethical norms. In contrast, both ocean fertilization and solar-radiation management carry significant ecological and technical vulnerabilities, along with corresponding ethical issues including the risk of unintended harmful consequences and the potential for CO_2 leakage from storage sites. Previous attempts at climate engineering have faced severe challenges related to technical feasibility, governance, and social, political, and environmental risks; nonetheless, shifting technological capabilities, public perceptions, and policy priorities call for reassessment. Given the absence of a singular comprehensive solution, addressing climate change effectively will likely depend on incremental progress across technologies, institutions, and collective behaviors [25, 26].

Interdisciplinary Approaches to Climate Engineering

Current climate policies aim to reduce greenhouse-gas emissions to prevent a doubling of atmospheric CO_2 by 2100. Climate engineering involves large-scale actions to directly alter temperature, such as Earth's surface cooling. An interdisciplinary framework compares climate engineering strategies using criteria including technical potential, cost effectiveness, ecological risk, public acceptance, institutional capacity, and ethical concerns. The framework analyzes strategies relative to abatement efforts, providing a broader assessment of potential risks and benefits. While abatement remains the most desirable policy, strategies such as forest and soil management for carbon sequestration merit broad-scale application. Other strategies like biochar production and geological carbon capture and storage are rated lower but warrant further research. These differences between agricultural and climate engineering may explain people's acceptance of agricultural interference in nature while being skeptical towards climate engineering. Participants in the NERC's public debate project stress the difference between doing something deliberately and doing it accidentally. They argued that it is wrong to experiment with depositing sulfur in the stratosphere, but burning coal and oil, causing greenhouse gases, was a necessity. Another perspective warns that climate engineering may be the first step on a slippery slope toward global climate management, with the potential for harmful techniques to be exploited once climate control becomes possible. Public debates highlight that interference with natural systems, such as climate engineering, might legitimize further interference. Climate engineering, combined with natural climate variability, causes regional differences in impact, leading to political challenges in experiments and implementation. Some scholars compare climate engineering testing to nuclear tests near populated areas and medical experiments on vulnerable populations, calling for international governance. Overall, climate engineering meets cost-benefit analyses given the range of functions considered, but uncertainty remains [27, 28].

CONCLUSION

Climate engineering represents both a scientific frontier and a societal dilemma. As global efforts to limit greenhouse gas emissions falter, the appeal of technological interventions to cool the planet or remove atmospheric carbon is growing. However, the deployment of such technologies is fraught with uncertainties ranging from ecological side effects and unpredictable regional climate disruptions to questions of global equity, consent, and moral responsibility. While Carbon Dioxide Removal offers a more gradual and potentially less controversial approach, Solar Radiation Management holds the promise of faster results but at higher political and environmental costs. To responsibly navigate the future of climate engineering, the international community must prioritize transparent research, robust public engagement, and the development of a coherent legal and ethical framework. Ultimately, climate engineering should not be viewed as a substitute for emission reductions, but rather as a potential supplementary tool one that requires caution, cooperation, and foresight to ensure it benefits humanity without creating new global threats.

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CITE AS: Mwende Wairimu G. (2025). The Science of Climate Engineering: Risks and Benefits. EURASIAN EXPERIMENT JOURNAL OF ENGINEERING, 5(1):100-106.