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Between the sun and us: Expert perceptions on the innovation, policy, and deep uncertainties of space-based solar geoengineering

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A R T I C L E I N F O

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A B S T R A C T

Space-based geoengineering is gaining attention, if not necessarily traction, as a possible "break the glass" solution to mitigate the worst impacts of climate change and facilitate the transition to a low-carbon future. Though still on the periphery of discussions around climate mitigation and geoengineering, space-based methods that would deflect or block incoming sunlight, and thereby diminish how much radiation ultimately reaches the Earth, could offer advantages, notably, by avoiding the need for difficult trade-offs and decisions in terms of land and resource use on Earth. Aside from a few specialist-oriented studies, the literature on space-based geoengineering remains limited. In this study, we utilize a large and diverse expert-interview exercise (N = 125) to provide a first critical examination of the promise and relevance of space-based geoengineering for tackling climate change, including perhaps as a source of renewable energy, its feasibility and prospective risks, as well as key actors and issues related to commercialization and governance. To our knowledge, no other study has employed empirical data of any kind to examine perceptions of space-based geoengineering, let alone in relation to other kinds of climate-intervention technologies. Not only does the current research represent the first of its kind, it also provides a foundation for more informed, comprehensive deliberations around this interesting, possibly even necessary solution to climate change.

1. Introduction

All-too-slow progress towards climate mitigation, along with insufficient funds and investment in climate adaptation, are placing the agreed-upon objective of the Paris Agreement on a limit of 1.5C further out of reach. In turn, "Plan B″-strategies utilizing carbon-sequestering 'negative emissions technologies' (NETs) and sunlight-reflecting 'solar geoengineering' (or solar/Earth radiation management, SRM/ERM) are attracting further attention [1–3], as a way to flatten the trajectory of emissions reductions required and facilitate the transition to a low-carbon future. Climate interventions which have been proposed range from the commonplace, like forestry and agricultural management, to the radical and untested, such as stratospheric aerosol injection and large-scale direct air capture – along with even more revolutionary but immature concepts.

A paradigmatic example is *space-based solar geoengineering*, through use of "sunshades" or "sun shields" to defract, deflect, or block incoming sunlight and thereby diminish how much radiation ultimately reaches the Earth [4–6]. Starting from the twin premises that emissions reductions are unlikely to occur at a sufficient pace to avoid the most extreme impacts of climate change and that planet-bound NETs or SRM will face difficult land and resource trade-offs and unintended consequences, space-based methods purport to offer a way out for our environmental and climate challenges. Interestingly, proposals have also pointed to significant spin-offs for space travel and exploration and even the potential use of sunshields as a source of renewable energy, alongside climate mitigation.

Despite its potential, aside from a handful of specialist engineering studies, the literature on space-based geoengineering is limited – and with no studies assessing the potential of this technique in relation to or against other climate-intervention technologies to our knowledge. In

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List of abbreviations

CDR	Carbon Dioxide Removal
ENMOD	Environmental Modification Convention
ERM	Earth Radiation Management
ESA	European Space Agency
GEO	Geosynchronous Orbit
IPSS	Inter Planetary Sun Shade
ISS	International Space Station
ITAR	International Traffic in Arms Regulations
LEO	Low-Earth Orbit
NASA	National Aeronautics and Space Administration
NETs	Negative Emissions Technologies
RF	Radio Frequency
SAI	Stratospheric Aerosol Injection
SCoPEx	Stratospheric Controlled Perturbation Experiment
SEL	Sun-Earth Lagrange point
SRM	Solar Radiation Management

this study, we thus utilized a large expert-interview exercise (N = 125) to offer the first critical examination of the promise and relevance of space-based geoengineering for tackling climate change, its feasibility and prospective risks, and the key actors and issues related to commercialization and governance. To our knowledge, no other study has employed empirical data to examine the commonalities and differences within expert perceptions of space-based solar geoengineering. Not only is the current research therefore the first of its kind – it also provides the foundation for more informed future deliberations, i.e., the extent to which investments in this novel climate-intervention technology may dovetail with our transition to a low-carbon future, the potential necessity for employing other NETs and SRM approaches, and the aim to explore, understand, and potentially inhabit other areas of the solar system.

The paper proceeds as follows. It first offers a literature review engaging with the surprisingly rich history of space-based geoengineering. Then it discusses the promise, risks, actors, and governance dilemmas that may accompany deployment. It concludes with insights for research and policy.

2. Background and literature review

Though this study is the first to explore perceptions towards space-based geoengineering (along with a range of other NETs and SRM approaches) [see Refs. [7,8]], some of the underlying concepts have circulated in scientific networks for up to a century. Before delving into how such approaches are viewed now, it is important to gain a sense of: (i) arguments why space-based geoengineering should be considered at all; (ii) the various ideas and proposals; and (iii) and the potential technical, public-facing, and legal reasons for why space-based geoengineering has not yet gained much traction.

2.1. Why space-based geoengineering?

There are a few ways to define space-based geoengineering. First, we can refer to general aspects of the approaches themselves. Despite their differences in terms of location, technology, and size or scale (see Section 2.2), all space-based geoengineering strives to avoid the worst impacts of climate change by modifying how much solar radiation goes in and out of Earth's atmosphere. In every case, this is accomplished through the use of an occulting structure between the Sun and us that reduces the amount of sunlight reaching the Earth. Drawing on the historical example of the "Little Ice Age", calculations point to needing to block around 2% of incoming solar radiation to compensate for the cumulative impact of human-caused global warming [9]. Indeed, when diminished solar-spot activity resulted in only a 0.25% decrease in solar radiation during this period, winter temperatures of 1.8 °C below average were recorded, as well as visible effects such as the freezing of the Thames River in London [10].

Another way to define space-based geoengineering is by distinguishing it from the geoengineering approaches that directly modify the Earth's atmospheric, terrestrial, or oceanic processes. In contrast to negative-emissions technologies and some solar radiation management techniques, space-based methods set themselves apart, literally, by being situated beyond the Earth's biosphere. This *extraterrestrial* potential is a frequent argument in favor of space-based geoengineering: to avoid (or even negate) climate change while minimizing direct impacts on the Earth and, in turn, not being contingent on the uncertainties and dynamic feedback loops between, e.g., various layers of the atmosphere [4,5,9,11–16].

Critically, space-based approaches do not offer an answer to the root cause of global warming: the amount of greenhouse gases in the atmosphere. To its proponents, though, this is not a criticism. Instead, they argue that space-based geoengineering, like other forms of solar geoengineering, focuses on temperature rather than emissions reductions – ideally, both kinds of efforts should be coupled, but it is better to have the former on hand if the latter fails. Space-based geoengineering (if one suspends immediate objections to near-term cost and technical feasibility) would also offer greater predictability and controllability, in terms of a more uniform effect across the globe [15,16]. In particular, such techniques could simplify climate mitigation by focusing attention on a single parameter: the amount of solar insolation the Earth receives [4,5]. In the words of Kennedy et al. [[4]; *stress* in original], being able to modulate the amount of sunlight would mean "transforming the "solar constant" to a *controlled solar variable*" – one which we (theoretically) can tweak in line with our (evolving) knowledge and circumstances. As a final remark, proponents highlight that, if space-based approaches fail to work or have unintended side-effects, they are fully reversible, in that any structure could be left to drift off into outer space.

2.2. Ideas for space-based geoengineering

The concepts for the various elements of space-based geoengineering have been around for up to a century here, current thinking adopts past concepts intended for space travel and employs them as solutions for climate change. In this way, the history of thinking and conceptualization on space-based geoengineering is marked by periodicity and a punctuated interest over the last decades. In general, when the topic of climate change is higher up on the agenda, such ideas appear more often – but they have gained more traction over time as a parallel issue of prospective technoscience.

The first takeaway from this literature (see Table 1) is the diversity of strategies (and attached metaphors) for diminishing the amount of solar radiation reaching the Earth. As a sampling, there is a 2000-km-wide, 10 μm-thick glass shield which could refract sunlight away from the Earth [17]; light-scattering clouds of dust, either from the Moon or a near-Earth asteroid which would be captured, towed, and gravitationally tethered in a useful position, to act as "sunscreen" for the Earth"

Table 1
Overview of space-based geoengineering proposals.

Article	Option	Location	Description
Early [17]	Thin reflecting or refracting glass shield	SEL1	2000-km-wide, 10 μm-thick glass shield to refract sunlight away from Earth
Seifritz [11]	Large mirrors mounted on satellites	SEL1 (or SEL2/3)	Examines general principles for temperature reduction through “satellites bearing large lightweight mirrors”
Mautner and Parks [12]	Fleet of solar screens and deflectors	SEL1, orbit of Sun, or low Earth orbit (LEO)	Aims to reverse 2 °C of global warming by intercepting 3% of incoming solar radiation as well as try to mitigate ozone/UV issues
Mautner [13]	Reflective screen of thin film (interwoven with mesh, perhaps) Dust ring (of lunar or asteroid material) in orbit around Earth	Equatorial ring in LEO	Examines cost and potential to avoid 2–5 °C of global warming by intercepting 3–7% of solar radiation, while noting issues with stability and interference with other space activities
Hudson [23]	“Space parasol” using an array of screens	SEL1 (LEO and GEO also considered)	Demonstrates preferability of SEL1 option to those in Earth orbit
Teller et al. [20]	Metallic “small-angle scatterer”	SEL1	Envisions a scattering system of the same area but lower mass than other proposals by being located at SEL1 rather than LEO
Roy [10]	“Solar sail” which is 100,000 square kilometers in length	Unspecified, seems to be SEL1	Particular focus on ability of solar sails to “adjust the earth’s solar constant” through active and intelligent adaptive capabilities
McInnes [24]	Large solar shield	SEL1	Technical study of how to minimize mass of the shield as well as optimize location
McInnes [25]	Large solar reflectors Large solar absorbers	SEL1	Jointly explores possibility of engineering Earth’s climate through active cooling (to mitigate climate change) or active heating (to mitigate effect of advancing ice sheets)
Angel [9]	Cloud of 16 trillion “flyers”, together 100,000 km long	SEL1	Describes specifications and challenges for a cloud of small autonomous spacecraft weighing 1 g each and 1 m in length, including active stabilization and functioning as a unit as well as in terms of launch from Earth
Pearson et al. [19]	Planetary ring around Earth, made of passive dust particles (of lunar, earth, asteroid material) or controlled crafts “with parasols”	Equatorial ring in LEO	Highlights prospective risks for positioning in LEO, including interference with other satellites, disturbances on ambient light conditions, and shading mainly on tropics
Struck [26]	Dust cloud (of lunar or asteroid material)	SEL4/SEL5	Only in appropriate position occasionally, revolving between bouts of no change in insolation and intense changes higher than desired level (as well as a flickering effect)
Lunt et al. [27]	Space-based sunshade	SEL1	Climate-modelling exercise that reveals a decrease in solar radiation of 4% could result in temperatures 1.5 °C cooler in the tropics compared to pre-industrial times, versus 1.5 °C warmer at higher latitudes, with less sea ice and a drier world overall, especially at tropical latitudes
Irvine et al. [28]	Space-based sunshade	SEL1	Replicates the findings of Lunt et al. (2010) via a climate model with higher resolution, pointing to regional disparities between polar and equatorial regions vis-à-vis cooling effects
Kosugi [29]	Space-based sunshade	Unspecified, both SEL1 and LEO are mentioned	Climate-modelling exercise exploring cost-effectiveness of deployment of a sunshade alongside other climate-control measures, highlighting potential for ongoing increase in CO2 emissions and need for continuous decline in launching costs over time
McInnes [30]	Simple occulting disks vs. highly engineered refracting disks	SEL1	Compares advantages and disadvantages of two main types of proposals, signaling overall potential of sunshade concept and how continued technical development can increase viability of macroscopic designs
Bewick et al. [18]	Cloud of dust particles of asteroid material	SEL1	Calculates potential to capture a nearby asteroid and gravitationally anchor it in place at SEL1 to achieve reduction in solar insolation by upwards of 6.58%
Bewick et al. [21]	Saturn-style dust ring	Equatorial ring in LEO	Demonstrates potential of providing Earth with its own elliptical ring, but highlighting greater effect on tropical regions as well as the possibility of space-debris issues and seasonal variations
Kennedy et al. [4]	Swarm of 800,000 solar-energy collecting “Dyson dots” covering more than 1 million square kilometers	SEL1	Lays out potential for swarm of Dyson dots about the size of Texas to both “transform the “solar constant” to a controlled solar variable” and capture energy from the Sun to then be beamed back to Earth
Sánchez and McInnes [31]	Space-based sunshade or occulting disk	SEL1	Climate-modelling exercise illustrating how large-scale regional (or seasonal) variations can be mitigated through “out-of-plane sinusoidal motion”, that is, letting orbit of the sunshade not be fully in sync with the Earth
Salazar et al. [32]	Space-based solar reflectors on polar orbits	Near-circular orbits around polar regions	Explores possibility of using solar reflectors as a way to mitigate future natural climate variability, i.e., global cooling
Salazar and Winter [33]	Space-based solar reflectors, orbiting around Mars	Inclination of ≤90° to the orbital plane of Mars	Considers possibility of using space-based solar reflectors to heat up and prepare Mars for terraforming
IRS and Airbus [34]	Inter planetary sun shade (IPSS) with an area of 500,000 km	SEL1	High-level concept description of IPSS that would be built using in-situ materials from the Moon and by Gigasail factories to be set up at SEL1, with an expected cost of around 1 trillion US dollars, which is aimed to be potentially offset by harvesting and beaming solar energy back to Earth

Source: Compiled by the authors.

[18–20]; a “heliotropic dust ring” that would endow Earth with its own Saturn-style ring [13,21]; a swarm of 800,000 solar-collecting devices (“Dyson dots”) covering an area more than 1 million-square kilometers (i.e. about the size of Texas) that simultaneously functions as a “parasol” and captures energy from the Sun [4]; or a “flotilla” of upwards of 16 trillion feather-light, transparent flying disks, each weighing only 1 g, with tiny fins that gather solar energy and actively adjust their relative position to work in concert with the other disks [[9,16], see also [22]]. There are no shortage of ideas vying with one another.

How then are we to identify which of the many proposals are worthy of further consideration and investment? A first factor here is how well the various concepts could manage to deliver uniform shading across the entire sphere, while having minimal impact on the Earth itself. Location of the occulting structure emerges as key. We distinguish between the situation in low-Earth orbit (LEO) or geosynchronous orbit (GEO), and those in the "spatial regions of *meta*stability" [4]further away to Earth, known as Lagrange points. Owing to their greater proximity to Earth, LEO or GEO is undoubtedly a more convenient as well as potentially cheaper location.

However, several immediate problems have resulted in such proposals being broadly dismissed [4,6]. First, since such space is more heavily trafficked with important pieces of satellite infrastructure, or even just space junk in the vicinity, there is a much greater risk of collision [4]. Second, situating a structure in either LEO or GEO would create a transient shadow passing over the Earth, undercutting the objective of its being imperceptible as well as raising the prospect of adversely affecting animal life and photosynthetic processes [4,6,21,30]. In addition, as objects at LEO or GEO would not maintain a fixed relative position between Earth and Sun and would necessarily be in darkness for half of their orbit – reducing their effectiveness and having a less uniform effect whereby any reduction of sunlight would be more concentrated on the equatorial zone. This seems problematic since the equator is relatively less affected by climate change than the polar regions [35]. Furthermore, with uniformity of effect and imperceptibility as two of the principal objectives of space-based geoengineering – along with reversibility, also an issue with LEO proposals [21] – options set in near-Earth orbit are increasingly set aside in favor of those occurring further out in space [6,30].

Five potential Lagrange points exist which offer solutions to the "three-body problem" of how to maintain a (relatively) stable orbit of an object in relation to the Sun and Earth (see Fig. 1). Of these, most attention has focused on Lagrange Point 1 (L1), due to its position between Sun and Earth. As a first advantage, the greater distance to L1, which at 1.5 million kilometers from Earth is forty times farther away than GEO, effectively diminishes any risk of a transient shadow being detectible on Earth – and thus of impacting animals, plants, and humans. Instead of acting like a lunar eclipse, a sunshade at L1 (we opt hereafter to use "sunshade" when describing activities at L1) would have an effect closer to the shadow (or rather lack thereof) of a bird flying overhead – with any sunshade substantially smaller than, e.g., the Moon and four times further away, so that the Earth would not be in the dark umbra of its shadow (see Fig. 2).

The first well-understood technical difficulty for such proposals is how to ensure any sunshade at SEL1 does not float away. While SEL1 (and SEL2 and SEL3) is functionally a "spatial region of metastability" [4] – and quite a large one, at around 30 quadrillion cubic kilometers – it is not one of true stability. As such, the efficacy of a sunshade would depend on the extent to which it can be successfully placed in the much smaller "sweet spot" of SEL1 [5]. Without any kind of external intervention, whether through self-propulsion technology to maintain the orientation and altitude or external servicing and maintenance, space sunshades could drift out of ideal position in as little as a few years. This then raises questions of whether it would ultimately be less expensive to just replace components that drift out of place or to afford the means for their stability to be maintained. One separate alternative, given the passive stability of SEL4 and SEL5, would be to create, e.g., a dust cloud at either one of these points [see Ref. [26]]. As Kennedy et al. [4] underscore, however, use of such locations would come up against similar problems to those for LEO or GEO – objects, by only orbiting Earth, would only be in appropriate position occasionally, resulting in long bouts of no change in insolation followed by intense changes higher than the desired level.

Focusing exclusively on SEL1, we come to a last point of distinction: centralization and scale. Due to the significant (potentially conflicting) demands of having a sunshade large enough to deflect or block incoming solar radiation, which can be transported and set in place (as a whole or in parts) at a vast distance without being excessively expensive (or environmentally destructive), and able to maintain its position between Sun and Earth, there is robust discussion of the various proposals. Keith et al. [6] classified these into two camps: high-tech/low-mass versus high-mass/low-tech.

We focus on the former class, given the logistical challenges and costs of the high-mass approach. High-tech/low-mass concepts include proposals such as Angel [9] and Teller et al. [20] that aspire to have hundreds of thousands of smaller and lighter objects that could operate in unison, rather than one large sunshade. Using a more distributed approach, such proposals avoid launch-related difficulties from having to get a payload weighing as much as 100 megatons into orbit [see Ref. [17]] or, alternatively, the difficulties of in-orbit assembly or in-situ production on the Moon – on this point, we note there is already some experience with launching objects to SEL1, as this is where most Sun-observing satellites are located. As such, the extremely lighter mass of the respective components is envisioned to enable production on Earth, followed by launch into orbit, at which point a "solar sail" would be used to propel the stacks to their interplanetary position at light speed [5,10] – although the number of launches needed becomes astronomical [9]. Thus, proposals like the Inter Planetary Sun Shield (IPSS) from IRS and Airbus [34] opt for a combined approach that would produce and launch certain elements on Earth while employing lunar materials for others. In any case, a distributed approach necessitates the coordination of components in the constellation relative to each other, e.g., through pieces having "sensors and controls and even some degree of intelligence [to] observe their neighbors as well as the primary and the satellite, and … be able to maneuver to avoid crashes or other conflicts" [[5], p. 178; see also [16]]. If successful, this would yield a sunshade of the requisite magnitude and blocking potential, along with one with built-in robustness in case parts should fail. After all, it would be much easier to switch out a few thousand elements, while still being able to diminish solar insolation, than to replace an entire shield on the fly. Such robustness is crucial given the harsh conditions in which a sunshade will have to operate, to "withstand high radiation fields and continual assaults by the solar wind or even the occasional solar storm, and tolerate the occasional puncture by micrometeoroids" [[5], p. 178]. Capacity to cope with and maintain performance in such conditions is one further criterion to be kept in mind.

2.3. Immediate technical, public, and legal uncertainties and barriers

While a handful of groups are currently working on and developing space-based geoengineering, the consensus is that such approaches are "not a plausible near-term goal or aspiration" [[6], see also [29]]. Chiefly, concerns center on expected costs from researching, developing, and ultimately deploying such technologies – from $1 trillion [e.g. Ref. [34]] to $6–20 trillion [19]. This is not surprising given the magnitude of needed launches: for Angel's [9] solution with nearly a million micro-flyers, 20 (electromagnetic) launchers from Earth would send up a stack of flyers every 5 min for 10 years; that is, more than 2.1 million launches each year for a decade [see Ref. [5]]. As it now costs at least $10,000 dollars to launch one pound of payload into low-Earth orbit [34], the $1 trillion-figure is less a plausible estimate than "aggressive target" [9] – one requiring that launch costs be reduced to about $100/kg, through the increasing reliability of reusable launch technology and the greater involvement of the private sector, extensive in-space manufacturing and assembly capabilities [see Refs. [5,6]]), and "mass production of simple spacecraft units" using "self-replication of 3D printing platforms", all using in-situ resources on the Moon [[16], p. 278].

The typical rejoinder to questions of cost from those working on space-based geoengineering is inevitably that, when compared to the predicted damages from climate change, such figures begin to seem more reasonable [6]. Moreover, insofar as costs would be spread out along the half-century lifetime of the development, deployment, and

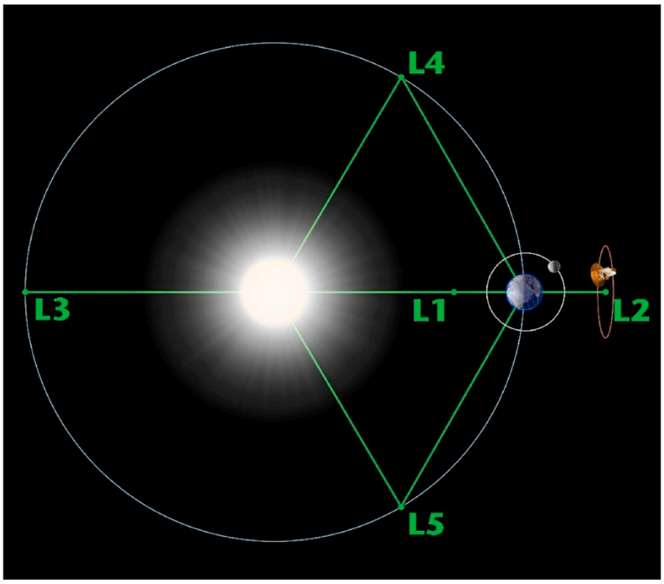

Fig. 1. Visualizing Alternate Lagrange Points in relation to the Sun and Earth. Source: [36]. Figure depicts the principal region being considered for sunshades (L1), along with others that have received more limited attention for various reasons. In contrast to the other three, L4 and L5 represent regions of true stability.

operation of the sunshield, an undertaking of this magnitude is better compared to other projects conducted by superpowers in the name of national security, such as NASA's space budget or the US′ F35 fighter program. Remarking on the Dyson Dots project, Kennedy clarified: "Nobody's going to build a 100-megatonne piece of tinfoil the size of Texas in one go …. an actual project would be incrementally built, incrementally deployed, incur incremental expense, and yield incremental benefits" [38] (see Fig. 3). By such a telling, the decision about whether to pursue a sunshade is not a one-time, trillion-level decision, but would rather consist of recurring, iterative decisions at a smaller scale, to be accompanied by tests of how well it works (or doesn't). Similarly, the IPSS scheme published by IRS and Airbus [34] identifies a sequence of targets out to 2030, whereby key technologies would be developed and demonstrated leading up to this crucial "decision point". In so doing, these actors aim to offer greater certainty regarding how such a project might develop and thereby assuage concerns over the massive costs.

Nevertheless, Keith et al. [6] highlighted the broad lack of interest in space-based techniques, and not only from those who fear it neglects the root causes of climate change or borders too closely on science fiction, but also even in geoengineering and space-technology communities – only 2% of articles on geoengineering consider space-based methods. Such reluctance may reflect the fact that the consideration of such methods is as close to science fiction as scientific practice – usually taken as thought experiments by aerospace engineers or astrophysicists. Indeed, the imaginative thought on what would be needed for an effective, cost-efficient sunshade simply highlights how far away resources and initiatives are at present. Fig. 4, designed as a vision for policymakers and the public, shows that necessary infrastructure and technological developments would include launchers to get equipment into low-Earth orbit, a functioning Moon economy to supply the raw materials and to enable manufacturing and logistics, various solar power stations and spacetrucks and, ultimately, the Gigasails produced in-situ in outer space.

On the one hand, the diverse range of technologies on (prospective) offer could provide "mutually reinforcing capabilities" that advance the mission of space travel [[4]; see also [5,11,39,40]]. Investments in space-based geoengineering could thus flow into key spin-offs of space technology that benefit other objectives: deflection of incoming asteroids; asteroid prospecting and mining; manned missions to Mars; extrasolar space travel; harnessing the power of the Sun for incredible amounts of renewable energy [4]; and environmental monitoring of critical, climate-relevant land, ocean, and atmospheric data [41–43].

Nonetheless, even if one is impressed by the scope and vision of this endeavor, the necessary extent of the technical developments introduces

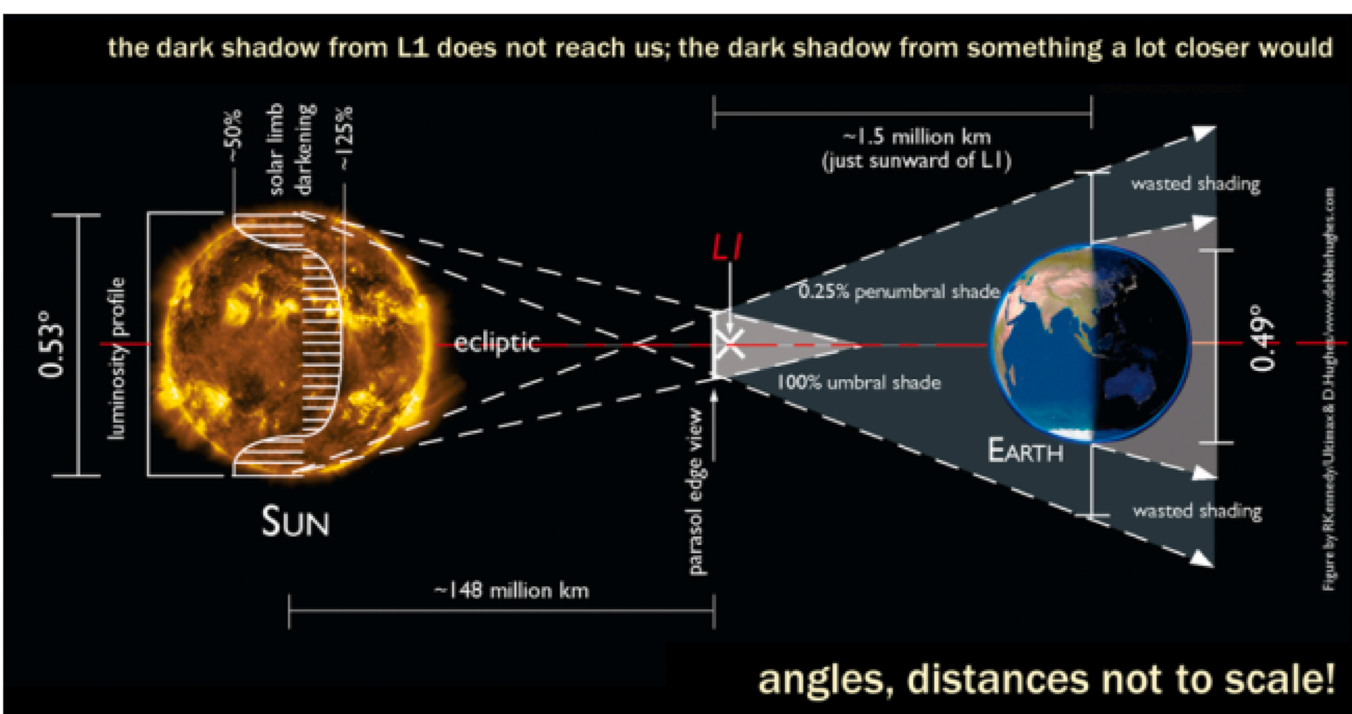

Fig. 2. Visualizing the Lagrange Point 1 between the Sun and the Earth. Source: [37]. The location of a sunshade at SEL1, four times the distance from the Moon to the Earth, means that no part of the Earth would fall in the umbral shade of a sunshade, thus avoiding any eclipse-like effect.

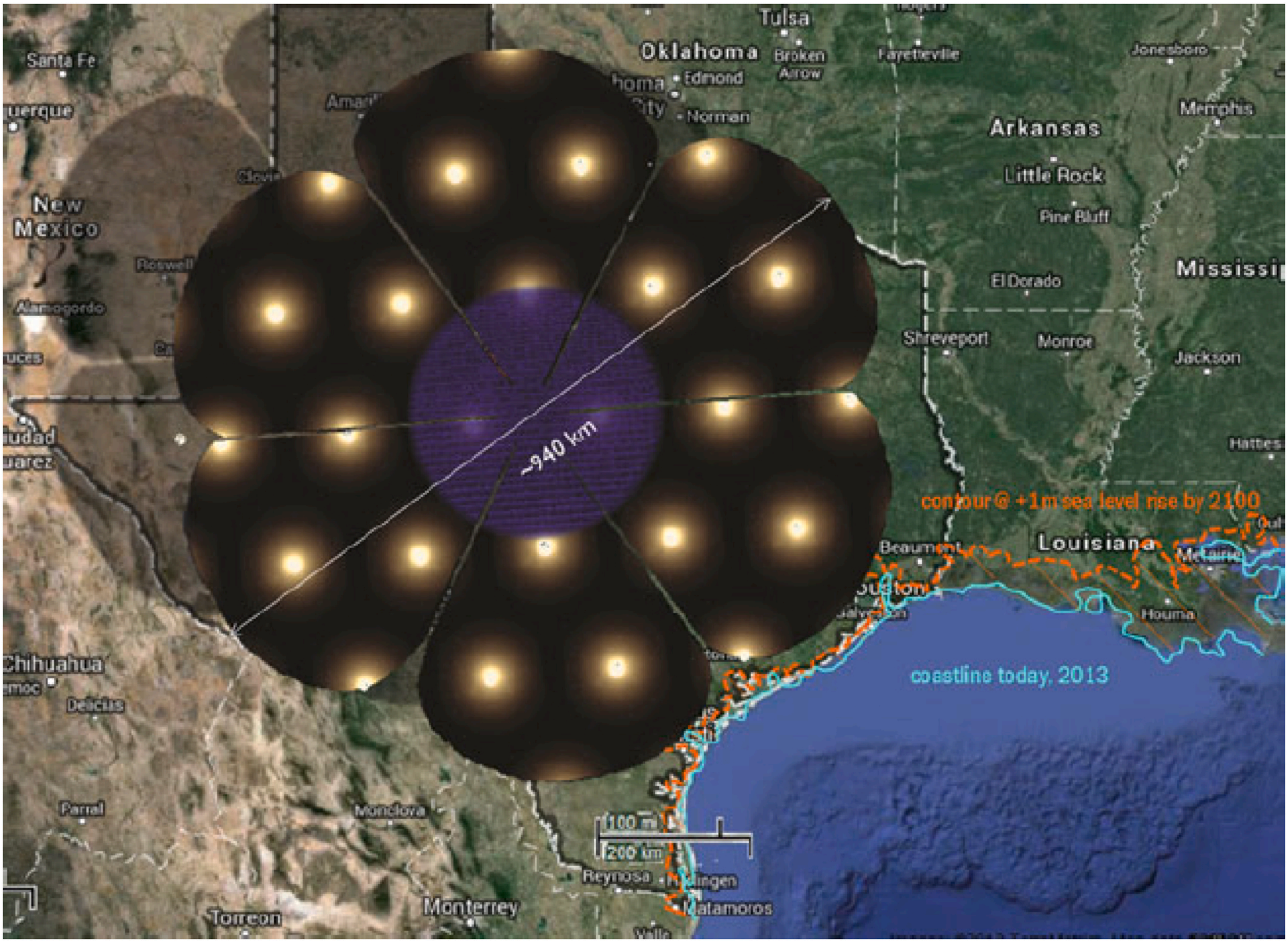

Fig. 3. A Texas-Sized Dyson Dot Proposal for a Sunshade. Source: [37]. Although intended to be composed of a swarm of almost a trillion devices (the Dyson dots), together these would cover more than 1 million-square kilometers.

substantial uncertainty for the project's viability by mid-century. Probably for this reason, even arguments in favor of space-based geoengineering tend to end with a call for any investment to be accompanied by additional funding for renewable energy [4,6,9,16,37]. Lest space-based geoengineering be taken to fully substitute for climate mitigation, simulations of a "sunshade world" reveal that it is not feasible to absolutely negate the damages from climate change [27–29]. Lunt et al. [27] revealed that, even if effects are small relative to other forms of geoengineering, using space-based methods to decrease solar radiation by 4% could result in temperatures 1.5 °C that are cooler in the tropics compared to pre-industrial times, versus 1.5 °C warmer at higher latitudes, along with less sea ice and a world that is drier overall, especially at tropical latitudes. Sánchez and McInnes [31] concluded, however, that such large-scale regional variations might be mitigated by "out-of-plane sinusoidal motion", that is, letting the orbit of the sunshade not be fully in sync with the Earth. In any case, much more understanding is needed of how potential climatic effects from the implementation of a sunshade would be distributed across the globe – and it is also unclear how much attention and resources the modelling communities on planet-bound solar geoengineering are willing to devote to space-based approaches.

To our knowledge, there is also zero discussion of how the public might respond to development and deployment of space-based geoengineering. It is worth mentioning here the frequency with which stories from science fiction are drawn upon for sense-making in this domain – films of the James Bond franchise, or Arthur C. Clarke's *Childhood's End* (1953). While fiction is certainly not fact, this offers an illustration of the kinds of concerns that might materialize among the public or be employed by those seeking to organize against the application of space-based methods.

One final real-world concern centers on the adequacy of extant legal and governance frameworks, engendering questions of how such projects would be governed, not least if they would entail the occupation and mining of the Moon or of nearby asteroids. As a first step, various authors [e.g. Refs. [6,44]] have pointed to the applicability of international treaties like the Outer Space Treaty of 1967, to which the United States, *inter alia*, is party. This treaty establishes outer space as "the province of all mankind", setting an open-access regime where any state is free to explore and use it. At the same time, as Bodansky [44] stated, parties are required under Article 9 to avoid "adverse changes in the environment of the Earth" as well as to consult other states if there is any question of such an effect, which would seem to have special relevance for space-based geoengineering projects. There is a further enjoinder that "the exploration and use of outer space … shall be carried out for the benefit and in the interests of all countries, irrespective of their degree of economic or scientific development." Keith et al. [6] have pointed to the existence of this treaty as a positively distinguishing feature of space-based approaches vis-à-vis other geoengineering techniques that lack such a legal framework. Another relevant organization is the U.N. Commission on Peaceful Uses of Outer Space, established under the auspices of the United Nations General Assembly in 1959, which strives to ensure that the benefits of space technologies are

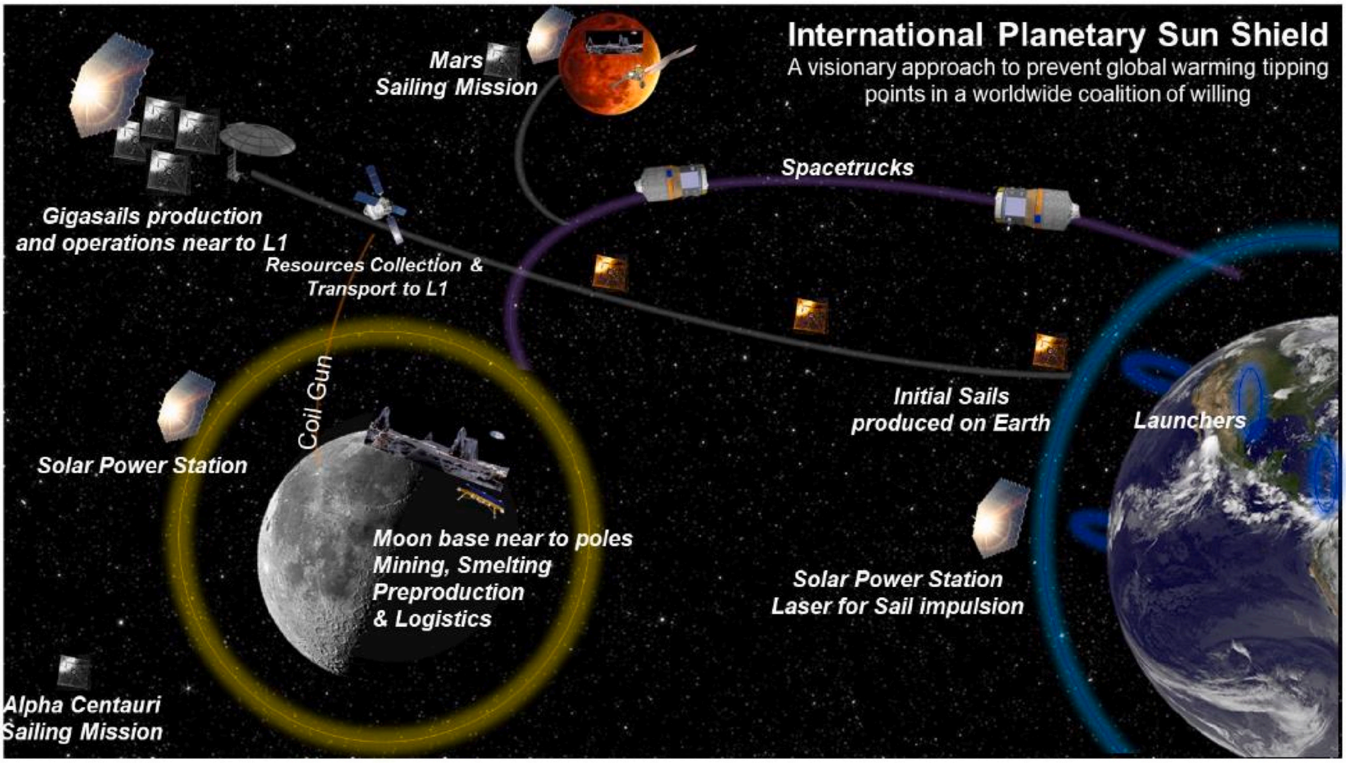

Fig. 4. The Visionary Approach of the International Planetary Sun Shield (IPSS). Source: [34]. Featuring missions to Mars and Alpha Centauri, Moon bases as well as coil guns and spacetrucks, this vision highlights the extent of development still required.

extended to all countries. No institution with the power to adjudicate disputes or make decisions has so far been established, however. Concerns have thus been raised over the extent to which these existing frameworks are insufficient to prevent an arms race in outer space or generally promote the use of the limited space available in geostationary orbit by all countries [see Ref. [41]].

3. Research design and conceptual approach

The limited understanding of the potential role of space-based geoengineering in relation to other climate-intervention technologies, along with an under-consideration of key issues such as public acceptability and governance, motivates the design of the current study. We seek to hold up a wider lens to space-based techniques to gain a more comprehensive appreciation of the opportunities and challenges that they present, while also situating such deliberations in direct relation to climate change. We adopt an open approach in presenting the results, letting statements from the experts speak for themselves and structure the discussion. This decision to opt for a descriptive analysis is done for both practical and principle-based reasons, given the novelty of the topic and lack of an appropriate conceptual framework which can be tested.

3.1. Research interviews

To explore the potential opportunities, challenges, and broad rationales for space-based sunshades, we conducted a set of *semi-structured interviews*, also described as “guided introspection”, “intensive interviewing”, or “responsive interviewing” [45–47]. This technique proves useful for comparing or contrasting participant responses to a set of common questions while also allowing discussions to consider and move in other directions and issues on which they may be uniquely situated to contribute. Since space-based sunshades represent a presently niche, nascent topic, interviews of this kind enable us to engage with unique sources of novel data, and to explore how the complicated, emerging developments in this domain intersect with and promote experts’ perceptions, beliefs, and values. Indeed, in their literature review, Keith et al. [6] explicitly called for “theoretical studies to refine the parameter space and map out the feasibility” of sunshades at SEL1. In our estimation, such a call should not be limited to studies of a theoretical nature but also seek to advance discussions and understanding of how diverse participants view such approaches.

We conducted 125 individual interviews with experts closely associated with negative emissions and/or solar geoengineering research, development, and commercialization from May to August 2021. The interview consisted of seven broad questions framed in relation to ten different negative emissions technologies and ten different solar geoengineering options, for a total of twenty options [see Ref. [7]]. We asked, *inter alia*, “What are the critical innovation gaps for space-based sunshades?“; “Who are the most important actors and stakeholders for the development and deployment of this technology?“, and “What are the serious risks that may arise from space-based geoengineering?“.

Recruitment and sampling of experts consisted of a mixture of advocates and critics of negative-emissions technologies and solar-geoengineering methods, while also involving those with direct expertise on space-based sunshades. In general, only those who have published high-quality, peer-reviewed research papers on the topic, or published patents and intellectual property, within the past ten years (2011–2020) were invited. Table 2 provides an overview of the demographics of the full sample, while Annex I lists all the 125 experts who participated. Given that interviewees were speaking on their own behalf, and given the sensitivity of the topic, the data from these interviews is presented as anonymous with a generic respondent number (e.g., R023 for respondent 23). While a quarter of respondents (N = 31) engaged with the proposals of space-based sunshades at least to some extent, this topic was the main focus of six participants. Thus, the assembled quotes do not reflect only those of individuals working specifically on sunshades, but also of those with expertise on climate-intervention technologies in general. Furthermore, we took an ethnographic approach that neither corrects nor problematizes responses, but rather presents the responses in an unfiltered manner (adhering to the

Table 2
Summary of the demographics of experts who took part in our study.

Summary information	No.
No. of experts	125
No. of organizations represented	104
No. of countries represented	21
No. of academic disciplines represented	34
Cumulative years spent in the geoengineering industry or research community	881
Average years spent in the geoengineering industry or research community	7.8
No. of experts whose current position falls into the following areas:	
Civil society and nongovernmental organizations	12
Government and intergovernmental organizations	8
Private sector and industrial associations	12
Universities and research institutes	94
No. of experts from the Global South	12

Source: Authors.

justice principle of recognition), that is, even if our respondents may have had misperceptions on specific points.

Nonetheless, our approach is not without its limitations. As a general point, studies of a qualitative nature tend to not necessarily be fully replicable given that replicating the same set of questions with the same participants may find the opinions or responses of the interviewees having changed in the interim, either because their views have changed or for extraneous reasons related to daily life – and, that is, even assuming that all of the experts would still be available and willing to be interviewed. As a flipside to the granting of anonymity, moreover, there is the tendency for respondents to be more willing to be openly critical of the potential risks and downsides that exist. Crucially, this is not because the authors have selected for only these comments but rather because anonymity itself seems to provide the space for participants to also consider the negative aspects. At the same time, we note that even if respondents were generally more deprecatory than positive, the set of sunshade "entrepreneurs" equally tried to justify their work on or support for this specific technology in an increasingly crowded techno-political space – resulting in a dichotomy between a higher level of criticism from the set of experts as a whole and a more narrowly optimistic view put forward by those working on space-based methods. Finally, with respect to the composition of the expert sample (see Table 2), even though we did conduct interviews with experts from a range of stakeholder groups, the sample is broadly comprised of those working at universities or research institutes. Similarly, while there are a dozen participants from the Global South – characterized by either where the expert originally came from and/or their current location – this number is a small subset of the larger sample. At the same time, both the broad reliance on those at universities and research institutes and the predominance of perspectives from the Global North tends to reflect the broader population of experts researching and/or working on climate-intervention technologies at present. This feature is especially true of space-based geoengineering, given the few countries with spacefaring capabilities. In sum, we consider shortcomings of our sample to be (in part) a reflection of where the discussion is at present but not necessarily how it could and should look in the future.

4. Results and discussion

We group responses from the expert participants into the following analytical themes that emerged inductively from the interviews: climate change and the promise of space-based geoengineering (Section 4.1); feasibility and risks of space-based geoengineering (Section 4.2); and key actors, commercialization, and governance (Section 4.3).

4.1. Climate change and the promise of space-based geoengineering

Many experts spoke to a potential role for space-based geoengineering when it comes to tackling the climate crisis, though opinions were broadly divided on how viable it would ultimately be.

4.1.1. Climate change as a driver of interest and investment

On the whole, there was significant interest among the group of experts in the potential of space-based geoengineering to address climate change, with at least one expert (R031) linking interest in this topic to the recent school-strikes movement:

> Two years ago, I would say I was triggered to the sense of urgency that was created by Greta Thunberg and others that we actually are late in doing climate action. We need to do something. I was asking myself what could space technology do on that?

Even if not focused on space-based geoengineering, another expert (R070) laid out the imperative for further examination of how to modify solar radiation, given that:

> It looks like in the upcoming decades it will almost be unethical to not apply solar radiation management due to the significant damages that we will see to our ecosphere and our planet in general.

When asked in the context of the interview to consider all twenty NETs and SRM options, some experts (R022, R024, R092) noted a preference for such an approach, often given the opportunities it presented for tackling climate change without directly interfering in the Earth's biosphere. For instance, R024 argued that:

> We understand that Earth is a finite system. And we understand that everything we do on Earth has a trade and comes at the expense of something else. And it's only by going outside that system that you can get fundamentally new capabilities without impacting some other value on Earth. And that's, I think, the unique value proposition.

Another distinguishing feature, for R092, was its controllability and reversibility, and that the low costs of other approaches might ultimately be misleading:

> Someone's going to do a cost-benefit analysis and decide, "Hey, we could build these sunshades, but it would be far cheaper to put all these sulphates in the upper atmosphere." That may very well be true. Cost per ton. Cost per erg [unit of energy equal to 10^{-7} J] not coming in. It makes a lot of sense. But once you've put it up there, how long is the latency? How long is it going to be there? If you start having birds fall out of the sky and crops failing, how long is it going to take before you decide, "Oops, we had an unintended consequence," and you try to reverse it. It could take years, decades maybe.

Thus, R092 proposed space-based geoengineering as ultimately being less risky when all factors were considered:

> With sunshades, you fly them out there, and if you have some unforeseen consequence occur, you just fly them off into deep space and you go back to where you were. So, in terms of risks to the planet, I think this is the least risky approach that I have seen. Because at every step it is completely reversible.

Indicating another reason to prefer sunshades or "mirrors in the sky" to options like marine cloud brightening and stratospheric aerosol injection, R041 also noted that:

> … once it is there, you don't have to build it every year, but you have to build it or restore it every few decades or something like that.

Lastly, couching their decision in terms of an ideal world, R022 reasoned that:

> All things being equal, I'd prefer for us to be able to do it with space-based measures, because that doesn't involve putting chemicals into the environment. It's a more universal cooling, and it can be tweaked more easily. Except in this world, I prefer it not to be that, because that would cost trillions of dollars.

Since we are living in a less-than-ideal world, however, R022 concluded that the idea "*should be on the backburner*" for now, while research and development continues to be undertaken. In a similar manner, although not ruling out a major technological break-through taking place in the next decade, both R002 and R008 determined that space-based methods would likely not be practical by the time we would need them to hit net-zero levels of CO2. Having first wondered if space-based methods were a viable, urgently necessary option or "*innovation for the sake of innovation*", R116 ultimately concluded that:

> A lot of people would say if there is this solution that can save us, for instance, all these islands which are being buried by water, they need dramatic fixes. In the West we're thinking, "Oh, in 100 years' time." Those countries are thinking, "We're dying now."

Given its much longer timeline, space-based geoengineering thus seems a poor fit for immediately helping the vulnerable. Hence, a few experts (e.g., R031, R070, R116) interested in space-based methods specified that it must not be seen as a substitute for climate mitigation. This was succinctly expressed by R031:

> The biggest risk, as for all geoengineering, is that if we put effort in such an activity there is the possibility that some politicians may think, "Let's just make a 2 million square-kilometer sail and we can go on with our CO2 emissions …. Plan A for me is always to reduce climate emissions. This is always Plan A. We see this technology only as Plan B.

Organized around the idea of a "climate airbag", R031 argued for a role of a sunshade as part of the toolbox, even setting out the conditions under which they envisioned it working:

> It's a Plan-B climate-airbag solution. It's not meant to stay there more than ten to twenty years … after that it will be removed because, in that time, we need to be able to reduce our climate emissions. If not, you can think again about producing these sails and so on, but I think it's always to be seen as a temporary countermeasure.

Though proposing a slightly distinct scheme, R024 also envisioned a quasi-partnership between space-based geoengineering and another SRM method, notably, stratospheric aerosol injection:

> We're going to have to sustain solar radiation management for on the order of a century. SAI gets you started, but you don't want to do it for 100 years. The sunshade lets you stop doing SAI after a decade or so … and then SAI becomes this fallback position in case you're not able to sustain such a technologically advanced intervention.

Consequently, a further group of experts (R035, R051, R061, R075), even if critical of space-based geoengineering, were keen to stress the importance of giving space to research and development on new options, even those appearing "*batty*", in the words of R35. R061 affirmed that "*everything should be on the table*", to which R075 added: "*Why not? You can always write a PhD dissertation on this sort of stuff*." However, there was also a sense that, at some point, the rubber has to meet the road. R061 insisted that:

> Investments are finite. We cannot put all our efforts in all of them. We have to obviously distribute our time and energy amongst those. And since they do not all come at the same cost in terms of experimentation – the question is how much time and effort should we devote to which?

The implication, as expressed by R035, is that once we look closely at the implications of something like space-based geoengineering:

> It's just not sensible. Your gut feeling will tell you that putting lots of tiny little mirrors at the L1 point is not sensible, but there we are.

Turning this around, R092 (and R116) forcefully argued that focusing only on climate mitigation while failing to develop a countermeasure would not only be a mistake but fundamentally unjust:

> There are some in the environmental movement today who, with good intention – I don't impugn their intentions – want to basically say, "Okay. Full stop across the board. No more increases in carbon emissions. We have to decrease to carbon zero. Go." Well, US, and Europe and Japan and wherever, we can probably cut 25% of our energy usage and still be okay …. But there is a big chunk of the world which doesn't have that luxury. And they're going to need energy to have the same basic quality-of-life issues that we have. And for us to tell them, "To save the planet, you have to be dirt poor forever," is immoral. Totally, completely, 100% morally abhorrent to me.

Even if "*it's a longshot*" (R057) and "*decades out*" from being realistic (R075), multiple experts made certain to emphasize that both the nature of the development and the scope of the climate crisis meant that we would need to start now. Having advocated for seeing space-based geoengineering as a "climate airbag", R031 asserted that:

> … we need to start developing this technology right now because otherwise we will not be able to have this airbag in time when we face the problem of tipping points falling at the latest in, I would say, 2040.

Ultimately, a few experts (R024, R031, R092) invoked past crises and challenges to highlight the stakes involved as well as how societies then had risen to the occasion – whether the United States travelling to the Moon after John F. Kennedy's call, the Human Genome Project, or more recently, the transformation wrought by the COVID pandemic. R092 provided a particularly poignant example, completely unrelated to space:

> The Dutch building all of the dikes and dams off their coast. That would be my analogue. It is something that they decided to do to preserve their way of life and protect their land.

4.1.2. Potential as source of renewable energy and climate mitigation

According to a few experts, space-based geoengineering offered the potential to indirectly mitigate the worst impacts of climate change. Though a host of different concepts were floated, the core idea is that if it were possible to capture (and transmit back to Earth) a fraction of the massive amount of solar energy coming in contact with the sunshade, this could feasibly substitute for the need for energy production on Earth. R024 offered the following summary of one such vision:

> It's not just an inert thing between us and the sun, but something that's photovoltaic and has a phased RF [radio frequency] array on the back and can transmit power back to Earth.

By way of an estimate, R092 declared that the expected amount of energy "*depends on the size of the sunshade that's ultimately put out there, but it's in the Gigawatt to Terawatt class.*" More optimistically, R024 claimed that:

> If you can make it work, you can produce limitless energy for anybody on Earth. Again, I mentioned the sunshade would produce about 70 Terawatts which is about the entire necessary energy that we're projected to need in 2050.

According to R092, such an approach would offer multiple advantages, even versus other forms of renewable energy:

> When you look at that compared to conventional solar panels it is much more efficient for packaging, much less expensive in terms of dollars per watt, and really makes good use of your deployed structure.

In this way, R024 argued that a sunshade could ultimately, on its own:

> address all three pillars of a global response to the climate crisis: it could get you clean energy, it could get you solar radiation management, and it can get you carbon dioxide removal – those other two pillars, by beaming energy back to Earth.

Notably, R024 highlighted the potential to thereby free up land that would otherwise be reserved for massive solar farms, arguing "*those are going to eventually be worth more for their land area than for the photovoltaics they contain*." However, another expert (R104) envisioned a prospect of space-based solar together with more conventional types of "*maximally deployed, distributed clean energy systems*", remarking that:

> I actually think we're going to find space-based solar, despite Elon Musk's objections, is going to appear more attractive than some of these carbon management options.

Though still hypothetical, some experts' insights on how this would work are also indicative. R024 noted RF arrays, remarking that: "*to the terrestrial energy system, it looks a lot like solar*". Another possibility, according to R092, would be to use microwave lasers (or masers) to transmit back to Earth:

> What you do, is you take your sunshade, and you cover it with photovoltaics. You couple that to a microwave beamer, or a laser beamer, and you beam the energy back to earth. That's not as far-fetched as it sounds … a flight experiment will fly next year for a project called LISA-T: Lightweight Integrated Solar Array and Antenna. Basically, it is taking state-of-the-art, thin-film photovoltaics and putting them on our solar-sail substrate and deploying a little sail and taking that power and powering the spacecraft.

Separately, they also noted that an intersection with other initiatives in space:

> NASA is actually looking at using lasers to beam power to robotic spacecraft in the outer solar system. We're not doing that anytime soon. It's a study. But it's being examined seriously because of all the breakthroughs in laser power.

4.2. Feasibility and risks of space-based geoengineering

The question of exactly how much space-based geoengineering would cost as well as the types of risks it posed were both frequent points of discussion. Whether costs might prove to be an insuperable obstacle for such efforts was however a point of disagreement.

4.2.1. Costs and financial risks

Several experts (R020, R031, R057) first noted that the notion of sunshades or mirrors in space has an extensive history. For instance, R031 observed that "*initial ideas were coming up already 30, 40 years ago from NASA*." In the end, though, R057 concluded that, after brief consideration, "*space interventions* [were] *hastily rejected after some back-of-the-envelope calculations based upon then-current launch costs*." R020 similarly offered that space-based methods were "*quickly disregarded*" when the costs were resolved to be "*astronomical*".

Meanwhile, for others like R069, the notion of space-based geoengineering was classified as one of the "*crazy ones*" not worthy of consideration:

> I'm not going to speak about space mirrors or anything, that's a little beyond what anyone who is really seriously working in this area is writing about these days.

Using even stronger language, R085 put forth:

> They're lunatic. Is that sufficiently clear? I don't think they're worthy of our serious consideration, both on technical and economic and other grounds.

Labelling it a "*crazy idea*" (R031) and "*insane*" (R081), respectively, R031 and R081 focused on the magnitude of the effort that would be needed to have a space mirror at SEL1:

> *This thing would be huge, it would be 1 million square km, three times the size of Germany …. You build these shades on Earth and then you send it up via a rocket and travel it to SEL1. But if you look at that you need millions of rocket-starts to bring up the pure mass of these things.* (R031)

> Think about the pay load these people have to shoot out into outer space … a typical rocket is a few hundred tons and carries a payload of two to three tons. Even if you take all of the rockets and all the missiles in history, everything we have shot out to space, I would really like to know how many tons we have cumulatively done in history compared to the weight of this one satellite. (R081)

In fact, R070 could provide an answer to R081's question, noting that in order to:

> reduce the incoming solar flux by 2%, for a period of 20 years, we would need to launch between 30,000 and 2.7 million spacecraft …. At the moment I think the number of spacecrafts that have been launched in total is something around 20,000. So we would need the same amount of launches that we have had in the history of humanity. So it would definitely be a significant increase.

For R114, it was the advancements which would be needed for this idea to become feasible that were troublesome, such as "*setting up a Moon-based economy*." Also, R070 tipped the challenge of "*communication with such a system … because of radiation coming from the Sun disturbing signals*", and R035 highlighted the energy needed "*to launch them up there continuously because they wouldn't stay there*" – referencing the quasi-stability of L1. In addition, another challenge highlighted (R057, R092, R106) was whether the positioning and control of sails could be maintained effectively and cheaply enough to keep it flying. Notably, R092 observed that:

> … these big sails will not be perfectly flat, you're going to have all sorts of distortions and sunlight pressure-induced disturbance torques across this big structure.

To several experts (R002, R008, R011, R091), such issues offered sufficient cause to relegate the idea to history's dustbin. R011 encapsulated the prevailing critique thusly:

> The way I look at it, space-based reflectors are so speculative and so potentially expensive and dangerous that they're not going to be implemented any time in our lifetime so I, sort of, dismiss that as anything that might actually happen.

Occupying a more middle ground, the costs and long timescale were not necessarily a reason for outright dismissal for some, even if they were reluctant to offer full support. For instance, R075 framed the matter in relation to other activities in space:

> We keep sending vehicles to Mars. We don't really know why we are doing it. It's fundamental science, and it's cool and awesome, so why not sort of prime for something like this? Basically, you could imagine one of the next NASA probes is some vehicle that we sent to the Lagrange point, and figure out whether we can suspend it there and keep it there for a while, and take a bunch of pictures, and then the thing disappears.

At the same time, there was pushback from many experts (R020, R024, R031) on what they saw as the mistaken tendency to describe cost as something fixed and unchanging. In the first place, R031 claimed that the final figure "*depends on the possibilities and the technology that we have available*". A number of experts (R020, R024, R057, R088, R092, R097) cited developments and the recent transformation in the space industry in terms of technologies and the involvement of new actors (Fig. 5). R020, R057, and R116 acknowledged how commercial interests have re-awakened interest in space-based methods, with R057 pointing to "*privatization and the tenfold-fall in launch costs*" and R116 marveling at the massive increase in satellite launches:

> Since 1957, the United Nations Office for Outer Space Affairs has 11,000 objects on its register … But in the next decade, 100,000 satellites have been set to be launched. They're received licenses for that. That's a 10-fold increase. … Once upon a time, if you told people we're going to be launching 100,000 satellites in a decade, they would have never believed you, because we only launched 10,000 in 50 years.

In response to their own question of how to bring down the costs of getting materials out to L1, R106 mused that:

> We have seen interesting developments of private space-service providers reducing costs of launching stuff into space. Nobody would have thought about this huge network of satellites or communication just 10, 15 years ago. We have seen interesting developments of cost reduction in the context of space, so I would not rule out that technology.

On this point, R092 was eager to provide historical context of how the technological frontier can shift quickly. Espousing a "*Moore's law for solar sails*", they described how sails evolved over a decade from the NanoSail-D at 10 m^2 to "*Solar Cruiser [at] 1600 m^2 … and the design is scalable up to 10,000m^2*", bringing us ever closer to the size needed for a sunshade (R092).

Furthermore, many experts (R024, R031, R075) wished to state that any costs, even if in the trillions, would not have to be paid as a lump sum – but in a graduated fashion, depending on how the technology performed. This view was best expressed by R031, who observed that:

> To develop these technologies you need to go in phases. The first phase we are currently looking at is really pure technology development. This is also the phase that will not cost so much money … This technology-development phase is planned, I would say, for the next 10–15 years to really then decide, "Do we have all the necessary technologies together? Is it possible to build such a system? If yes, what does it cost?"

In their view, most of the financial commitment would only come in ten or fifteen years with the decision of whether or not to "*build up the Moon factories and the Gigafactories in space to do the mass production*", with the aim of having the initial sails ready by 2050. Instead of speaking of trillions of dollars, R075 contended that costs for the foreseeable future were more in the range of "*tens of billions of dollars*". In fact, continuing in this vein, R024 remarked that, under the auspices of the Artemis Accords, the new coalition collaborating on returning to the Moon, "*the billion or so to get started is already being spent, it's already on the roadmap*". In other words, it may not even – so they argued – require any new money to be spent.

Lastly, according to two of the experts (R024, R031), it is this context and reference to space and other large-scale projects that is crucial and frequently omitted. With reference to the US fighter-jet program, R031 emphasized that development "*has cost $1 trillion, just for one fighter [while] the damage that is created by going from 2° to 3° per year is around $1 trillion to $1.5 trillion.*" In view of the extensive risks of climate change, and while allowing that the costs will be "*incredibly expensive*", R024 turned to a quote from former President Lyndon Johnson to emphasize where they felt the priorities should lie, and highlight the capabilities of state actors:

> To paraphrase Lyndon Johnson, "Trillion here, trillion there, pretty soon you're talking real money." We spent $5 trillion on Coronavirus and we're coming out of it stronger than ever. And this just goes to show, "what is money from a state perspective?"

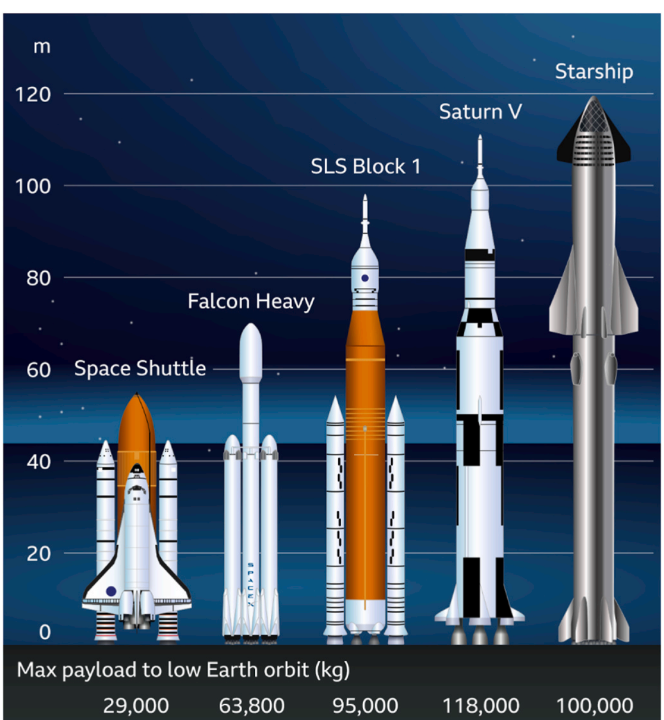

Fig. 5. Maximum Payload Size in the History of Space Travel. Source: [48]. While the maximum payload that can be transported has increased greatly, from early days to SpaceX's new reusable Starship system, it massively lags what would likely be needed for deployment of a sunshade.

4.2.2. Climate modelling and environmental risks

Beyond the costs and financial risks, experts pinpointed potential environmental impacts, though not as often. First, a few experts (R041, R070, R092) highlighted how little we currently know, with R092 citing the lack of "*detailed, credible climate models*". Drawing a line between space-based geoengineering and solar radiation management techniques like marine cloud brightening, R041 underscored the common issue of uneven changes in surface temperatures across the globe, whereby cooling in the tropical regions might occur alongside warming at higher latitudes. Noting the complexity of the climate system, they argued:

since temperature differences are what is driving the wind system and the Earth's climate system, then, for example, the monsoons could collapse. You see, at the moment, due to climate change, the monsoon is getting stronger, the rain is getting stronger, hurricanes are getting stronger and so forth. That could lead to a collapse of the monsoon system, which would leave 2½ billion in India and China, without solid food bases.

R092 indicated another reason for concern:

> There are very big differences in how heat deposited by the sun affects temperatures and climate at the equator versus the poles … If we decrease by 3.5%, is that only going to benefit people at the equator? Is it only going to benefit mitigating the effects at the poles? Is it going to be evenly disturbed across the globe? Is it going to be 70% of the effect felt above latitude Y?

R033 however disagreed, noting that:

> The first climate-model analysis that was done two or three years ago did show that the reduction of the temperature is more or less equal. It will be a little bit higher on the equatorial area, so the reduction is a little bit more there than on the poles. There is also very limited impact on other things like rain. There are no dramatic changes on the Earth's climate from the sunshade.

Here, R033 seems to be referencing the findings by Sánchez and McInnes [31], but it is worth keeping in mind that the climate modelling by Lunt et al. [27] did signal potential for regional disparities, mostly in terms of temperature and precipitation. Moreover, another lingering issue is the extent to which a risk would need to be only plausible rather than scientifically established to elicit concern. Taking together "*the difficulty in attributing changes in environmental systems to particular actions and then the whole background of misinformation, conspiracies, and what not*", R007 speculated that:

> Say you put up a sunshade or some sort of mirror, and then something else happens, somewhere in the world, and then people are going to attribute it to that. They're going to draw a direct line between A and W, regardless how many points are in between.

Indeed, a further concern from R041 was the effect that modifying solar radiation would have on crop health, among other effects, arguing that there is a need to ask:

> *"What are all the effects of what is getting in?" From vitamin building in the human skin to harvests in the field, to ocean currents and the wind system, and whatever else. All that would be affected by reducing the incoming radiation.*

Pointing to questions like this, R007 thus asserted that such uncertainty not only posed additional political and social barriers to acceptance and funding, but could even prompt liability lawsuits:

> In a typical tort case, the science just has to be plausible, it doesn't have to be proven. So, you could get any number of climate scientists just coming in and saying, "Oh yes, this mirror up here, that's what worsened your almond crop in California, so we'll give you damages."

Other experts (R024, R070) mulled over the potential of coronal mass ejection or solar storms to damage the sunshade. In particular, R024 wondered if a sunshade would "*be robust in the face of something like a Carrington Event, one of these once-in-a-century, once-in-two-centuries events that just really messes up everything in space*." While difficult to model, such unexpected events could make it risky to count on a sunshade in the long term, especially in view of its prospective costs and resulting termination-shock effects if it were to suddenly be removed. For this reason, R024 emphasized the need for and relevance of on-Earth testing of "*static loading*" and "*how do they behave in certain sun storms*" to better assess the prospective risks and to develop potential countermeasures: "*maybe in a solar storm situation we need to move the sails out of the center and reduce the sail area facing to the sun*."

For R081, the fact that space-based geoengineering ignores the levels of carbon dioxide was also a crucial issue, one that they saw as symptomatic of all SRM options:

> What do you do about CO2? Let the oceans turn into vinegar and say we have solved the problem? I mean, it's even more one-sided as a technology … So what are we going to do about the CO2 problem then?

Nonetheless, according to R024, the greatest risk would be that "*you can't build it fast enough*" given the mounting impacts of climate change. In comparison to such risks, R024 dismissed any others, e.g., for biodiversity, that may result from a sunshade. Interestingly, they also pointed to a coupling between a sunshade and stratospheric aerosol injection to speed up climate intervention while having an option in case the sunshade should fail for whatever reason:

> Space-based climate intervention is very much a complimentary technology to, specifically, stratospheric aerosol injection (SAI). And having SAI as a developed and deployable technology provides you a backstop against … both not being able to move fast enough and of termination shock. And there are a lot of reasons why you might have a termination shock from some architecture that is fundamentally based on access to space. We almost lost access to space in the last century, it's not assured.

This idea of "access to space", raised by R024, moreover resonated with important philosophical considerations introduced by R116. Notably, what is valuable to us, to humanity, when we think about the "space environment"? Is it just that we aim to mitigate space debris to avoid collisions, in which case R116 suggests we need to stop thinking of space as being boundless and infinite:

> With all these mega-constellations, and all of these new infrastructures filling up the space environment. We would have to be as equally conscious that the space environment also has a carrying capacity, which people don't think about because they think that space is huge. But the spots where you would want to use have a carrying capacity. And that needs to be calculated.

R116 continued that, if we started to think in terms of "carrying capacity", this would necessitate difficult decisions about tradeoffs between competing interests. Recall the statement by Kennedy et al. [4] on GEO as the most valuable "real estate in cislunar space", which probably means it should be reserved for communications and climate-monitoring satellites. More provocatively, R116 considered what it would imply to think of "*the space environment as one that is worthy of protection*", before raising some of the immediate objections that could be expected:

> It's a hard case to make because space is so hostile. When something is hostile, it seems difficult to say that it should be protected. Protected from what?

At the same time, R116 highlighted an unintended effect of SpaceX's recent activities in raising appreciation of the space of the environment, notably, by prompting outcry from the astronomy community. Ultimately, even while themselves finding the prospect of interplanetary travel and bases on the Moon (see Section 4.3.3) to be attractive, they concluded by remarking generally:

> I think the lessons that we learned from Earth is that if you don't have a sustainability mind-set from the very beginning, you will end up reaching carrying capacity, and then you're going to be scrambling to figure out what do this.

4.2.3. Military and weaponization

Another common risk that was discussed related to the potential for military involvement and/or weaponization. On this point, some experts (R003, R057, R064, R070, R081, R092) could be seen wrestling with the vulnerability of such a large object, drawing on key cultural touchpoints to do so. For instance, R064 predicted that:

> The one thing that I could see in a real sci-fi future warfare kind of way is low-orbit solar shields, straight out of 'The Simpsons', where you've got the ability to specifically target a solar shield over a particular region.

Similarly, R081 evoked the James Bond film, "Diamonds are Forever":

> The shading satellite can perhaps also be manipulated, so that the shading affects certain hemispheres more than others, producing cold in a new kind of Arctic seasonal cycle outside the seasons. You can shade the Northern Hemisphere in summer and perhaps then we

> will have no summer and we'll have a winter, or something else, who knows what these guys can come up with. The possibility of abuse is enormous.

Keeping with the sci-fi-inspired approach, R024 identified the risks should a sunshade fall into the wrong hands:

> There is this dictum in science fiction: basically, anything big enough to be interesting is also big enough to be oppressive. You have to make architectural decisions that make it not a weapon. It needs to be not a weapon, it needs to be not weaponizable, it needs to be placed within a security architecture where its peaceful use is assured.

Thus, R070 entertained the risk of one of the control centers being the target of a terrorist attack, leading to partial or complete loss of connection to the sunshade. Even then, according to R024, such an issue could be mitigated through technical-design solutions such as allowing a system to "*revert to local control*" – where, in the event of a crisis, a cohort of nearby personnel would be in place to take over manual operations – or making it "*disaggregated into … an uncountable number of elements*". At the same time, solutions of a political nature would also need to be considered, such as ensuring a sunshade "*not be disruptive to the balance of power on Earth*" (R024). Citing its conflict-increasing potential as a reason for opposition, R003 forcefully stated:

> I don't care for sunshades, they're all too high-tech. They can be used for military means. They're against the ENMOD treaty.

Here, they explicitly referenced ENMOD, or the Environmental Modification Convention, a UN-level treaty in force since 1978 that expressly prohibits military or hostile use of environmental-modification techniques with widespread, long-lasting, or severe effects. Signatories include the United States, Russia, Canada, Brazil, India, and a number of European countries. Moreover, given the potential consequences of geoengineering techniques in general, and of space-based methods in specific, for the environment, biosphere, atmosphere, and so on, there are questions of whether compliance with ENMOD may entail significant restrictions on the use of such activities (or even their experimentation) – e.g., if any restrictions would be placed only on activities undertaken for hostile purposes or if the occurrence of (adverse) environmental impacts, even if unintended, are sufficient grounds for their prohibition.

On a more mundane level, R116 wanted to understand where the related infrastructure would be situated on Earth: namely, the ground stations and receiving stations needed for communication, the landing rights, or even the equipment needed to collect the energy transmitted back to Earth (see Section 4.1.2). Specifically, they noted the need to get permission from the countries involved as well as, more generally, the fundamental lack of attention to how things might change on Earth:

> It's one thing to put this infrastructure in space where it feels like, "Well, you're not harming anyone. Space belongs to all of humanity, so you're not taking anything away from someone." But the networks that it connects with are going to be here on Earth.

Moreover, in contrast to the optimism of R024, R070 posited that bringing more actors into the fold could theoretically exacerbate rather than mitigate the level of risk:

> Options that depend upon the expansion of an aerospace or space industry are a security risk, as you are bringing high-tech space industries into countries that don't normally have them. Players gain new capabilities that they didn't have before, and these could spill-over into an arms race or new technology being available to new actors.

At the same time, several experts (R024, R033, R070, R092) were dismissive of the prospect of a sunshade itself being the target, whether by rogue actor or terrorist group, noting the distance from Earth, how much spacecraft would be needed, etc. For instance, R024 underscored that:

> It's a very large structure. It would take a mature and robust space military capability to bring that down. It's four times farther than the moon, so no power without access to space is going to be able to get at it, except in terms of a cyber vulnerability. I think that it's possible to architect it to not be particularly cyber-vulnerable.

Indeed, R092 explicitly wondered what reason or motivation a terrorist group might have to want to target a sunshade at SEL1, even if they had the capabilities needed. R070 therefore suggested that (unfortunately) there would be other, better options available to them:

> For example, if you look at stratospheric aerosol injection, this is much easier to implement by a single rogue nation instead of developing a space-based system.

Even in the case of a cyber-attack, two experts (R024, R092) were not all that concerned. Indeed, R092 recalled a past incident where exactly this happened for support, stating:

> Of course, it could be taken over. Bad actors have taken over satellites already … Nothing really bad has happened from it. The stories I've heard are that they took control of it and didn't do anything but let everybody know we had control of it. That's been fixed. Things are now encrypted. You've got a lot more security for that kind of thing.

R024 was similarly sanguine on the prospects of dealing with a possibly hostile actor like Syria or North Korea, before ultimately offering "fallback positions", such as pairing a sunshade with something like stratospheric aerosol injection:

> That's why you keep stratospheric aerosol injection in the back pocket. And that also speaks to how you can discourage … I'm not going to say rogue nations, but disgruntled nations …. But if those were disrupted, then the balance of power on Earth would be able to resume stratospheric aerosol injection.

4.2.4. Social license to operate and social acceptability

This then brings us to the matter of the public and whether the idea has a social license to operate, or instead if it will engender perceptions of social rejection. Regarding the public's reaction, many respondents were fatalistic given prior experiences plus the aborted SCoPEx trial (R085) [see also [49]]. R024 expressed uncertainty about the prospect of getting everyone to agree on any one course of action, before noting there are "*some communities who simply have a sort of spiritual connection that rejects interference with nature, and that's something that they're entitled to and we have to accept and to work with.*" Reflecting on one instance, R031 declaimed forcefully that:

> … most of the climate-oriented people … tell me I am crazy because they always say, "Let's stop the emissions and then we don't need that damn technology stuff. Technology has brought us to the situation. We don't need technology. Let's go back to the Stone Age."

In contrast to the deep-seated pessimism of these quotes, other experts were of the opinion that the fantastical aspects of space-based approaches could actually captivate the public. Sketching out a point of distinction with CDR methods, R35 supposed that:

> … because it's like science fiction, and because they've seen a lot of science-fiction stuff and it's quite easy to understand – you put this mirror up there, and it reflects the sunshine and, "Good, we've got a nice parasol and we're all keeping cooler" – that side of things might be acceptable, whereas some of the more technical carbon-dioxide removal-type techniques might not be understandable.

Of course, they were also quick to remark that, as soon as discussions turned to "*cost and who's going to pay*", then perceptions might not be so positive. For R116, the crucial consideration was the extent to which the public and other societally relevant issues were taken seriously, not least as space-based geoengineering is likely to ultimately come to represent "*critical infrastructure*":

> It's okay to do technical fixes, so long as you're carrying people along and carrying society along. That's probably where I'm at because I'm not a critic of technology. What I'm a critic of, is not building society at the same time. Or thinking that because we've got the technology, we're saving the world.

That being said, R092 lamented that it was not just the public but possible scientific collaborators who might react aggressively. They offered the following anecdote:

> When I proposed putting in some information about the sunshade, this person said, "If we do that, I won't work on the book, because that's not the answer. The answer is to stop putting out carbon." It was a dogmatic, basically disappointing answer from a scientist. It was extremely dogmatic. So yes, I think there may be some who say, "This is an excuse not to reduce carbon output. You're still feeding the problem, therefore don't do it. Or if you do it, we might do something to sabotage."

4.3. Key actors, commercialization, and governance

Experts described the relevance of a diverse, though relatively narrow, group of actors from both the private and public sectors, focusing in particular on those in the so-called spacefaring nations. The ways in which the actors would interact with one another, as well as the kind of governance approaches that would be appropriate, were however a source of divergence.

4.3.1. National governments, spacefaring nations, and governance

On the topic of the key actors, there was broad agreement among the experts. First and foremost, owing to the capabilities required, the great "spacefaring nations" would play a key role (R024, R070, R075, R088, R090, R092). Countries like China, Russia, the European Union and the United States – specifically, ESA and NASA, the space agencies of the latter two – were thus mentioned frequently, along with those such as South Korea, India, and Japan. Due to the scope of the project and severity of the climate crisis, several experts pointed to the need for collaboration among these countries (R024, R070, R075, R088), but the question of what form such collaboration would take was less clear.

Many experts (R024, R031 R092, R116) were however quick to highlight the manifold gaps in governance that exist at the moment, with R031 summarizing the situation thusly:

> There is no United Nations climate authority, whatever you call it. But in the end, at a certain time point, I would expect something like this because you need to find a way to set up governance for these things. Today there is no governance for that.

Accordingly, R088 indicated the need to set up a new group that could facilitate collaboration, drawing on a fictional example for inspiration:

> There was a movie where they [wanted to] colonize Mars, and then, on Earth, they had this global thing almost like the UN, but it was all about the colonization of space. I think you would have a similar foundation that would be staffed by delegates from all around the world, that would represent each one of these major space agencies.

To this end, two experts (R024, R70) stressed the need to avoid any sunshade becoming a source of conflict (Section 4.2.3), with R024 proposing a design approach that promoted inclusion:

> It could be, and should be, split up into several parts. You could have a North American element, a European element, a Chinese element, and an Indian element. And these could exist under a treaty organization, where they are working together towards a common climate goal, but also supporting their own nationally controlled security architectures that balance each other out to stabilize the security posture on Earth.

Finding inspiration (or lack thereof) in the status quo and existing arrangements, R092 noted that the International Space Station offers an actual case of an "*international collaboration [between] former adversaries, competitors*". In particular, R031 noted that:

> Europe has provided a certain element to the ISS, the Columbus module, but there are also Russians working on the ISS. There are Americans, Japanese, and so on. The same needs to be true for setting this up

From the perspective of the United States, R092 also pointed out that:

> When it comes to certain elements of export-control laws and ITAR [International Traffic in Arms Regulations] restraints, the collaboration with the Russians on the International Space Station is explicitly exempt from that law, by law: things relating to the maintenance of the ISS. That is an existence proof, in my opinion, that should such a collaboration be deemed strategically important, there could be ways to get around some of these laws that countries have which restrict collaboration and partnership.

Were such an exemption not readily extended to the development of a sunshade, this would pose tremendous obstacles for collaborations between the United States and, say, Russia or China. On a less positive note, R092 then went on to examine the notable lack of international collaboration around the mitigation of space debris:

> To me, that is the canary in the coal mine …. because we are all polluting space with debris, and we need to mitigate it and keep it from getting worse. There are some agreements internationally. There are self-imposed policies that countries have agreed to place on themselves, and other countries have not. If we can't even agree not to junk up lower-earth orbit, I would have difficulty believing we can agree to collaboratively build these big sunshades.

Although perhaps undermined by the subsequent Russian anti-satellite missile test in November, R092 was relatively positive at the time that an approach of self-policing could work well – even if notable countries such as China have not signed on. Consequently, R024 and R070 highlighted an explicit role for the United Nations, under the auspices of which such a "*hegemonic sunshade authority*" could operate. R070 explicitly mentioned this could ensure that "*every country in the world would have a voice to express their opinion and their desires concerning such a system.*"

Rather than a forum only between countries, however, R116 envisioned a need for a governance structure to manage disputes among communities and their interests, i.e., over the use of space:

> From a governance standpoint, right now the astronomy community are fighting with the space community because the astronomy community are saying, with all these satellites and all these objects going into space, we're no longer going to have clear skies. Clear skies, dark skies are part of humanity's history. Should we have more concern for astronomy? Or should we have more internet satellites?

Meanwhile, other experts (R031, R057, R088, R116) viewed a supranational body as crucial for mitigating the harmful and unequal outcomes that may occur, most notably, to the Global South. R031, for instance, questioned:

> If some countries, let's say, there is a coalition of a willing 20 countries that want to start developing this technology, then they will do something that has an impact on the whole Earth. How can you ensure that you have strong agreement of all people involved?

Similarly, R057 offered a "*direct democratic critique*" that highlighted the risks of such an object being under "*completely concentrated technocratic control*" – albeit in the context of a sunshade at LEO or GEO which could be regionally targeted. According to R024 (and R070), this pointed to yet another reason it was crucial to have more actors involved:

> What's different from this space race to the last is that it is intended to be a commercial domain and not just a national domain. … and I can only speak from my perspective as a liberal member of it – but the Global North wants everybody to be involved in the space arena, we want commercial space actors from every nation to be involved, and we want them to be able to conduct their business peacefully, under a strong security umbrella.

Instead of just one past space era having existed, R116 distinguished four, with the fourth, which they called "Space 4.0", denoted by a "*new democratisation of space where you have companies, and developing countries, and all these actors all going into space*." Indeed, the hope of R116 is for the current era to give way to a new one which would no longer be driven just by technology:

> We have to be thinking about human rights, and equity, and justice, and all those things. Which is not about technology. All those things that we want in the future of space, which is for people to be able to live, work, and be in space. Technology is not the challenge. It's the social aspects that are going to be the challenge. Because we have all these social problems here on Earth, but on Earth, at least you can be independent from the system. Once you get into space, those social issues are ever more important because your life completely belongs to the company, or the country, or whoever took you there.

4.3.2. Private actors, commercialization, and investment

For all these reasons, there was substantial interest among experts in how to involve the private sector (R020, R022, R024, R031, R070, R088, R090 R092, R097, R116). What is more, due to growing investment in launch capabilities and space tourism, the same firms tend to be mentioned by experts: Boeing, United Launch Alliance, Airbus, Raytheon, SpaceX, Blue Origin, OHB, and Virgin Galactic. Similar to the list of countries involved, the initial stages of the development and deployment of a sunshade is set to be dominated by a small group with the necessary capabilities – indeed, to R092, the private firms could be seen as an extension of the big spacefaring countries, representing another mode of their involvement. What is more, R116 envisioned these "*big ticket*" items as being of the kind that would be readily attractive to larger firms looking to maintain their relevance:

> Working on geoengineering stuff takes a big company. It takes big resources and things like that. So, it's an easy way to stay ahead of the game because you know that there won't be many competitors.

Pointing to how things are typically managed in the space sector, multiple experts (R024, R031, R088, R092) remarked that, even if the private sector would be handling the actual activities, this takes place "*under the direction of international and national supervising organizations*" (R024). Describing how such a process works, R031 commented that:

> The actors will need to come of course from the space industry. But in the end the space industry is not the customer for these things. They are just actors in terms of executing.

Furthermore, due to the scope of the project and the number of components, both R031 and R088 sketched out just how extensive even the bidding and awarding of government contracts to work on sunshade development could be. R031 proposed that:

> For something like this you are going to have a million subs [subcontracts] that are out there, each bidding on a small piece of it, that are all private.

The optimism of various experts stemmed partly from what they saw as the potential profitability of the nascent space industry. R097 pointed to synergies "*with space exploration, space tourism, space mining, the lunar-landing industry, and rockets or high-altitude vehicles that could get into the stratosphere*", before explaining:

> It's going to be a profitable industry, starting out with space tourism. And then it may be profitable by going to the moon again. It will be profitable eventually when we start mining asteroids.

In fact, R022 wondered whether much direct funding on space-based geoengineering would even be ultimately required:

> because the innovations will come from people who are working on space stuff for other reasons, to get stuff into space more cheaply for their own reasons, and this technology would piggyback off of them.

Similarly, describing the potential circumstances and motivation for the private sector taking the lead, R092 underscored that:

> If there's a profit to be made … if there's gold in those hills, somebody is going to go digging.

Still, a number of experts (R031, R061, R081, R088, R092) were unsure if these efforts would pan out. In strong terms, R088 declared that:

> There is no business case to be had, so the private industry isn't going to go after it.

On this point, R081 saw a potential reason for concern from a government perspective, even if it were to be undertaken by private firms:

> Let them lose their money. But with Airbus and Raytheon, it's very likely to be public-sector money.

Furthermore, bundling space-based geoengineering with ocean iron fertilization and stratospheric aerosol injection, R061 criticized the viability of options that offered no co-benefits to other actors, before concluding: "*It would need to serve climate mitigation or it's a complete waste of time.*" R031 similarly stated that, from a private-industry perspective, there is: "*not a real business case because the implementation of such a thing is so far away.*" Instead, to the extent that business opportunities do exist, these are exclusively of a "*short term*" nature relating to the development of the new technologies. As a result, R031 remarked that the researchers involved, including those working for private firms, have to do so on a limited or even voluntary basis. On this point, R024 identified a few such groups in the research space, underscoring (along with R070) the global nature of such efforts:

> There is an American group, they've been doing it for 20 years. They're called the Dyson Dots group. The Chinese are working generally on low-Earth orbit sunshades [along with] bridges with Latin American researchers to bring them in.

Nevertheless, this raises the broader question, in the words of R031, of: "*Who is paying for it?*" In response, R024 and R092 concluded governments would have to step up and lead the way. Still, at least one expert (R070) was optimistic that private firms would continue to play a role in investigating and developing potential solutions, despite the absence of any obvious business case:

> Normally in industry that is not really how we go about things. Normally we try to make a buck where we can, and this time we were

really asked to just provide an answer. So, yes, it is a nice position to be in for once.

That being said, there was one domain in which the two experts imagined that a business model may exist: renewable energy (see Section 4.1.2). In characteristically glowing terms, R024 called it: "*the most exciting thing about the sunshade* [that] *would enable commercialization of space-based solar power as a spin-off.*" Mention of spin-offs refers to the potential for certain concepts of a sunshade project to potentially even become self-financing through the production and transmission of solar power back to Earth. According to R024, it is this possibility of providing resources and necessary goods that is not only often overlooked but would help to attract funding to this new (extra)geographical and technological frontier:

> All frontiers finance themselves by providing goods back to the home country. You have to have something to give back to where the money is to get the money to flow. And this is a thing in the space-research community that nobody has truly figured out. Everybody has an architecture, but nobody has a really solid demand driver for why somebody would want to invest the billion dollars to get started or trillion dollars to really mature the economy.

4.3.3. Prospects of a moon economy

One notable point of difference, especially among those working on space-based geoengineering, is the extent to which viability depends on the existence of a Moon economy. Indeed, R024 argued that setting up operations on the Moon was one of two critical hurdles for a sunshade to be viable:

> One of them is reducing the cost of launch from Earth. And the other one is learning how to make use of the resources in space, because you can't just take it all as a camping trip with you.

In this vein, many experts (R024, R088, R092) outlined the general difficulty of launching into space, let alone on the scope envisioned. For instance, R088 pointed out: "*There are very minute windows of time in different positions that you can launch things from space*". Thus, the issue of timing adds another layer of complexity for managing the logistics of getting a sunshade up and running. Moreover, four experts (R024, R031, R088 R092) underscored the availability of all the necessary resources on the Moon – whether solar energy or production materials – and without the consequences that can attend to mining and manufacturing on Earth. According to R024:

> You cannot beat the mass-to-weight, you cannot beat the cost, you cannot beat the ability of just making it with local resources. All you need is metals and silicon. So solar is just a wonderful, wonderful technology for space, for these kinds of large-space projects.

In continuation, R031 set out the ultimate vision of what a Moon economy (or "in-space resource utilizations") would entail, describing the "*mining process to get the regolith out of the moon, the necessary metals, for example, aluminum, lithium, titanium*" which would be the first part. Then, after transporting the raw metals into space, there is the manufacturing process set up at SEL1:

> In the end you need to set up Gigafactories in space [which] need to be mostly automated but also manned – astronauts need to be there to do the unforeseen things because automation is one thing, but the automation can break. It's like if you look into a car factory today. Of course, there is much [that is] automated but there are still people. We also need to have the same thing in space.

Nonetheless, R088 clarified that, even if certain individuals would be "on site", operations would still have to be principally automated:

> It would have to be robots and stuff because, at the scale you are talking about, we are not going to send 100,000 people into space to colonize the Moon to run all this. You would keep it much smaller and then automate as much as possible through robotics that are, again, probably powered through solar powers.

On the other hand, some like R092 were reluctant to tie the fortune of space-based geoengineering too closely to the prospects of a Moon economy (Fig. 6). Indeed, they listed off developments that some experts have proposed, such as asteroid mining (Fig. 7) and mass production in space, which would first need to work properly. Framing things in a more personal manner, they offered a warning of the risks of banking on the "miracle" of Moonbases:

> I've been waiting on my Moonbase since 1971 … I don't mean to be a pessimist, but I think if we wait until we have this miracle to occur, where we have this industrial base in space that can do something like manufacturing fine, thin films and photovoltaics, it's not going to be in time to do anything.

In fact, R092 put the timeline of when a Moon economy could be expected at a century or more:

> If it were 100 years from now, under the most optimistic scenario of SpaceX, Blue Origin, and governments and the Artemis Accords, and the Lunar Village, and everything else, and we had a lunar infrastructure, I would be telling you, "Oh yes. Let's do it from the Moon." But I don't think we have 100 years. So, I'm skeptical of putting the Moon in the critical path.

Indeed, even some strong advocates for an in-situ, space-based approach (R024, R031) were also clear-eyed about likely obstacles. R024, perhaps the most optimistic of all experts, commented:

> To be transparent, it's all innovation gaps, nobody has made use of space resources. The largest thing we've ever put into space is about 100,000 times smaller than a sunshield.

On this point, R088 specified that the largest thing "*we've actually put together and assembled that lives in space*" is the Interplanetary Space Station – though this is in orbit around the Earth. Regarding the prospect of a mirror or sunshade larger than this, R088 commented that:

> We used to have a saying that before you could build an aircraft, you had to build enough paperwork to fill three times the volume of the aircraft you are building. This would be a different order of magnitude to that, so just the amount of time, the schedule for this thing would be insane, the risk of the timeline. I don't think anybody would have any clue and whatever schedule anyone came up with, I would be willing to bet money off the bat that it is going to be too short and it would take significantly longer than what they think.

For this reason, an implicit consensus appears to be emerging that a "hybrid approach" could be the way to go, especially in the near term. Here, while calling for "supporting *and advocating the building of an in-space infrastructure*", R092 (with R088) underscored that doing everything on the Moon should not be the default. Rather, the crucial consideration, in R092's words, was what the overall environmental impact of any space-based approach would be:

> If it's a net positive in terms of benefit to the environment – after you take into account how much it costs to launch, what particulates the rockets put into the air, etc. After you do all that, if launching a sunshade is a net-green positive, even if it's from the Earth, it's still worth doing.

Similarly, R088 stressed the difficulties of setting up manufacturing operations on the Moon:

> Getting stuff from the Earth to the Moon to be able to start manufacturing on the Moon, it is really pricey … then you have to get it from the Moon to somewhere else in the space, so it goes back to

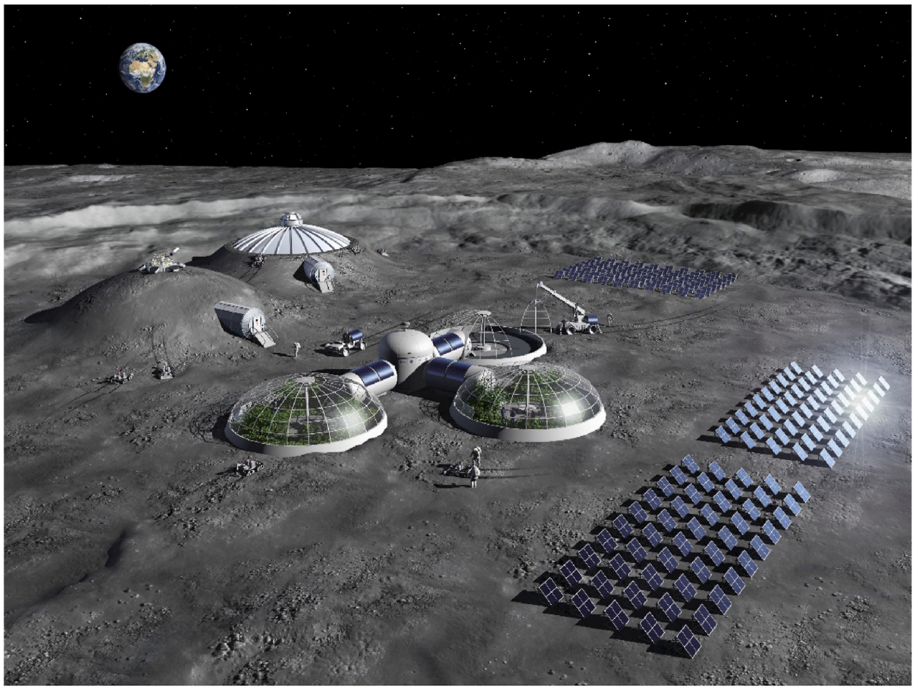

Fig. 6. Artistic Concept of a Moon base. Source: [50]. Solar panels for energy generation, greenhouses for production of food, and housing built into the lunar regolith are all displayed.

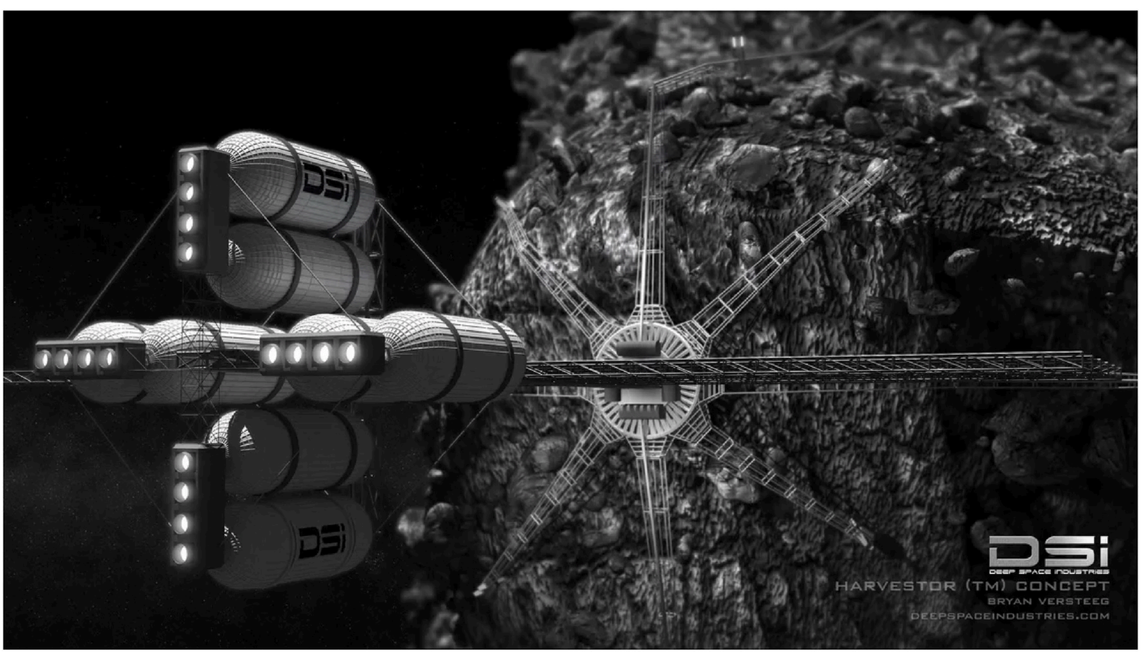

Fig. 7. Harvestor Concept for Asteroid Mining, from Deep Space Industries. Source: Deep Space Industries and Bryan Versteeg, in Ref. [51]. The Harvestor, powered by solar panels, would have the ability to capture and harvest asteroids, then transporting materials to a preferred location. Subsequently acquired by another firm, its focus shifted to small satellites.

> the other challenge of you have to build it in pieces and go assemble it out in space, which is not impossible but it is really, really complex.

Even while admitting some of the difficulties involved however, R024 could ultimately not truck with such logic. Rather, they explicitly saw this as avoiding "*the "hard stuff" of learning to work with space resources*". To their mind, this challenge was not only necessary to the undertaking at hand but part of the allure:

> If you're making a 100 by 100-m sunshade-element, you're going to have to make on the order of 100 million of those things. So are you doing the one hard thing over and over again by launching them? Or do you figure out how to do the hard things first and then make everything else easier?

Of course, they noted, there were a variety of technology gaps to be filled, such as manufacturing at scale in zero gravity, assembling large structure in space as well as mining for lunar resources. Nonetheless, in the opinion of R024, a good many of the difficulties were a matter of perception, particularly for those accustomed to working in space:

> There is this lens that space missions are really, really hard, and because space missions are really, really hard, everything that you stack onto that chain becomes exponentially harder … and therefore this idea that planetary science, using large amounts of energy on a planetary surface, and smelting and refining and manufacturing is somehow going to be just magically harder than it is on Earth.

With specific reference to mining the lunar surface, they concluded "*it is essentially* 19th-*century technology … that is not rocket science but depends on rocket science.*" Furthermore, counter to any discussion of a need for advanced manufacturing or "AI models for resource prospecting", R024 contended that "*there's nothing that you can't do with today's computer technology.*"

5. Conclusion: deep uncertainties and the unknowable future

Our first-of-its-kind empirical examination of expert perceptions of space-based geoengineering demonstrates that the public and even scientific discourse on such methods, though nascent and often diverging, focuses on a core set of issues – helping to provide the kind of understanding of the potential and feasibility of sunshades called for by Keith et al. [6], among others. These include its promise and relevance for tackling climate change – indeed, the ebb and flow of interest tends to run parallel to the salience of the impacts of climate change over the last three decades – and the "astronomical" costs and overall feasibility of employing these methods any time soon. In total, undercurrents of pessimism prevailed regarding (i) if such options were ultimately too speculative and if investment was better directed elsewhere, (ii) if, by explicitly not considering root causes of global warming, further attention to space-based proposals could cultivate a moral hazard, and (iii) if such methods would be viable by the time we would need them to forestall the worst impacts of climate change. Along with concerns over the potential for triggering military conflict and exacerbating social inequalities on Earth – even if the prospect of a sunshade itself being a target was not seen to be too severe – the chief takeaway according to the interviewed experts is that space-based geoengineering could not be *the* solution to problems on Earth.

At the same time, this is not to conclude it could not be *a* solution or might not perform a critical function, either as part of a toolbox of climate-intervention options or as a "climate airbag" on its own. Indeed, experts were broadly unwilling, perhaps surprisingly, to dismiss the notion of space-based geoengineering out of hand. Pointing to how a suitably placed sunshade – at SEL1 and not in low-Earth orbit – could avoid the direct changes to the atmosphere and biosphere and conflicts over land and resource use likely to attend other approaches to geoengineering [e.g. Refs. [1,3,15]], many experts were broadly positive about the concept itself, even though unsure about its ultimate workability. In specific, both the envisioned couplings with a future Moon economy or interstellar exploration, whereby funding for space-based geoengineering could piggyback off or complement that for the burgeoning space industry, and the possibility of massive amounts of space-generated solar power that would be beamed back to Earth were often mentioned as possible game-changers.

Accordingly, a majority of experts were open to keeping space-based options on the table, notably, by continuing to invest in research and development to better understand the prospective risks and benefits. The most notable research gap identified by experts centered on a lack of detailed climate modelling on the impacts of a sunshade, in specific, if it would cause uneven changes in temperature and rainfall. Additional questions were raised over how (indeed if) development and deployment of a sunshade could be effectively and collaboratively governed, in accordance with established treaties and without any adverse effects on democratic rule – of the kind routinely and vividly highlighted by the roles of sunshade-like objects in the science-fiction literature. According to the advocates of space-based geoengineering among the expert group, committing to invest in research and development would amount to "taking an option" on its possible use, but crucially at a fraction of the ultimate cost. By their telling, it is a matter of tens of billions instead of trillions of dollars over the next decade – leading up to a wholesale determination to be made by 2030 on whether to go all in.

The insights provided by the various experts in solar geoengineering, or those with backgrounds in the aerospace industry, reflect an interest in further precautionary research, not only on the risks and benefits but on the kinds of socio-economic structures that may emerge around development and deployment of space-based geoengineering – but not at the expense of solar geoengineering, carbon removal, or the mitigation and adaptation activities deemed more immediately feasible.

Given our focus on experts, and the limited awareness of this option at present, one notable domain for future research is on public perceptions and understanding. For instance, how would the public likely respond to calls to invest in space-based geoengineering? Will they accept and support use of public funds for this purpose? What particular concerns might they present around our potential reliance on space-based methods? And how do these compare or contrast to those of experts?

More generally, our assessment of "going to space" for climate protection brings to the fore urgent but also existential questions about humanity's role in caring for the planet versus our desire to colonize outer space and explore the rest of the universe. At its core, there is a degree of desperation and defeatism to proposals for space-based geoengineering – they imply we have failed severely to manage our problems on Earth and must escape them by giving up, or at least not exclusively relying on, conventional forms of mitigation and adaptation. But there is also a degree of optimism and hope where space-based options, through cross-pollination of funding and technology streams, could catapult humanity into a new frontier of moon-based economies, asteroid mining, and the capacity to truly kickstart the revolution so often discussed in, but so far limited to, science fiction. Such hope was expressed most fervently by R024, who described the potential of "*using space for the betterment of humanity*", and of the sunshield itself as the "*highest and best use of space resources* [which could] *kickstart humanity's expansion into space*". Whether space-based options ultimately embolden us to take climate sustainability more seriously or permit us to discard or even justify problems on Earth through the potentially false promises of a distantly better future remains to be seen.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Annex I. List of 125 semi-structured expert interview respondents

Name	Actor Type	Gender	Country	Institution
[Anonymous Aerospace Engineer]	Private Sector + Industrial Associations	Male	Germany	[Aerospace and space systems company focusing on integrated spacecraft]
Aganaba, Timiebi	Universities + Research Institutes	Female	USA	Arizona State University
Asayama, Shinichiro	Government + Intergovernmental Organizations	Male	Japan	National Institute for Environmental Studies
Bauer, Christopher Dean 'Casey'	Private Sector + Industrial Associations	Male	USA	Raytheon Space and Defense
Bazilian, Morgan	Universities + Research Institutes	Male	USA	Colorado School of Mines
Bellamy, Rob	Universities + Research Institutes	Male	United Kingdom	University of Manchester
Beuttler, Christoph	Private Sector + Industrial Associations	Male	Switzerland	Climeworks
Biermann, Frank	Universities + Research Institutes	Male	Netherlands	Utrecht University
Boettcher, Miranda	Universities + Research Institutes	Female	Germany	Institute for Advanced Sustainability Studies (IASS)
Brauer, Uwe	Private Sector + Industrial Associations	Male	Germany	Planetary Sunshade Foundation
Brickett, Lynn	Government + Intergovernmental Organizations	Female	United States	Department of Energy
Briggs, Chad	Universities + Research Institutes	Male	USA	University of Alaska, Anchorage
Brown, Marilyn	Universities + Research Institutes	Female	USA	Georgia Institute of Technology
Bruce, John	Private Sector + Industrial Associations	Male	Canada	Carbon Engineering
Buck, Holly Jean	Universities + Research Institutes	Female	USA	University at Buffalo
Burns, Wil	Universities + Research Institutes	Male	USA	American University
Caldeira, Ken	Universities + Research Institutes	Male	USA	Breakthrough Energy, Carnegie Institution for Sciences, and Stanford University, and Stanford University
Camilloni, Ines	Universities + Research Institutes	Female	Argentina	University of Buenos Aires (and Harvard University)
Carton, Wim	Universities + Research Institutes	Male	Sweden	Lund University
Centers, Ross	Private Sector + Industrial Associations	Male	Germany	Planetary Sunshades
Chalecki, Beth	Universities + Research Institutes	Female	USA	University of Nebraska Omaha
Chavez, Anthony E.	Universities + Research Institutes	Male	USA	Northern Kentucky University
Clarke, Leon	Universities + Research Institutes	Male	USA	University of Maryland
Clarke, William S. (Sev)	Private Sector + Industrial Associations	Male	Australia	Winwick Business Solutions
Cobo Gutiérrez, Selene	Universities + Research Institutes	Female	Switzerland	ETH Zurich
Cox, Emily	Universities + Research Institutes	Female	United Kingdom	Cardiff University
Creutzig, Felix	Universities + Research Institutes	Male	Germany	Mercator Research Institute on Global Commons and Climate Change (MCC)
Delina, Laurence	Universities + Research Institutes	Male	Hong Kong	Hong Kong University of Science and Technology
Di Marco, Leon	Private Sector + Industrial Associations	Male	United Kingdom	FSK Technology Research - Consultant
Dooley, Kate	Universities + Research Institutes	Female	Australia	University of Melbourne
Draper, Kathleen	Civil Society	Female	USA	International Biochar Initiative
Elliott, David	Universities + Research Institutes	Male	UK	The Open University
Erbay, Yorukcan	Private Sector + Industrial Associations	Male	United Kingdom	Element Energy
Felgenhauer, Tyler	Universities + Research Institutes	Male	USA	Duke University
Florin, Marie-Valentine	Universities + Research Institutes	Female	Switzerland	EPFL International Risk Governance Center (IRGC)
Forster, Piers	Universities + Research Institutes	Male	United Kingdom	University of Leeds
Frumhoff, Peter	Civil Society	Male	USA	Union of Concerned Scientists
Fuhrman, Jay	Government + Intergovernmental Organizations	Male	United States	Pacific Northwest National Laboratory (PNNL)
Fuss, Sabine	Universities + Research Institutes	Female	Germany	Mercator Research Institute on Global Commons and Climate Change (MCC)
Gambhir, Ajay	Universities + Research Institutes	Male	United Kingdom	Imperial College London
Geden, Oliver	Government + Intergovernmental Organizations	Male	Germany	German Institute for International and Security Affairs (SWP)
Ghosh, Arunabha	Civil Society	Male	India	Council on Energy, Environment and Water (CEEW)
Grant, Neil	Universities + Research Institutes	Male	United Kingdom	Imperial College London
Gruebler, Arnulf	Universities + Research Institutes	Male	Austria	International Institute for Applied Systems Analysis (IIASA)
Guillen Gosalbez, Gonzalo	Universities + Research Institutes	Male	Switzerland	ETH Zurich
Haberl, Helmut	Universities + Research Institutes	Male	Germany	BOKU Vienna
Haigh, Joanna	Universities + Research Institutes	Female	United Kingdom	Imperial College London/Grantham Institute
Hamilton, Clive	Universities + Research Institutes	Male	Australia	Charles Stewart University
Hartmann, Jens	Universities + Research Institutes	Male	Germany	University of Hamburg
Hawkes, Adam D.	Universities + Research Institutes	Male	United Kingdom	Imperial College London
Healey, Peter	Universities + Research Institutes	Male	United Kingdom	Oxford University
Heap, Richard	Civil Society	Male	United Kingdom	Carbon Removal Center, Foresight Transitions
Hepburn, Cameron	Universities + Research Institutes	Male	United Kingdom	Oxford University
Herzog, Howard	Universities + Research Institutes	Male	United States	MIT
Heyen, Daniel	Universities + Research Institutes	Male	Germany	TU Kaiserslautern (formerly ETHZ)
Heyward, Clare	Universities + Research Institutes	Female	Norway	UiT - the Arctic University of Tromso
Honegger, Matthias	Universities + Research Institutes	Male	Germany	Institute for Advanced Sustainability Studies (IASS)
Horton, Joshua B.	Universities + Research Institutes	Male	USA	Harvard University

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Name	Actor Type	Gender	Country	Institution
Irvine, Pete	Universities + Research Institutes	Male	United Kingdom	UCL
Jinnah, Sikina	Universities + Research Institutes	Female	USA	UC Santa Cruz
Johnson, Les	Government + Intergovernmental Organizations	Male	USA	NASA Marshall Space Flight Center
Kammen, Daniel	Universities + Research Institutes	Male	USA	UC Berkeley
Karami, Khalil	Universities + Research Institutes	Male	Slovenia/ Germany	University of Ljubljana/University of Leipzig
Karlsberg Schaffer, Madeleine	Civil Society	Female	USA	SilverLining
Keller, David	Universities + Research Institutes	Male	Germany	GEOMAR - Helmholtz Center for Ocean Research Kiel
Keller, Klaus	Universities + Research Institutes	Male	USA	Penn State University
Kravitz, Ben	Universities + Research Institutes	Male	USA	Indiana University
Kruger, Tim	Private Sector + Industrial Associations	Male	UK	Origen Power
Kuswanto, Heri	Universities + Research Institutes	Male	Indonesia	Institut Teknologi Sepuluh Nopember
Lawrence, Mark	Universities + Research Institutes	Male	Germany	Institute for Advanced Sustainability Studies (IASS)
Lehmann, Johannes	Universities + Research Institutes	Male	USA	Cornell University
Lenton, Andrew	Government + Intergovernmental Organizations	Male	Australia	CSIRO
Lin, Albert	Universities + Research Institutes	Male	USA	UC Davis
MacMartin, Doug	Universities + Research Institutes	Male	USA	Cornell University
Mahajan, Aseem	Universities + Research Institutes	Male	United States	Harvard University
Malik, Abdul	Universities + Research Institutes	Male	Saudi Arabia	King Abdullah University of Science and Technology (formerly Grantham Institute)
McLaren, Duncan	Universities + Research Institutes	Male	United Kingdom	Lancaster University
Mengis, Nadine	Universities + Research Institutes	Female	Germany	GEOMAR - Helmholtz Center for Ocean Research Kiel
Merk, Christine	Universities + Research Institutes	Female	Germany	Kiel Institute for the World Economy
Michaelowa, Axel	Universities + Research Institutes/Private Sector + Industrial Associations	Male	Switzerland	University of Zurich/Perspectives Climate Group
Montserrat, Francesc	Universities + Research Institutes	Male	Netherlands	Project Vesta/Royal Boskalis Westminster N·V.
Moore, John	Universities + Research Institutes	Male	Finland	University of Lapland/Arctic Center
Moreno-Cruz, Juan	Universities + Research Institutes	Male	Canada	University of Waterloo
Morrow, David	Universities + Research Institutes	Male	USA	American University
Muri, Helene	Universities + Research Institutes	Female	Norway	Norwegian University of Science and Technology (NTNU)
Obersteiner, Michael	Universities + Research Institutes	Male	United Kingdom	Oxford University
Odoulami, Romaric	Universities + Research Institutes	Male	South Africa	University of Cape Town
Parker, Andy	Civil Society	Male	UK	SRM Governance initiative
Parson, Edward `Ted' A.	Universities + Research Institutes	Male	USA	UCLA
Pasztor, Janos	Civil Society	Male	Switzerland	Carnegie Climate Governance Initiative
Pidgeon, Nick	Universities + Research Institutes	Male	United Kingdom	Cardiff University
Pinto, Izidine	Universities + Research Institutes	Male	South Africa	University of Cape Town
Pongratz, Julia	Universities + Research Institutes	Female	Germany	University of Munich
Preston Aragonès, Mark	Civil Society	Male	Norway	Bellona Foundation
Rahman, Mohammed Mofizur	Universities + Research Institutes	Male	Germany	TH Cologne - University of Applied Sciences
Raimi, Kaitlin T.	Universities + Research Institutes	Female	United States	University Michigan
Reiner, David	Universities + Research Institutes	Male	United Kingdom	Cambridge University
Renforth, Phil	Universities + Research Institutes	Male	United Kingdom	Heriot-Watt University
Reynolds, Jesse	Universities + Research Institutes	Male	USA/ Netherlands	UCLA/Independent Consultant
Rickels, Wilfried	Universities + Research Institutes	Male	Germany	Kiel Institute
Robock, Alan	Universities + Research Institutes	Male	USA	Rutgers University
Rothman, Dale	Universities + Research Institutes	Male	USA	University of Denver
Rouse, Paul	Universities + Research Institutes	Male	United Kingdom	University of Southampton
Schleussner, Carl	Civil Society	Male	USA	Climate Analytics
Schmidt, Joern	Universities + Research Institutes	Male	Germany	Kiel Institute
Schneider, Linda	Civil Society	Female	Germany	Heinrich Boell Foundation
Scott, Vivian	Universities + Research Institutes	Male	United Kingdom	Edinburgh University
Simonelli, Lucia	Civil Society	Female	United States	Carbon 180
Smith, Pete	Universities + Research Institutes	Male	United Kingdom	University of Aberdeen
Smith, Steve	Universities + Research Institutes	Male	United Kingdom	Oxford University
Smith, Wake	Universities + Research Institutes	Male	USA	Harvard University
Spangenberg, Joachim	Universities + Research Institutes	Male	Germany	Sustainable Europe Research Institute SERI Germany e.V
Stephens, Jennie	Universities + Research Institutes	Female	USA	Northeastern University

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Name	Actor Type	Gender	Country	Institution
Stoefs, Wijnand	Civil Society	Male	Belgium	Carbon Market Watch
Sugiyama, Masahiro	Universities + Research Institutes	Male	Japan	University Tokyo
Sunny, Nixon	Universities + Research Institutes	Male	United Kingdom	Imperial College London
Surprise, Kevin	Universities + Research Institutes	Male	USA	Mount Holyoke College
van Vuuren, Detlef	Government + Intergovernmental Organizations	Male	Netherlands	PBL Netherlands Environmental Assessment Agency
Vaughan, Nem	Universities + Research Institutes	Female	United Kingdom	University of East Anglia
Victor, David	Universities + Research Institutes	Male	USA	UC San Diego
Vivian, Chris	Government + Intergovernmental Organizations	Male	UK	GESAMP
Wagner, Gernot	Universities + Research Institutes	Male	USA	NYU
Wolske, Kimberly S.	Universities + Research Institutes	Female	United States	University Chicago
Wood, Robert	Universities + Research Institutes	Male	USA	University of Washington
Workman, Mark	Universities + Research Institutes	Male	UK	Energy Futures Lab, Imperial College London

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