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Climate action in space: A sustainable development framework for sunshades at Sun-Earth Lagrange Point 1 ☆

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Abstract

Sunshades in space have been proposed as a geoengineering method to mitigate climate change by reducing incoming solar radiation. Sunshade concepts are gaining attention as a lower-risk but higher-cost alternative to terrestrial solar radiation management approaches, such as stratospheric aerosol injection. However, the literature is limited, and the absence of a structured development framework complicates the evaluation, comparison, and maturation of these concepts. A shared standard that reflects the wide-ranging aspects of sunshade deployment could streamline efforts, accelerate progress, and improve the recognition of sunshades in the international climate change debate. While aiming to provide sustainability from space, a deployed sunshade must also follow sustainability principles in space given its scale. At the same time, the required industry on Earth should align with broader sustainability goals, ensuring that it does not undermine ongoing efforts towards a sustainable future. Therefore, as a first step, this paper analyzes the applicability of internationally recognized sustainability frameworks – namely the United Nations Sustainable Development Goals and the European Space Agency's Environmental Impact Indicators for space systems – by employing a content analysis methodology on a representative selection of literature. The insights gained, along with criteria derived from the geoengineering literature, shaped the 18 Sunshade Development Criteria (SDC), a framework for sustainable development. Subsequently, this paper analyzes the case study literature based on the SDC to draw conclusions on the state of the art of the sunshade domain. This framework is the first of its kind and this study is the first that employs a systematic content analysis to evaluate the sunshade literature. The findings indicate that a detailed assessment and comparison of sunshade concepts remain challenging because of the field's fragmentation. Although criteria such as side effects, controllability, and the overall context of climate change have been covered, significant gaps remain. These include technical maturity, global warming potential, sustainability considerations, distribution of spatio-temporal radiative forcing, public perception, social acceptability, global inequalities, and impacts on the space segment. Addressing these gaps is essential, and the SDC serve as a crucial tool to facilitate this maturation. Beyond purely technical considerations, this paper introduces an interdisciplinary perspective on the sunshade domain while demonstrating this approach through its methodology and proposed framework. It seeks to advance sunshade concepts and guide their sustainable development and deployment to address climate change. Ultimately, it aims to increase the acceptance of sunshades in the international debate on whether and how we should intervene in the climate.

Keywords: Climate change; Space-based climate action; Sunshades; Space sustainability; Sustainable development; Content analysis

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Nomenclature

AD^2	Advancement degree of difficulty
AL_2O_3	Aluminium oxide
AR6	Sixth Assessment Report of the IPCC
CDR	Carbon dioxide removal
CTP	Climate tipping point
CSE	Circular space economy
EII	ESA Environmental Impact Indicator for space systems
ESA	European Space Agency
FSC	Fuglesang Space Center
GHG	Greenhouse gas
GMT	Global mean temperature
IEEE	Institute of Electrical and Electronics Engineers
IPCC	Intergovernmental Panel on Climate Change
IPSS	International Planetary Sunshade System
ISRU	In-situ resource utilization
L	Lagrange point
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
OHB	OHB System AG
PSF	Planetary Sunshade Foundation
RF	Radiative forcing
RSS	Realistic Sunshade System
SAI	Stratospheric aerosol injection
SBSP	Space-based solar power
SDC	Sunshade Development Criteria
SDG	UN Sustainable Development Goal
SEL	Sun-Earth Lagrange point
SG	Solar geoengineering
SRM	Solar radiation management
SRP	Solar radiation pressure
TRL	Technology readiness level
UK	United Kingdom
UN	United Nations
UNEP	United Nations Environmental Programme
UNOOSA	United Nations Office for Outer Space Affairs

1. Introduction

“Climate change is happening now. Floods, droughts, heatwaves, and other climate-related hazards are becoming more intense, longer and more frequent” (European Environment Agency, 2023). However, global greenhouse gas (GHG) emissions continued their historically high growth rates in 2024 (Lan et al., 2025). The present scientific knowledge on climate change is summarized by the Intergovernmental Panel on Climate Change (IPCC) in their latest report, the Sixth Assessment Report (AR6) (IPCC, 2023). It evaluates the goal of the 2015 Paris Agreement of keeping global warming well below 2 K compared to preindustrial levels likely to be exceeded (Horowitz, 2016; IPCC, 2023). In fact, the implementation of current climate policies can result in a global mean temperature (GMT) increase of 3.2 K by 2100 (Lenton et al., 2019; Armstrong McKay et al., 2022; IPCC, 2023).

The current warming of around 1.5 K touches the lower end of climate tipping points (CTPs), such as the melting of major ice sheets (Armstrong McKay et al., 2022). CTPs are critical thresholds that, if triggered by even small perturbations, lead to major and irreversible changes in the climate system (Lenton et al., 2008; Lenton et al., 2019). Even by staying within the Paris Agreement’s goal of 2 K warming, a significant GMT increase by 15 % (Horowitz, 2016; NOAA, 2023), several CTPs are expected to be triggered. The urgency of not letting the GMT rise even further becomes evident.

In this context, geoengineering, as deliberate large-scale manipulation of the environment (Keith, 2000), has been discussed as a *complement to* – not a substitute for – mitigation and adaptation efforts (Belaia et al., 2021; Borgue and Hein, 2023). Indeed, some authors consider it even too late for mitigation and adaptation-only scenarios (Keith, 2000; Wigley, 2006; Shepherd, 2009; Kosugi, 2010; Belaia et al., 2021; UNEP, 2023). This is because present climate change is driven by past accumulated emissions in the atmosphere, resulting in delayed warming effects (Keith, 2019). Even if net zero emissions were achieved today, temperatures could continue to rise for decades (IPCC, 2022b; Planetary Sunshade Foundation (PSF) and Fuglesang Space Center (FSC), 2023). Thus, reducing the GHG output to net zero would only slow the warming, not reverse the trend. As a potential solution, in an ideal scenario, geoengineering would *temporarily* be used to cool the Earth and its atmosphere, allowing humanity to transition its GHG footprint to net-negative. This could restore atmospheric GHG levels to preindustrial conditions, a task that unfortunately must be considered “virtually infinite” in terms of human lifespan (Keith, 2019; Belaia et al., 2021). However, taking action now with a strategy that includes sunshades may keep future warming below levels of the Paris Agreement, preventing CTPs from being reached.

Geoengineering is not to be confused with a permanent or sole solution. In fact, it cannot be a solution as it does not address the cause of anthropogenic climate change, which is the release of GHGs into the atmosphere. Furthermore, even the most optimistic scenarios show that no realistic geoengineering method is able to fully mitigate anthropogenic climate change, primarily due to the increasing side effects with increasing deployment. Therefore, only a combined mitigation-adaptation-geoengineering strategy may tackle climate change sufficiently (Belaia et al., 2021).

Among different solar radiaton management (SRM) methods, sunshades have been proposed as a lower-risk but higher-cost alternative to terrestrial geoengineering approaches such as stratospheric aerosol injection (SAI). They are considered to be among the most efficient SRM methods (Shepherd, 2009; Sánchez and McInnes, 2015; OHB System AG, 2020). The costs are mainly driven by the launch of their high mass of around 10^6 tonnes to 10^8 tonnes into space (Fuglesang and De Herreros Miciano, 2021; Borgue and Hein, 2023). However, the cost of climate change is estimated to be much higher (Ellery, 2016; Belaia et al., 2021; Deloitte, 2022; Borgue and Hein, 2023; Romano et al., 2023). The risk is lower since the atmospheric chemistry of the planet would not be directly altered, and the solar radiation spectrum reduction and composition can be adjusted to maximize the effect and minimize side effects. In addition, any sunshade system would be scaleable and fully reversible.

Despite their potential, the literature and research on sunshades is limited (Kosugi, 2010; Keith et al., 2020; Baum et al., 2022), facing large uncertainties and knowledge gaps. There are many challenges to overcome, ranging from social and ethical to technical and economic ones. Moreover, questions about risks, governance, and impact on sustainable development in space and on Earth need to be answered (IPCC, 2021).

In this field of uncertainties, sunshade concepts are evolving independently, without a unified development framework (e.g., design guidelines) to discuss and evaluate alternatives (Boyd, 2008; Kosugi, 2010; Boyd, 2016; Fuglesang and De Herreros Miciano, 2021). To address this gap, a framework is needed to facilitate systematic development. Such a framework would enable comprehensive and objective evaluations, identify knowledge gaps, measure progress, assess risks, support decision making, inform policy development, and foster dialogue and research. By providing a shared language and structure, it promotes interdisciplinary cooperation and ensures that diverse perspectives are considered.

In light of these challenges and promises, two research questions guide this work: (i) How can a conceptual development and evaluation framework that incorporates sustainability aspects help advance the maturity and applicability of the sunshade research domain? And subsequently, (ii) How far has the sunshade domain matured?

Hence, this paper introduces a novel framework for the sustainable development of sunshade concepts, providing the ground for comprehensive assessments as these concepts mature. Once fully developed, they can be compared with other geoengineering options and potentially serve as alternatives or complements to SRM methods.

The paper is structured as follows. Section 2 provides an overview of sunshade concepts and Section 3 presents the selection principles of the analyzed literature and details the content analysis methodology. Section 4 investigates framework approaches within the sunshade domain to gain insights and to avoid duplicating work. With a similar intention, Section 5 investigates sustainable development frameworks outside the sunshade domain, selecting two for further analysis, and applies a content analysis to the case study literature. Building on the insights from Section 4 and Section 5, Section 6 introduces a comprehensive set of 18 Sunshade Development Criteria (SDC). In Section 7, these SDC form the basis for a second content analysis of the case study literature to derive the status of sunshade development and to demonstrate their applicability. Subsequently, Section 8 discusses the results and Section 9 provides final remarks on this work, along with directions for future research.

2. Background on sunshade concepts

The most discussed space-based geoengineering approach relies on using sunshades, thin structures placed between the Earth and the Sun, to limit the amount of sunlight reaching Earth. Sunshades are considered to be costly and technically challenging. However, they are one of the most efficient SRM technologies in terms of cooling effect per radiative forcing (RF) (Lenton and Vaughan, 2009; Shepherd, 2009; Sánchez and McInnes, 2015). RF "describes any imbalance in the Earth's radiative budget caused by human or natural interference with the climate system" (Lenton and Vaughan, 2009). Furthermore, sunshades are the least invasive geoengineering method. This leads to a higher predictability of desired and undesired effects, and simultaneously, side effects are expected to be less significant compared to other geoengineering approaches.

The first concepts were independently introduced by Seifritz (1989) and Early (1989). Seifritz proposed large mirrors mounted on satellites, and Early suggested a thin reflecting or refracting glass shield, both placed at Sun-Earth Lagrange point 1 (SEL_1). At SEL_1, the effects can be controlled and, if necessary, eliminated, since without ongoing station keeping efforts, any sunshade placed will disappear in a matter of weeks through the influence of solar radiation pressure (SRP) (Early, 1989; Keith, 2000; Sánchez and McInnes, 2015).

Later, McInnes (2002) presented the concept of a large solar shield also at SEL_1, while Angel (2006) proposed a cloud of trillions of smaller "flyers" at the same location. Kennedy et al. (2013) introduced their concept of "Dyson Dots", consisting of a Texas-sized swarm of solar energy collecting sails at SEL_1. The concept brings another potential use case to the sunshade as it would be able to capture and beam enough solar energy to Earth to meet present and future energy needs.

Sánchez and McInnes (2015) stated that non-uniform shading is required to achieve a uniform cooling effect and presented dedicated orbits and techniques to do so. A year later, Ellery (2016) primarily proposed a manufacturing concept using lunar resources and self-replicating technology that would enable low-cost space-based geoengineering, introducing a more practical and feasibility-oriented view while relying on current and near-term technology.

In view of advancing climate change, concepts have evolved that provide a more holistic and practical view and, at the same time, address specific technical challenges. For instance, Fuglesang and De Herreros Miciano (2021) published their concept of a "Realistic Sunshade System" (RSS). They highlight solar sail technology and reusable heavy launchers as the main challenges to overcome. Taking into account different development speeds, a conservative and optimal sunshade design was introduced. Aiming to be entirely launched from Earth by the middle of the century, an implemented RSS at SEL_1 is evaluated feasible if the technology development starts now.

In 2020, the "Planetary Sunshade" concept built from space resources was published by Centers et al. (2020) and Jehle et al. (2020). The concept was then – in collaboration – developed towards the "International Planetary Sunshade System" (IPSS) by Fix (2021); Maheswaran (2021); Maheswaran and Fix (2021). It is currently undergoing further development (Maheswaran et al., 2022; Acker, 2023; Maheswaran et al., 2023; Maheswaran et al., 2023b; Maheswaran et al., 2023c; Maheswaran et al., 2023; Brauer et al., 2023; Ganzmann, 2023; Mindermann et al., 2024; Town et al., 2025). The authors propose a shift over time from using terrestrial to lunar resources, while leveraging current and future technology development trends, to increase the feasibility of the project. In a later stage, the IPSS aims to deliver space-based solar power (SBSP) from SEL_1 to Earth to meet global energy needs.

Borgue and Hein (2023) proposed an ultralight and near-zero SRP sunshade design utilizing advanced solar sail concepts of the National Aeronautics and Space Administration (NASA) (Burton et al., 2005). The Earth launch concept aims to reduce the required launch mass by a factor of 10^2 to 10^3. However, this concept requires an additional disposable membrane layer or another type of space transportation to reach SEL_1, which contributes to the launch mass.

The lightest sunshade concept to date was published by Szapudi (2023). Szapudi's tethered shield concept aims to require only 1% of the total infrastructure mass to be launched from Earth. The Earth-manufactured sunshade would utilize lightweight tethers to be attached to a balancing mass placed towards the Sun. It is suggested that the balancing mass comes from lunar dust or an asteroid. The 37.000-tonne shield could therefore be placed very close to Earth, resulting in a relatively small sunshade surface area, which in turn requires only twice the mass that has been launched off Earth to date, as estimated by the author. However, the proposed launch mass does not include the infrastructure required for the manipulation of the orbit of an asteroid, lunar mining activities, and transport of the former to SEL_1, which is important when comparing it with holistic approaches, such as the RSS and IPSS.

Most concepts aim for a GMT reduction of 1 K to 2 K, resulting in a permanent sunlight attenuation of 0.5% to 1.8%. For reference, an attenuation of 1.8% equals six days of completely obscured sun per year (Bromley et al., 2023). Sunshades differ mainly in optical surface properties, average areal density, and size and number of sunshades or objects. Another way to categorize concepts is whether they are manufactured on Earth and launched by chemical or electrical propulsion, or whether they primarily or partly rely on in situ resource utilization (ISRU) and in-space manufacturing. ISRU concepts aim to utilize lunar regolith or asteroid resources to minimize the environmental impact of frequent rocket launches and related industries, while preserving valuable materials on Earth.

The scale of any concept is outstanding and would require decades of global effort. Recent concepts that do not use celestial bodies as part of their mechanism range from 10^6 tonnes to 10^8 tonnes, with a sunshade surface area on the order of 10^6 km^2 (Fix, 2021; Fuglesang and De Herreros Miciano, 2021; Baum et al., 2022; Borgue and Hein, 2023), although a 15 kg to 24 kg precursor mission has recently been proposed (Coco et al., 2025). Production and deployment of sunshades would therefore require an Earth- and space-based economy comparable in size to the global automotive industry (Fuglesang and De Herreros Miciano, 2021).

3. Material and methods

This work introduces a novel framework for the sustainable development of sunshades. It enables determining the status of development and provides the ground for comprehensive assessments as these concepts mature. Initially, a survey was conducted to identify existing frameworks and criteria inside and outside the sunshade domain to avoid duplicating work (see literature selection principles in Section 3.1). At the same time, a representative selection of the sunshade literature was made that serves as the case study literature (see Section 3.1, as well). While there was no comprehensive development framework found within the sunshade literature, two external frameworks have been found applicable. The case study literature was then evaluated by a content analysis on the coverage of the two frameworks (for content analysis methodology, see Sec-

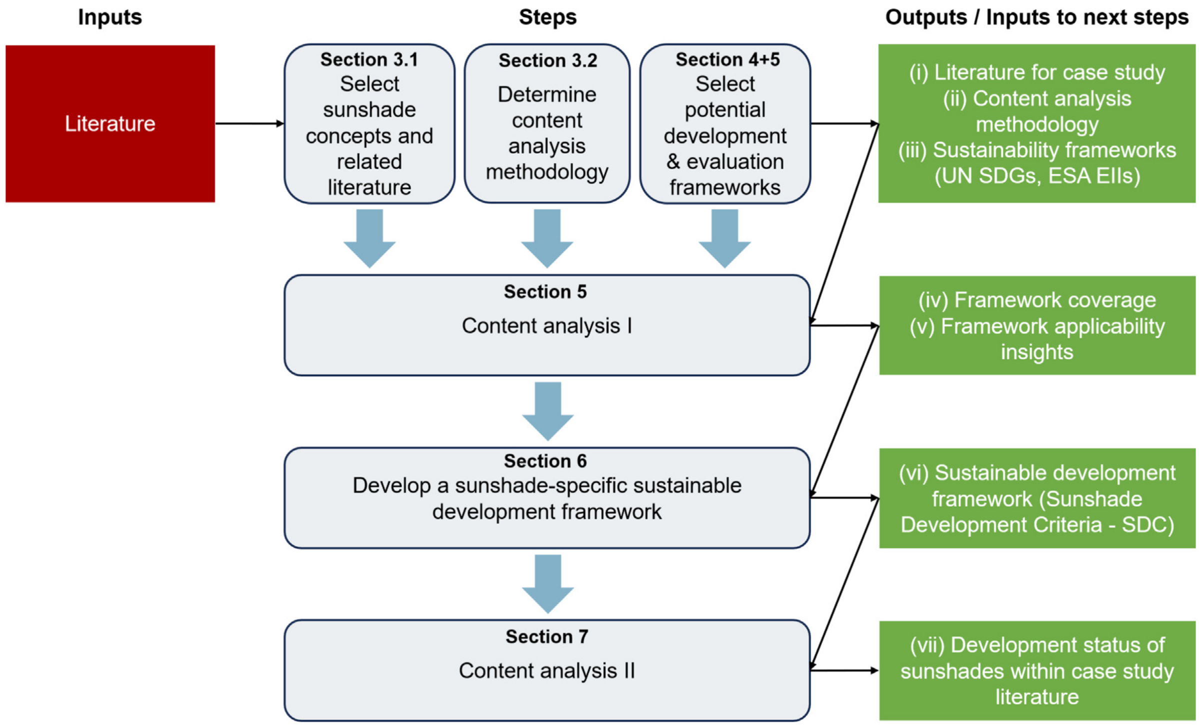

Fig. 1. Methodology for developing the proposed SDC and deriving the development status of sunshades within case study literature.

tion 3.2). Based on the findings, a sunshade-specific framework was deemed necessary and subsequently developed. A second content analysis of the case study literature was conducted to determine the current state of sunshade development. The applied methodology is presented in Fig. 1.

3.1. Literature selection

Peer-reviewed journal articles on the sunshade topic are still limited; therefore, the authors decided to investigate also grey literature such as official or technical reports, conference proceedings, theses, etc. A total of 85 publications spanning from 1989 to 2025 have been examined.

First, an online search has been conducted to find wide-ranging sustainability assessment frameworks and criteria to evaluate space systems and activities on Earth, without being geoengineering specific. The objective was to find well-defined frameworks and criteria accepted by the international community, so the keywords have been {sustainability OR space} AND {criteria, indicator, taxonomy, index, metric, measure, assessment, life cycle assessment, evaluation}.

Subsequently, the search has been extended to the general and space-based geoengineering literature. The focus was on the literature that includes both terrestrial and space-based geoengineering concepts, as it was expected that this type of literature would always include criteria that can be applied to compare different approaches. Keywords for this search have been {sunshade OR space-based geoengineering} AND {geoengineering, solar radiation management, criteria, evaluation, assessment}. For all keyword searches, Google Search and the Google Scholar, Scopus, and Institute of Electrical and Electronics Engineers (IEEE) Xplore data bases have been used. This investigation also brought the different sunshade concepts to light, as Fig. 1 shows. Through direct contact with some of the authors, it was discovered that OHB System AG (OHB) had carried out a system study of SRM methods (OHB System AG, 2020), including sunshades, and partial access was kindly granted.

However, some relevant literature known to the authors was not identified using the initial search approach. To address this, the literature review was supplemented by applying a snowballing method (Wohlin, 2014), where the most recent publications were reviewed and their references scanned to identify additional journal articles and other relevant sources. This process was repeated iteratively, moving step by step backwards in time through the most frequently cited publications, eventually tracing back to the earliest publications in the field. Indeed, this method successfully led to the “discovery” of publications that were not detected by the initial search and pointed to some previously unknown works as well.

Since one of the main objectives of this work is to investigate the development status of sunshades, particularly at SEL_1, as it seems the most viable “short-term” approach to the authors, it was necessary to select literature from the gathered pool for further analysis. As stated before, the literature that focuses exclusively on sunshade concepts is limited, which is why the literature

Table 1
Overview of sunshade concepts and related literature selected for this study, organized by publication year within each category. The principles for selecting the literature are detailed in Section 3.

Author, year	Title
Sunshade concepts	
Seifritz, 1989	Mirrors to Halt Global Warming?
Early, 1989	Space-based solar shield to offset greenhouse effect
McInnes, 2002	Minimum Mass Solar Shield for Terrestrial Climate Control
Angel, 2006	Feasibility of cooling the Earth with a cloud of small spacecraft near the inner Lagrange point (L1)
Kennedy et al., 2013	Dyson Dots: Changing the solar constant to a variable with photovoltaic lightsails
Sánchez, McInnes, 2015	Optimal Sunshade Configurations for Space-Based Geoengineering near the Sun-Earth L_1 Point
Ellery, 2016	Low-Cost Space-Based Geoengineering: An Assessment Based on Self-Replicating Manufacturing of in-Situ Resources on the Moon
Fuglesang, Herreros, 2021	Realistic sunshade system at L_1 for global temperature control
Roy, 2022	The solar shield concept: Current status and future possibilities
Borgue, Hein, 2023	Transparent occulters: A nearly zero-radiation pressure sunshade to support climate change mitigation
IPSS contributors, 2020–2025	Space Resources to Stop Global Warming: a Planetary Sunshade (Centers et al., 2020); A Planetary Sunshade Built from Space Resources (Jehle et al., 2020); Feasibility Study of a Sunshade in the Vicinity of the Sun Earth L1 Lagrange Point (Fix, 2021); Analysis of Logistical Construction Aspects of a Sunshade Concept in the Vicinity of the Sun Earth L1 Lagrange Point (Maheswaran, 2021); The International Planetary Sunshade - An Umbrella Project to Foster International Collaboration to Mitigate Global Warming (Maheswaran et al., 2022); Parametrized Sunshade Design Study for an Evolutionary Sunshade Concept (Acker, 2023); The International Planetary Sunshade System - An Umbrella Project Combining Sustainable Energy Supply with Mitigation of Global Warming (Maheswaran et al., 2023); International planetary sunshade concept with a function-integrated and scalable support structure based on coreless filament winding (Maheswaran et al., 2023); Development of a modular logistics concept enabling the deployment of the IPSS system (Ganzmann, 2023); Long-span fiber composite truss made by coreless filament winding for large-scale satellite structural systems demonstrated on a planetary sunshade concept (Mindermann et al., 2024); Preliminary Structural System Design for Planetary Sunshade (Town et al., 2025)
Related literature	
Keith, 2000	Geoengineering the Climate: History and Prospect
Lenton, Vaughan, 2009	The radiative forcing potential of different climate geoengineering options
Shepherd, 2009	Geoengineering the climate: science, governance and uncertainty
Kosugi, 2010	Role of sunshades in space as a climate control option
Vaughan, Lenton, 2011	A review of climate geoengineering proposals
Corner et al., 2013	Messing with nature? Exploring public perceptions of geoengineering in the UK
OHB System AG, 2020	Solar Radiation Management: Detailed SRM Study Report
Belaia et al., 2021	Optimal climate policy in 3D: mitigation, carbon removal, and solar geoengineering
Baum et al., 2022	Between the sun and us: Expert perceptions on the innovation, policy, and deep uncertainties of space-based solar geoengineering
UNEP, 2023	One Atmosphere: An independent expert review on Solar Radiation Modification research and deployment
PSF, FSC, 2023	State of Space Based Solar Radiation Modification

involving sunshades alongside other geoengineering approaches was also selected. The selection was made based on scientific citations, variety of perspectives, online reads or views, media attention, publication date, and relevance to the research questions of this paper. The aim was to show the development of the literature over time and to derive a clear picture of the state of the art. Subsequently, the literature selection, as presented in Table 1, was designed to reflect this progression, serving as a comprehensive case study.

Regarding the IPSS, several publications were gathered as they complement each other. This illustrates a limitation of the study, as some concepts and publications are more extensive than others. On the other hand, it is exactly what this study is trying to clarify. Additionally, the selection of primarily peer-reviewed journal publications is contrasted with grey literature, such as official institution reports, in a few select cases.

3.2. Content analysis

The publications listed in Table 1 were thoroughly analyzed, including their appendices. A content analysis methodology was employed, in which the existence and frequency of certain concepts were examined (Elo and Kyngäs, 2008; Schreier, 2012; Krippendorff, 2019). “Content analysis entails a systematic reading of a body of texts” and “increases a researcher’s understanding of particular phenomena” (Krippendorff, 2019). This method of assessing the existence and frequency of nodes and themes ensures a systematic evaluation of the content and facilitated the organization of data across different publications and frameworks. For example, each of the United Nations Sustainable Development Goals (UN SDGs) served as a node, while the framework of all 17 UN SDGs served as the overarching theme.

The assessment considers the presence of the underlying concept of a node rather than requiring its explicit mention. The approach entails the challenge that different coders may link different content elements, such as a statement, paragraph, table, or figure, to different nodes–or, conversely, may not assign a relevant content element to a node at all. To address this, a shared understanding and consistent terminology was established through discussions among the authors prior to the assessment. These discussions were revisited throughout the coding period, helping to resolve questions and discuss issues as they arose.

Eventually, the evaluation needs to capture how many times a certain node is triggered per publication to derive how intense a given publication addresses it. A simple assessment scheme, shown in Table 2, allows for a subsequent evaluation of node coverage among sunshade concepts and related literature. In addition, it serves as a useful tool for identifying trends, correlations, and gaps in the literature. In this way, it is possible to evaluate and summarize what is known and what remains undiscovered in a particular field (Crossan and Apaydin, 2010). Through an iterative approach, it has been found that assigning a range of 1 to 10 content elements (+) and more than 10 content elements (++) provides a meaningful distinction between low, medium, and detailed coverage without being arbitrary. The thresholds were established after an initial review of the literature, revealing that most publications with detailed coverage typically presented more than 10 content elements per node. Setting a higher threshold (e.g., 20) would risk underestimating substantial contributions, while a lower threshold (e.g., 5) would make it difficult to differentiate between moderate and comprehensive coverage. The use of “no coverage” (-) reflects the absence of any meaningful engagement with the node or theme in the literature. It is important to note that this approach focuses on analyzing the frequency of the content and does not provide a qualitative rating (positive or negative) of contributions. Examples of content elements that contributed to specific coverage scores (i.e., frequencies) will be provided in the respective Section 5 and Section 7.

Table 2
Introduction of a simple assessment scheme to quantify criteria coverage within the literature. A content element refers to, e.g., a single statement, paragraph, table, or chart. The methodology is detailed in Section 3.2.

Coverage	Score	Value [–]	Description
None	-	0	No content element can be assigned to a node.
Low to medium	+	1	One to ten content elements can be assigned to a node.
Detailed	++	2	More than ten content elements can be assigned to a node.

This assessment methodology was applied to the 22 selected sunshade concepts and related literature and was conducted for 51 nodes, belonging to three themes. This resulted in 1,122 data points, which means one coverage score for each node within each publication. To assess the theme coverage of a given publication or node coverage across all 22 publications, “cumulated coverage” is introduced. Cumulated coverage is calculated by adding the individual coverage scores of the rows (representing the theme coverage of a publication) or columns (representing the node coverage across all publications) from the respective data sets presented in Section 5 and Section 7. The sum of the individual scores was subsequently transferred to the corresponding value as outlined in Table 2. To ensure comparability, these total values were normalized with the maximum possible score. For example, detailed coverage (++ score, value 2) of a node in all 22 publications results in a maximum cumulative coverage value of 44, corresponding to 100% cumulative coverage and providing a benchmark of the status quo.

4. Framework approaches within the sunshade domain

As introduced in Section 1, we refer to a framework as a set of criteria. However, a development framework (e.g., design guidelines) can evolve into an assessment framework once both the subject being evaluated and the framework itself have reached sufficient maturity. Therefore, these terms are interchangeable in our context, enabling us to conduct a broader search in the literature.

In 2019, about 500 geoengineering-related journal articles were published (Keith, 2019). The amount of literature on sunshades is lower by at least one order of magnitude (Baum et al., 2022). To the best knowledge of the authors, there is no peer-reviewed work that focuses on evaluating different concepts in a comprehensive and systematic assessment. Only Baum et al. (2022) presented an overview of 23 space-based geoengineering proposals in 2022, providing short concept descriptions, but their work focuses on expert perceptions on space-based geoengineering in general.

Additionally, Shyur and Keith (2019) presented an annotated bibliography of space-based geoengineering, briefly describing 13 space-based geoengineering concepts according to “Type, Location, Mass (tonne), Area (km^2), Material, Notes and concerns”. Those brief overviews are typically found in the introduction sections of the space-based geoengineering literature, but these rather technical criteria do not provide a foundation for a comprehensive and systematic assessment.

A closer look at the peer-reviewed sunshade literature reveals the lack of standardized frameworks to describe the concepts. The authors use very different approaches when answering similar questions, such as “What is to include in sunshade mass estimations?”, or while addressing the same criterion such as effectiveness, which is often confused with efficacy, efficiency, and effectivity. Since these criteria differ from each other (Enrique and Marta, 2020; Cunff, 2020), difficulties and accuracy issues arise when trying to compare concepts. Authors also focus on very different topics when proposing a concept, and when addressing similar topics such as side effects, it is often done in different depth. Hence, the information given is rather fragmented, and a comprehensive assessment is challenging. It should be noted that contributions from grey literature, such as Chesley et al. (2023), present conceptual frameworks with a focus on technical aspects, along with environmental and governance considerations. This is an important step towards resolving this lack of standardization.

More promising is to look into the literature that covers sunshades among other geoengineering methods, since these fields have a larger body of literature available. The majority of this literature consists of rather high-level assessments, while mainly qualitative criteria are used to compare concepts. However, these publications give a good starting point for finding sunshade-related development criteria.

One of them is the 2009 Royal Society report on geoengineering (Shepherd, 2009). They introduced four qualitative evaluation criteria, namely effectiveness, affordability, timeliness, and safety. In the report, each geoengineering method was evaluated by giving a rating from very low to very high, together with a short justification for each criterion, which can be seen for the example of space-based methods in Table 3. Through their assessment, they recognized the need for more comprehensive future evaluations and proposed eight criteria: legality, effectiveness, timeliness, impacts, costs, funding support, public acceptability, and reversibility. Although these criteria are a step in the right direction, they miss important aspects such as the potential for good governance, ethical considerations, and space-related issues associated with deploying sunshades. It may also be argued that costs, funding support, and compliance with the current, potentially insufficient legal system should not necessarily be the highest priority when discussing altering the planet's climate system.

OHB System AG (2020) then utilized and enhanced the initial four criteria of the Royal Society for their "Detailed SRM Study Report". Each criterion is separated into five levels, while each level is described and assigned to a value, except for safety, for which only high-level descriptions were given. As an example, the definitions and values of the timeliness criterion are presented in Table 4.

Table 4
OHB's detailed SRM study report timeliness trade-off criterion definition, adapted from OHB System AG (2020).

Criteria value	Description	Value [y]
1	The concept development and proof of concept will take a long time to execute.	> 15
2	There is a large delay in the concept development and proof of concept.	10–15
3	There is a medium delay in the concept development and proof of concept.	5–10
4	There is a small delay in the concept development and proof of concept.	1–5
5	Concept development and proof of concept can be achieved within the stated time.	< 1

While it is assumed that OHB is able to develop a sunshade system, it is noteworthy that safety is the most detailed described criterion, while the range of years for timeliness are rather short-term, which leads to the impression that the delicate but urgent situation is well understood.

Although these criteria allow for an initial analysis, which is important for decision making, there are natural limitations to any high-level approach. As an example, timeliness depends highly on effort and prioritization, and safety depends on proper use, sufficient research and engineering, and governance. Affordability is a matter of will and effectiveness is a rather simple approach to a complex issue. Furthermore, the aforementioned criteria depend on the deployment scale and location and do not represent the wide-ranging effects and side effects of a deployment. However, the use of high-level qualitative criteria seems unavoidable for now, as the data availability issue needs to be overcome first. This reflects the difficulty of determining appropriate development or assessment criteria in the space-based geoengineering domain.

Since we did not find a comprehensive, ready-to-use development framework applicable or dedicated to sunshades in the related literature, we are expanding our search to include widely accepted development frameworks outside the geoengineering domain. We find this approach necessary, considering that sunshade deployment would impact all aspects of life on Earth, which may already be reflected, at least to some extent, in those frameworks. This

Table 3
Qualitative evaluation of space-based geoengineering methods in the 2009 Royal Society report on geoengineering, adapted from Shepherd (2009).

Criterion	Description	Rating
Effectiveness	No inherent limit to effect on global temperatures SRM method so does nothing to counter ocean acidification.	High
Affordability	High cost of initial deployment (depends on mass required): plus additional operational costs (e.g. maintaining positions): but long lifetime once deployed.	Very low to Low
Timeliness	Would take several decades (at least) to put reflectors into space Once in place, reflectors would reduce global temperatures within a few years.	Very low
Safety	Residual regional climate effects, particularly on hydrological cycle No known direct biochemical effects on environment beyond possible effects of reduced insolation.	Medium

prevents duplication of existing work. Therefore, our next step is to assess whether these established frameworks can be applied effectively to the sunshade domain. Should this not be feasible or only partly, the insights gained will provide a solid foundation for proposing a dedicated sunshade development framework.

5. External frameworks applied to sunshade literature

The Royal Society report suggests that geoengineering criteria can be broadly categorized into technical and social criteria (Shepherd, 2009). Hence, one primarily social framework and one primarily technical framework are selected for an initial evaluation. However, a sunshade system designed to address climate change and potentially bridge us to a net-negative emission world requires the creation of an entirely new industry, both in space and on Earth. Consequently, it is reasonable to argue that such a system should be developed sustainably to minimize the negative environmental, social, and economic impacts throughout all phases of the mission. This directs the scope of this search towards social and technical sustainability development frameworks. To ensure transparency, it is important that the selected frameworks are well defined and open-source.

5.1. United Nations Sustainable Development Goals

The latest IPCC report references the UN SDGs as essential for achieving ecosystem and planetary health, while highlighting that climate-resilient development should ensure human health and well-being, equity, and justice (UN, 2016; IPCC, 2022a). This aligns closely with the potential objectives of an ideal sunshade system. Given that the IPCC represents the global consensus on climate science, and considering that the SDGs were chosen from among many possible frameworks by the IPCC, the SDGs were subsequently selected as the socially oriented sustainability framework for the initial content analysis of this work. In addition, the SDGs explicitly identify climate action as one of their main goals. The UN also positions itself as a capable governance body for coordinating global geoengineering efforts (UNEP, 2023). Therefore, given the widespread acceptance of the SDGs, they offer a promising framework to assess whether the impacts of sunshades on society and nature are adequately addressed in the literature. The 17 SDGs are listed in Table 5.

Fig. 2 shows the cumulated coverage of the UN SDGs in the case study literature. Similarly, Fig. 4 shows the evolution of the UN SDGs over time (in orange). Both figures visualize the data of Table 6. For both charts, a maximum coverage of 100% per UN SDG or publication can be reached, resulting from a detailed coverage. However, an average cumulated coverage of 30% was achieved, representing the average for both graphs.

In the following, three statements from the literature assigned to specific UN SDGs are provided as an example:

SDG-09 Industry, innovation, and infrastructure:

> The most substantial barrier to implementing the technology is the excessive cost of launching the materials. Research subjects currently under study include investigating materials, investigating the shape of the sunshades, and designing a control system for maintaining the position of the sunshades, which have large reflecting/deflecting areas with

Table 5
List of 17 UN Sustainable Development Goals (UN, 2016).

Nr.	Title	Definition
SDG-01	No poverty	End poverty in all its forms everywhere.
SDG-02	Zero hunger	End hunger, achieve food security and improved nutrition and promote sustainable agriculture.
SDG-03	Good health and well-being	Ensure healthy lives and promote well-being for all at all ages.
SDG-04	Quality education	Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all.
SDG-05	Gender equality	Achieve gender equality and empower all women and girls.
SDG-06	Clean water and sanitation	Ensure availability and sustainable management of water and sanitation for all.
SDG-07	Affordable and clean energy	Ensure access to affordable, reliable, sustainable and modern energy for all.
SDG-08	Decent work and economic growth	Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all.
SDG-09	Industry, innovation and infrastructure	Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation.
SDG-10	Reduced inequalities	Reduce inequality within and among countries.
SDG-11	Sustainable cities and communities	Make cities and human settlements inclusive, safe, resilient and sustainable.
SDG-12	Responsible consumption and production	Ensure sustainable consumption and production patterns.
SDG-13	Climate action	Take urgent action to combat climate change and its impacts.
SDG-14	Life below water	Conserve and sustainably use the oceans, seas and marine resources for sustainable development.
SDG-15	Life on land	Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss.
SDG-16	Peace, justice and strong institutions	Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels.
SDG-17	Partnerships for the goals	Strengthen the means of implementation and revitalize the Global Partnership for Sustainable Development.

Table 6
UN SDG coverage of sunshade concepts and related literature from 1989–2025. Metric: “++” – detailed coverage; “+” – low to medium coverage; “-” – no coverage. The methodology is detailed in Section 3.

Author, year / UN SDG	SDG-01 No poverty	SDG-02 Zero hunger	SDG-03 Good health and well-being	SDG-04 Quality education	SDG-05 Gender equality	SDG-06 Clean water and sanitation	SDG-07 Affordable and clean energy	SDG-08 Decent work and economic growth	SDG-09 Industry, innovation and infrastr.	SDG-10 Reduced inequalities	SDG-11 Sustainable cities and communities	SDG-12 Responsible consumption and prod.	SDG-13 Climate action	SDG-14 Life below water	SDG-15 Life on land	SDG-16 Peace, justice and strong institutions	SDG-17 Partnerships for the goals
Sunshade concepts																	
Seifritz, 1989	-	-	-	-	-	-	-	-	+	-	-	-	+	-	-	-	-
Early, 1989	-	-	-	-	-	-	-	-	+	-	-	-	+	-	+	-	-
McInnes, 2002	-	-	+	-	-	-	-	-	+	-	-	-	+	+	+	-	-
Angel, 2006	-	-	-	-	-	-	-	-	+	-	-	-	+	-	-	-	-
Kennedy et al., 2013	-	-	+	-	-	-	++	+	+	+	+	+	++	+	+	+	+
Sánchez, McInnes, 2015	-	-	-	-	-	-	+	+	+	++	+	-	++	+	++	-	-
Ellery, 2016	-	-	-	-	-	-	+	+	++	-	-	+	++	-	-	-	-
Fuglesang, Herreros, 2021	-	-	+	-	-	-	-	+	++	+	+	+	++	-	+	-	+
Roy, 2022	-	+	+	-	-	-	++	+	++	+	+	++	++	+	++	+	+
Borgue, Hein, 2023	-	-	+	-	-	-	-	+	++	-	-	-	++	-	+	-	+
IPSS contributors, 2020–2025	-	-	+	-	-	-	++	++	++	+	+	++	++	-	+	++	++
Related literature																	
Keith, 2000	-	-	+	-	-	-	+	-	+	-	-	-	++	++	++	+	-
Lenton, Vaughan, 2009	-	-	+	-	-	+	-	-	-	-	-	-	++	+	+	-	-
Shepherd, 2009	-	-	+	-	-	+	-	++	++	+	-	-	++	++	+	+	+
Kosugi, 2010	-	-	+	-	-	+	-	+	++	+	+	+	++	+	+	-	-
Vaughan, Lenton, 2011	-	-	+	-	-	+	+	+	+	+	+	-	++	++	++	+	+
Corner et al., 2013	-	+	+	-	+	-	-	+	-	+	++	++	++	-	-	+	-
OHB System AG, 2020	+	-	+	-	-	-	-	-	+	+	-	-	++	-	+	+	+
Belaia et al., 2021	-	-	+	-	-	-	-	+	+	+	-	-	++	-	+	-	+
Baum et al., 2022	-	+	-	-	-	-	+	+	++	+	+	+	++	+	+	+	++
UNEP, 2023	-	-	+	-	-	-	-	-	+	++	++	-	++	+	+	++	++
PSF, FSC, 2023	-	-	+	-	-	-	+	+	++	-	+	+	++	-	+	+	+

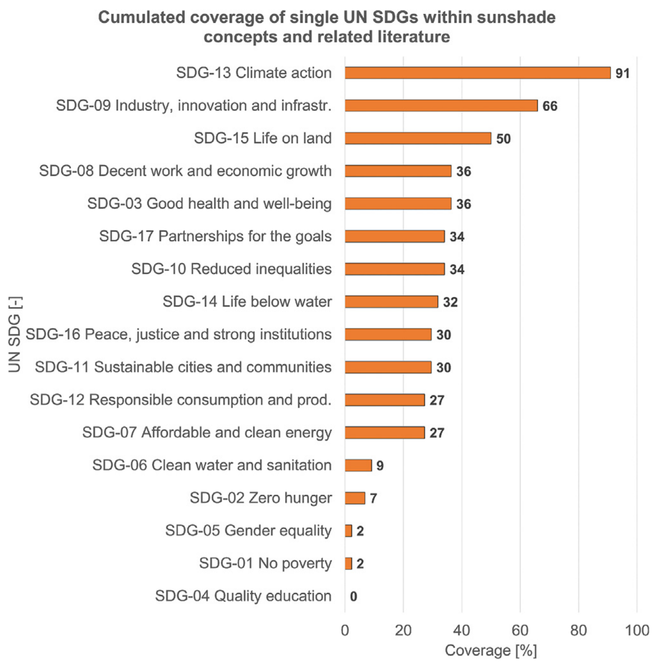

Fig. 2. Cumulated coverage of all 17 UN SDGs in the selected literature. Here, cumulated coverage represents the extent to which a UN SDG is discussed within all publications. Note that the maximum possible coverage is 100%. The underlying data set is provided in Table 6.

low weights while providing long-term reflection/ deflection of sunlight while stably positioned in space (Kosugi, 2010).

SDG-13 Climate action:

The Planetary Sunshade Foundation believes that solar radiation modification will be a necessary part of the global warming solution, safeguarding and complementing the transition away from fossil fuels and the removal of excess greenhouse gases from the atmosphere (PSF and FSC, 2023).

SDG-17 Partnerships for the goals:

The Planetary Sunshade is a large project, but achievable with commitment from the world's nations. Construction of the Sunshade would afford its creators significant prestige and economic opportunities, in addition to climate stability (PSF and FSC, 2023).

The evaluation of the coverage of the SDGs reveals several critical insights, highlighting both the focus and the gaps in previous and current research. As expected, SDG-13 Climate action stands out with the highest coverage at 91%, underscoring that climate-related concerns are the primary focus of sunshade literature. SDG-09 Industry, innovation, and infrastructure follows with 66% coverage, reflecting significant attention to the industrial and infrastructure challenges essential for the implementation of a large-scale geoengineering. This is due to the high mentions of the required industry, whether located in space, on Earth, or both, in combination with the need for an appropriate launch infrastructure and necessary innovation, such as in the field of solar sail technology.

In terms of environmental and socioeconomic impacts, the SDG-15 Life on land receives moderate attention at 50%, indicating some recognition of the effects on terrestrial ecosystems. Similarly, SDG-08 Decent work and economic growth and SDG-03 Good health and well-being are given moderate coverage, both at 36%. Although these areas are acknowledged, they may not be explored as thoroughly as the technological aspects.

SDG-17 Partnerships for the goals and SDG-10 Reduced inequalities each show 34% coverage, suggesting a recognition of the importance of global collaboration and equity. However, the moderate focus on these goals indicates that considerations of how the sunshade ecosystem and its effects can be implemented globally are underdeveloped.

Significant gaps are evident in broader socioeconomic and environmental considerations. SDGs related to marine ecosystems, energy, and water, such as SDG-14 Life below water, SDG-07 Affordable and clean energy, and SDG-06 Clean water and sanitation, show low coverage, ranging from 27% to 32%. More concerning is the minimal attention given to issues such as hunger and poverty, with SDG-02 Zero hunger, SDG-05 Gender equality, SDG-01 No poverty, and SDG-04 Quality education showing coverage as low as 0% to 7%. These are critical research gaps, particularly in assessing the potential impacts on vulnerable populations, such as the Global South. For example, a sunshade's influence on global food production and distribution must be examined, translating into research gaps on how a sustainable geoengineering world would operate.

Given the introduction of the SDGs in 2016, it was expected that coverage would increase in line with the increasing global focus on sustainability. However, the data in Fig. 4 do not show a corresponding increase in coverage, which is an unexpected result. The analysis suggests that addressing gaps, particularly those concerning broader socioeconomic and environmental implications, is crucial to improving the recognition and integration of the concept into global environmental strategies.

The SDGs provide a useful framework for identifying critical gaps, and it appears feasible to turn the results into a focused research agenda. However, the space segment, particularly the space sustainability aspect, is not reflected in the SDGs. Hence, we will move on to what is currently used among the European space industry to assess the environmental impact of space systems, including aspects of the space segment.

5.2. *European Space Agency Environmental Impact Indicators for space systems*

The European Space Agency Environmental Impact Indicators (ESA EIIs, EIIs) for space systems (see Table 7) were selected due to their specialized, rather technical focus

Table 7
List of 16 ESA Environmental Impact Indicators for space systems, adapted (ESA, 2016).

Nr.	Title	Definition
EII-01	Global warming potential	Indicates the level of RF due to GHG emissions (100 y).
EII-02	Ozone depletion potential	Stratospheric ozone depletion due to the emission of ozone-depleting substances.
EII-03	Human toxicity potential	Effect of emission of toxic substances on humans.
EII-04	Fossil resource depletion potential	Decreasing availability of natural resources (including energy resources) such as iron ore, crude oil regarded as non-living.
EII-05	Photochemical ozone formation potential	Tropospheric ozone formation due to action of solar light on primary pollutants, e.g., volatile organic compound.
EII-06	Freshwater eutrophication potential	Impacts of macro-nutrients nitrogen and phosphorus leading, mainly, to oxygen depletion because of dead algae degradation. Phosphorus is the limiting nutrient in aquatic ecosystems whereas nitrogen is the limiting nutrient in marine ecosystem.
EII-07	Marine eutrophication potential	Equals 6.
EII-08	Ionizing radiation potential	Effect on humans due to the emission of radioactive substances.
EII-09	Freshwater ecotoxicity potential	Effect of emission of toxic substances on freshwater ecosystem (fauna and flora).
EII-10	Marine aquatic ecotoxicity potential	Effect of emission of toxic substances on marine ecosystem.
EII-11	Air acidification potential	Accumulation of acidifying substances in the water particles in suspension in the atmosphere. Than acid rains modify the acid/base equilibrium of soil, groundwater, surface waters, fauna, etc.
EII-12	Primary energy consumption potential	Consumption of energetic resources (fossil, nuclear, biomass), expressed in MJ of primary energy.
EII-13	Gross water consumption potential	Water withdrawals due to industrial processes in lakes, rivers, oceans, and groundwater.
EII-14	Mass disposed in the ocean	Total mass of stages disposed in the ocean.
EII-15	AL_2O_3 emissions in air	Emissions in air of Aluminium oxide during launch event.
EII-16	Mass left in space	Total mass of space hardware remaining in orbit at the end of the mission.

on assessing the broad range of environmental sustainability impacts associated with space systems (ESA, 2016). Unlike general environmental frameworks, ESA EIIs address the unique challenges of space missions, such as the generation of space debris and the environmental impact of rocket launches. The indicators align with an ecodesign approach, aiming to minimize environmental impacts throughout the lifecycle of space systems. They cover a wide range of environmental concerns, including human toxicity, ozone depletion, and ecosystem effects. Given the scale of sunshade deployment, the importance of evaluating each EII becomes evident.

Introduced by ESA in 2016, these indicators provide guidelines for the European space sector. Since ESA is an established space agency that adheres to international standards and operates globally, the indicators are very well applicable to global space operations. Hence, by using ESA's EIIs, this study investigates if the sunshade literature applies to both European and global environmental standards in a space context.

Fig. 3 shows the cumulated coverage of the ESA EIIs within the case study literature. Similarly, Fig. 4 shows the evolution of the coverage of the ESA EIIs over time (in blue). Both figures visualize the data of Table 8. For both charts, a maximum coverage of 100% can be reached per ESA EII or publication, resulting from detailed coverage. However, an average cumulated coverage of 15% was achieved, representing the average for both graphs.

It is important to note that while the EII handbook (ESA, 2016) provides specific assessment units, the criteria coverage has been assigned based on their definition provided in Table 7. This approach was necessary to include statements that clearly contribute to the concept of an EII, even when specific units were not referenced.

In the following, three statements from the literature that have been assigned to a specific ESA EII are provided as an example:

EII-01 Global warming potential:

> Parameters related to space sunshade technology include the [. . .] CO_2 emission coefficient of placing a unit mass of sunshades [. . .] in space (Kosugi, 2010).

EII-12 Primary energy consumption:

> How much energy will be required to bring mirrors of the necessary size to the point L_1? If we assume that they consist of aluminium of mass 10 g m^{-2}, at least 45 million tonnes of material will have to be brought to L_1. We estimate that the energy required to do this is equivalent to the output of 30 nuclear power stations producing 1 GW for 20 years (Seifritz, 1989).

EII-16 Mass left in space:

> Once there, they remain on station for many decades until they wear out and are then plunged into the Sun, or are sent elsewhere to serve other purposes (Roy, 2022).

The EII-03 Human toxicity potential has the highest coverage at 34%, but it is important to recognize that this still represents a modest portion of the total possible cover-

Table 8
ESA EII coverage of sunshade concepts and related literature from 1989–2025. Metric: “++” – detailed coverage; “+” – low to medium coverage; “-” – no coverage. The methodology is detailed in Section 3.

Author, year / ESA EII	EII-01 Global warming potential	EII-02 Ozone depletion potential	EII-03 Human toxicity potential	EII-04 Fossil resource depletion potential	EII-05 Photochemical ozone formation potential	EII-06 Freshwater eutrophication potential	EII-07 Marine eutrophication potential	EII-08 Ionizing radiation potential	EII-09 Freshwater ecotoxicity potential	EII-10 Marine aquatic ecotoxicity potential	EII-11 Air acidification potential	EII-12 Primary energy consumption potential	EII-13 Gross water consumption potential	EII-14 Mass disposed in the ocean	EII-15 AL_2O_3 emissions in the air	EII-16 Mass left in space
Sunshade concepts																
Seifritz, 1989	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-
Early, 1989	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+
McInnes, 2002	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+
Angel, 2006	+	-	+	+	-	-	-	-	-	-	-	++	-	-	-	+
Kennedy et al., 2013	-	-	+	-	-	-	-	-	-	+	+	-	-	-	-	++
Sánchez, McInnes, 2015	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+
Ellery, 2016	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-
Fuglesang, Herreros, 2021	++	-	+	+	-	-	-	-	-	-	+	-	-	-	-	++
Roy, 2022	+	+	+	-	-	-	-	-	-	+	+	-	-	-	-	+
Borgue, Hein, 2023	+	+	+	-	-	-	-	-	-	-	+	-	-	-	-	+
IPSS contributors, 2020–2025	-	+	-	+	-	-	-	-	-	-	-	+	-	-	-	++
Related literature																
Keith, 2000	-	+	++	+	-	-	++	-	-	++	+	-	-	+	-	+
Lenton, Vaughan, 2009	-	-	-	-	-	-	+	-	-	-	-	-	-	+	-	-
Shepherd, 2009	-	++	+	+	-	+	++	-	-	++	+	++	-	+	-	-
Kosugi, 2010	-	+	-	-	-	-	+	-	-	+	-	-	-	-	-	-
Vaughan, Lenton, 2011	-	+	+	+	-	-	++	-	-	++	+	+	-	++	-	-
Corner et al., 2013	-	-	+	-	-	-	-	+	-	-	-	-	-	-	-	-
OHB System AG, 2020	+	-	++	-	-	-	-	-	-	-	+	-	-	-	+	-
Belaia et al., 2021	+	+	-	-	-	-	-	-	-	-	+	-	-	-	-	-
Baum et al., 2022	-	+	+	-	-	-	+	-	-	+	+	-	-	-	-	-
UNEP, 2023	-	++	+	-	-	-	-	-	-	+	+	-	-	-	-	-
PSF, FSC, 2023	-	+	+	-	-	-	-	-	-	+	+	-	-	-	-	-

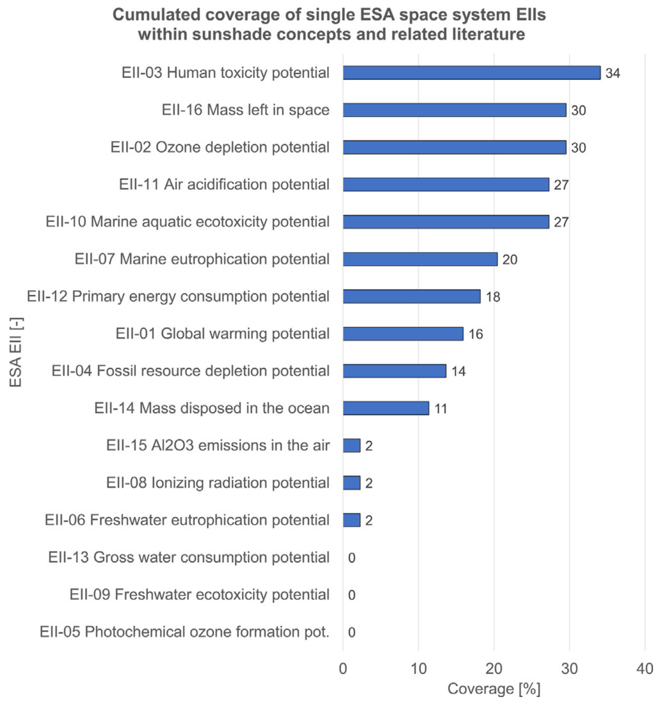

Fig. 3. Cumulated coverage of all 16 ESA space system EIIs in the selected literature. Here, cumulated coverage represents the extent to which an ESA EII is discussed within all publications. Note that while the maximum possible coverage is 100%, the x-axis limit is set to 40%. The underlying data set is provided in Table 8.

age. This suggests that many aspects of human toxicity related to sunshade deployment remain unexplored in the literature.

Both EII-16 Mass left in space and EII-02 Ozone depletion potential are covered at 30%. This indicates some awareness in the literature about potential space debris generation and the degradation of the Earth's stratospheric ozone layer due to emissions of ozone-depleting substances. However, considerations of space debris generation in the sunshade literature are far below the maximum, which is surprising given the vast amount of mass would be launched into space. It is of great interest to understand how much of this mass would remain, for example, in Earth orbits and at SEL_1, and whether this mass could be recovered and eventually incorporated into a circular space economy (CSE) to avoid debris generation. Unfortunately, the limited coverage of this topic is contrary to current efforts focused on minimizing space debris and ensuring long-term space sustainability.

Indicators related to terrestrial ecosystems, such as EII-11 Air acidification potential and EII-10 Marine aquatic ecotoxicity potential, show 27% coverage. This suggests that while the literature acknowledges these environmental impacts, the current level of coverage is inadequate for a comprehensive assessment. The potential for air acidification and harm to marine ecosystems, which are crucial considerations for any large-scale geoengineering effort, needs to be investigated more thoroughly.

The EII-01 Global warming potential, despite being directly relevant to the primary objective of sunshades, has only 16% coverage. This is particularly concerning, as it highlights a significant research gap in understanding how sunshades might influence global warming through their production and deployment to space. Beyond the sunshades themselves, it is crucial to consider the production of launch and space transportation vehicles as well as fuel production; just a few examples of this entirely new potential industry. As mentioned earlier, some authors advocate for outsourcing this industry to space to reduce the global warming potential. However, since climate change proliferates, it may be necessary to begin sunshade development and production on Earth now, and then gradually shift

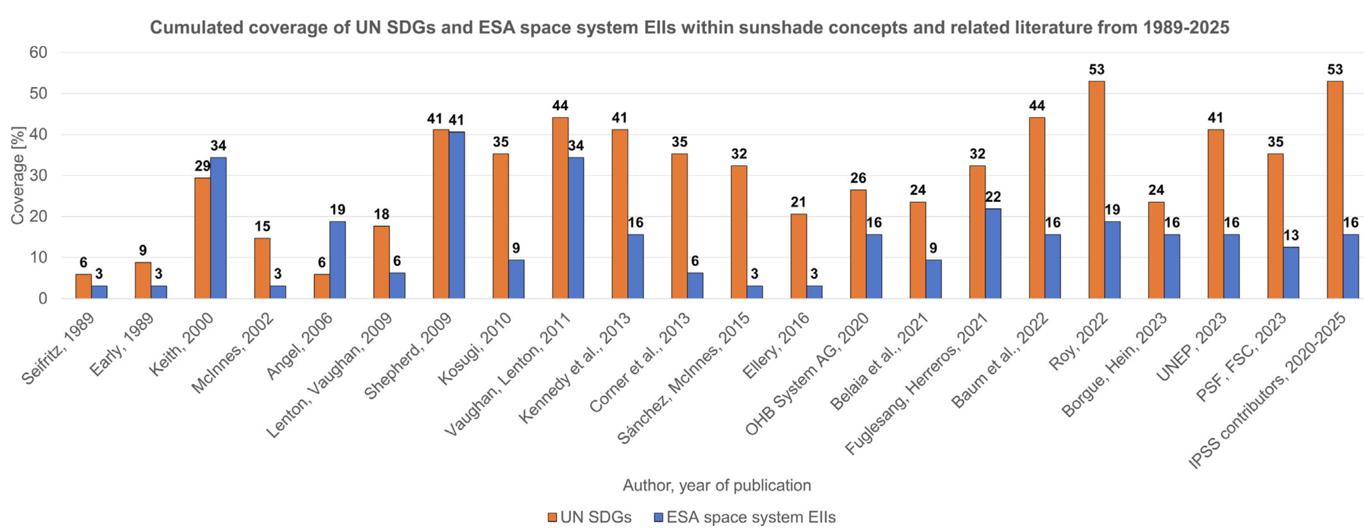

Fig. 4. Cumulated coverage of UN SDGs (in orange) and ESA space system EIIs (in blue) in the selected literature. Here, cumulated coverage represents the extent to which the UN SDGs and ESA space system EIIs are discussed within a specific publication. Note that while the maximum possible coverage is 100% each, the y-axis limit is set to 60%. The underlying data set is provided in Table 6 and Table 8.

towards space as the needed technology becomes available on a larger scale. Although the construction of sunshades in space using space resources seems like a favorable idea, the environmental impact of launching the required infrastructure is essential. Hence, the global warming potential needs to be assessed for different approaches to enable informed decision making. Similarly, the EII-04 Fossil resource depletion potential is covered only at 14%, highlighting an underestimation of the extensive resource consumption on Earth and in space that would be necessary for the production and deployment.

The coverage of indicators related to freshwater ecosystems, such as EII-06 Freshwater eutrophication potential, EII-13 Gross water consumption potential, and EII-09 Freshwater ecotoxicity potential is negligible, with some indicators showing 0% coverage. This is alarming, especially considering that freshwater ecosystems could be significantly impacted.

The EIIs provide a comprehensive framework and will become an appropriate tool for assessing the environmental impacts of sunshades once the literature has matured. For now, they primarily serve the important role of identifying research gaps. In particular, there has been no significant increase in coverage over time; see Fig. 4. Given these gaps, particularly in areas directly related to the objectives of sunshades, such as the global warming potential, resource depletion, and various ecotoxicity potentials, there is a pressing need to deepen research on these topics.

The content analysis of the coverage of ESA space system EIIs provides important insights. However, the EIIs do not fully address the unique challenges of geoengineering and in particular space-based sunshades. This represents the lack of frameworks specifically designed to evaluate the state of the art, covering the whole bandwidth of social, technical, geoengineering, and sunshade-specific perspectives. Hence, the need for a tailored development framework arises, which is proposed in the next section.

6. Sunshade Development Criteria

Informed by the extensive survey and study presented in previous sections, a set of 18 SDC was developed. Being the first comprehensive framework specifically for sunshade development, it offers a structured foundation for their development, evaluation, comparison, and maturation. This framework not only incorporates sustainability considerations but also acts as a design guide for the required ecosystem around the sunshade itself. It serves as a tool to identify gaps in current approaches and aims to facilitate discussions among different stakeholders ranging from engineers and researchers to policymakers in space systems, climate engineering, and sustainability governance.

Summarized in Table 9, the SDC aim to reflect the broad and far-reaching impacts of sunshade deployment on Earth and in space, capturing both the opportunities and the challenges. It intentionally offers a more balanced view by considering not only technical aspects but also social, environmental, economic, ethical, geopolitical, and scientific factors. Although the authors do not claim the SDC to be exhaustive, they do provide, for the first time, a structured approach to the sustainable and holistic development and evaluation of sunshades and their associated ecosystems.

6.1. Criteria definition

6.1.1. SDC-01: Radiative forcing potential

Lenton and Vaughan (2009) investigated the RF potential of 19 SRM and carbon dioxide removal (CDR) approaches, including sunshades. While they refer to "climate cooling effectiveness" (Lenton and Vaughan, 2009), the IPCC defines the RF potential as "change in net irradiance at the tropopause, after allowing stratospheric temperatures to readjust to radiative equilibrium" (IPCC, 2015).

However, spatio-temporal SRM is needed to achieve global uniform cooling (Sánchez and McInnes, 2015; Belaia et al., 2021). This type of control enables possible benefits, such as maximization of global welfare with respect to mitigation and adaptation only scenarios, preservation of biodiversity, prevention of CTPs, and pursuit of SDGs such as reduction of global inequalities (Belaia et al., 2021). Even redistribution of the risk of malaria in developing countries is envisaged (Carlson et al., 2022). In addition to the positive aspects mentioned, misuse of this very powerful technology is possible and would have unprecedented negative consequences.

It should be noted that a reduction in RF through SRM causes spatial and spectral patterns different from those of GHGs. This means that SRM methods, even when scaled to offset net global RF contributions through GHGs, cannot fully reverse the effects of GHGs on climate (Belaia et al., 2021), besides the simple fact that no SRM method removes any GHG from our atmosphere. However, sunshades have the advantage of being able to block certain infrared wavelengths, as opposed to scattering all of them like terrestrial SRM, allowing for significantly less perturbation of the global hydrological cycle while providing the same RF (Keith et al., 2020).

Using RF potential for defining a single concept's ability or comparison of different approaches avoids misinterpretations, as literature often proposes reductions in GMT based on different modeling and calculation methods, e.g., IPSS (Fix, 2021) and RSS literature (Fuglesang and De Herreros Miciano, 2021), while RF potential is a transparent criterion about a concept's capability. Hence, in this work the RF potential refers to the ability to generate scaleable spatio-temporal RF to achieve a global uniform cooling effect, while it is up to discussion whether a global uniform cooling effect is the desired outcome.

Table 9
List of 18 Sunshade Development Criteria.

Nr.	Title	Definition
SDC-01	Radiative forcing potential	Ability to generate scaleable spatio-temporal RF to achieve a global uniform cooling effect (Sánchez and McInnes, 2015; Belaia et al., 2021).
SDC-02	Deployment time	It is divided into two periods: The time required from (i) today to the start of deployment, e.g. including development time, and (ii) from there to full deployment.
SDC-03	Lifetime of effect	Time until the effect no longer triggers measurable changes after partial and full deployment, taking into account heterogeneity of decay rates.
SDC-04	Efficacy	"Ability to effect surface temperature changes" (Lenton and Vaughan, 2009).
SDC-05	Side effects	Captures human, environmental, economic (including costs), and all other unintended consequences associated with the generation of spatio-temporal RF that differ from a uniform distribution of cooling effect.
SDC-06	Controllability	The system must allow for transparent control, including independent and open source monitoring, implementation of a transparent governance framework, continuous maintenance and replenishment, and low and assessable risk of failure. The aim is to ensure that the system is used solely for the benefit of humanity, making it a technical and social challenge.
SDC-07	Reversibility	Ability to undo the effect and the understanding of how long the process takes, together with the social, political, technical, and economic consequences of such action (Shepherd, 2009).
SDC-08	Technology readiness level	Assessment of space technology maturity introduced by NASA in 1970s (Tzinis, 2021).
SDC-09	IPCC mitigation scenarios and data	Incorporation of the latest IPCC findings, particularly given pathways.
SDC-10	Integrated assessment	Incorporation of the sunshade's deployment impact, along with mitigation and adaptation measures, into regional and global climate change assessment models.
SDC-11	Sustainability	"Meeting the needs of the present without compromising the ability of future generations to meet their own needs" (UNOOSA, 2021; UN, 2023), applied indefinitely both to Earth-based and future space-based generations.
SDC-12	Ethics	Ethical concerns, such as moral hazard, technical fix argument, slippery slope argument, unpredictability argument, termination shock and concerns about enhanced weather control.
SDC-13	Governance	"Technical, legal, ethical, economic and other concerns" that "need to be balanced carefully in a policy (...) framework which is international in scope and remains flexible in light of fresh evidence" (Shepherd, 2009). It must be applicable to "small-scale outdoor experiments, technology development, financing (...)[,] deployment" (UNEP, 2023), operations, and phase-out.
SDC-14	Wording and framing	"The way we describe things and the analogies we use have an influence on how facts are perceived" (OHB SE, 2022).
SDC-15	Public perception	In a technology context, "all kinds of perceived benefits, barriers, or risks associated with a specific technology" (Arning et al., 2019).
SDC-16	Energy justice	"A global energy system that fairly disseminates both the benefits and costs of energy services, and one that has representative and impartial energy decision making" (Sovacool et al., 2017).
SDC-17	Social acceptability	"The outcome of a collective judgment or collective opinion of a project, plan or policy" (Gouvernement du Québec , 2023).
SDC-18	Social justice	"The objective of creating a fair and equal society in which each individual matters, their rights are recognized and protected, and decisions are made in ways that are fair and honest" (Oxford Reference, 2023).

6.1.2. SDC-02: Deployment time

The deployment time is a frequently mentioned criterion. However, a detailed study is currently missing. It is an important factor to know because it heavily influences mitigation and adaptation strategies. Furthermore, the deployment time is influenced by technological readiness, funding, regulations, and scalability.

In line with the work of Lenton and Vaughan (2009); Vaughan and Lenton (2011) and the UN (UNEP, 2023), the deployment time is divided into two periods: The time required from (i) today to the start of deployment, e.g. including development time, and (ii) from there to full deployment. The first phase depends on research, testing, and policy decisions, while the second is driven by logistic and deployment challenges. A dynamic scenario-based assessment is essential to account for technological and geopolitical variability.

6.1.3. SDC-03: Lifetime of effect

The lifetime of effect for different geoengineering methods was assessed by Vaughan and Lenton (2011). In their previous work they introduced the effect decay rate (Lenton and Vaughan, 2009), which can be seen as a similar approach, but the lifetime of the effect adds valuable information about the progression of the effect's decrease.

In line with their work, the lifetime of effect is given here as the time until the effect no longer triggers measurable changes after partial and full deployment, taking into account the heterogeneity of decay rates. In the case of sunshades, the lifetime of effect is also influenced by factors such as degradation from fast-traveling microparticles, micrometeoroites, radiation, and solar flares (see the depreciation rate in Kosugi (2010)). This requires determining the replenishment rate and maintenance strategies needed to ensure the sunshade's efficacy over time.

6.1.4. SDC-04: Efficacy

Efficacy generally means reaching the desired goal. It must not be confused with efficiency, which means accomplishing something with minimal resources and effectiveness, which is the ability to produce a desired result (Enrique and Marta, 2020; Cunff, 2020).

In the context of geoengineering, Belaia et al. (2021) defines that "efficacy captures the limited ability of ...[SG] to reduce aggregate climate damages due to the heterogeneity of climate response to SG" (SG means solar geoengineering, which equals SRM), while Lenton and Vaughan (2009) define it as the "ability to effect surface temperature changes" with respect to different geoengineering methods (Lenton and Vaughan, 2009; Sánchez and McInnes, 2015; Belaia et al., 2021).

Efficacy is challenging to assess, but is highly relevant for decision making. While effectiveness is already covered by RF potential, and efficiency is part of the sustainability criterion, efficacy specifically addresses the ability of the sunshade to achieve its intended climate control outcomes. This is crucial for understanding both its performance and the time it may take to observe these changes after the deployment. As Lenton and Vaughan's definition of efficacy is more accessible, it has been adapted for this work.

6.1.5. SDC-05: Side effects

Sunshades are very likely to cause unintended side effects (Lunt et al., 2008), and trade-offs must be made regarding non-geoengineering scenarios, the latter of which are likely to be more costly (Belaia et al., 2021; Deloitte, 2022). In that context, Belaia et al. (2021) included side effects within impact criterion that "captures the human and environmental side effects and costs associated with producing the SG's RF".

Belaia et al. (2021) also assume that side effects increase with quadratic influence when SRM is used to fully offset anthropogenic climate change, resulting in the same damage as climate change would cause. Therefore, investigating this criterion is of utmost importance.

The economic side effects, i.e., costs for sunshade development, production, deployment, operations, maintenance, and end-of-life strategies, should be expressed as a percentage of the gross world product per year. In addition, it is important to determine the economic benefits that sunshades might bring in relation to the cost of climate change to facilitate cost-benefit analysis. However, this work will not introduce a separate cost criterion, which is explained later in this Section. Instead, it will see costs as the economic part of the side effects criterion (i.e., how much of the yearly gross world product will be "consumed" in the decades to come).

To summarize, the criterion side effects captures human, environmental, economic (including costs), and all other unintended consequences associated with the generation of spatio-temporal RF that differ from a uniform distribution of cooling effect.

6.1.6. SDC-06: Controllability

The need for the ability to control a given geoengineering method after deployment is often mentioned as a key capability among the literature (Vaughan and Lenton, 2011; Sánchez and McInnes, 2015; Fuglesang and De Herreros Miciano, 2021; Bromley et al., 2023). However, there is more to it than "just" implementing spatio-temporal RF.

The design of a sunshade system must allow for transparent control, including independent and open source monitoring of all activities, implementation of a transparent governance framework, continuous maintenance and replenishment, and low and assessable risk of failure. The aim is to ensure that the system is used solely for the benefit of humanity, making it a technical and social challenge.

6.1.7. SDC-07: Reversibility

In their reports, both Shepherd (2009) and OHB System AG (2020) came to the conclusion that a more detailed assessment is needed, which led the former to propose a set of criteria that future geoengineering proposals should address, with the goal of greater comparability. Those criteria include reversibility, which can be understood as the ability to undo the effect and the understanding of how long the process takes, together with the social, political, technical and economic consequences of such action (Shepherd, 2009). Especially in the context of space-based geoengineering, no system should be implemented without knowing how it can be reversed and how long it will take – hence, reversibility is added to the SDC.

6.1.8. SDC-08: Technology readiness level

The technology readiness level (TRL) methodology was introduced by NASA in the 1970s and is used to assess the maturity of space technology (Tzinis, 2021). However, most likely due to the conceptual nature of the sunshade literature, TRL methodology is rarely applied. Only IPSS-related publications (Fix, 2021; Maheswaran, 2021; Maheswaran and Fix, 2021; Maheswaran et al., 2022), Fuglesang and De Herreros Miciano (2021), and Borgue and Hein (2023) apply the TRL methodology to a different extent.

Borgue and Hein (2023) additionally use the advancement degree of difficulty (AD^2) methodology, which is used to assess the risk of developing new technologies and addresses the limitations of TRL, as the latter does not address the difficulty of reaching a higher level (Bilbro, 2008).

It is suggested that at least the TRL standard will be adapted by future sunshade-focused publications to allow for comparative studies but also to provide information on the current state of the art, allowing research gaps to be addressed and, e.g., informed decision making on resource allocation.

6.1.9. SDC-09: IPCC mitigation scenarios and data

The IPCC assessment reports, such as the latest AR6 (IPCC, 2023), represent the most comprehensive work on climate change and the global scientific consensus. Therefore, it is of utmost importance that future work incorporates those findings, particularly the given pathways. This would increase the scientific relevance of any sunshade concept and generally enhance the credibility of the field, while allowing for evidence-based assessment.

6.1.10. SDC-10: Integrated assessment

As stated in Section 1, the deployment of sunshades, if considered necessary, must only be implemented as a supplement to a strong mitigation and adaptation scenario. This highlights the need for any geoengineering concept to be evaluated in the same integrated manner to ensure comparability and informed decision making. Furthermore, it is likely that several geoengineering methods will be implemented at the same time, and this possibility should also be reflected in the assessments.

Wigley (2006) proposed a combined mitigation and geoengineering (SAI method) strategy to address the increase in ocean acidity in an SAI-only scenario. Kosugi (2010) evaluates sunshades from a cost-effectiveness point of view, in combination with CO_2 mitigation efforts. Belaia et al. (2021) went further and published an integrated assessment model that incorporates SG, CDR, and mitigation into an assessment model to analyze trade-offs, but did not include adaptation.

It should be built upon these modeling efforts to enable informed decision making. Hence, the integrated assessment criterion refers to the incorporation of the sunshade's deployment impact, along with mitigation and adaptation measures, into regional and global climate change assessment models.

6.1.11. SDC-11: Sustainability

Sustainability is a fundamental criterion that addresses both Earth- and space-related contexts. In 1987, the UN Brundtland Commission defined sustainability as "meeting the needs of the present without compromising the ability of future generations to meet their own needs" (UN, 2023). This concept is typically built on three pillars: environmental, social, and economic.

In the space context, the Guidelines for the Long-term Sustainability of Outer Space Activities, adopted by the UN Office for Outer Space Affairs (UNOOSA) in 2019, extend this definition. According to UNOOSA, the long-term sustainability of space activities is "the ability to maintain the conduct of space activities indefinitely into the future in a manner that realizes the objectives of equitable access to the benefits of the exploration and use of outer space for peaceful purposes, in order to meet the needs of the present generations while preserving the outer space environment for future generations" (UNOOSA, 2021).

As noted in Centers et al. (2020), the deployment of sunshades raises important sustainability challenges in space, necessitating the integration of sustainability principles (e.g., ecodesign) from the early design stages. One way to achieve this may be through the implementation of a CSE, moving away from the linear "make, take, waste" approach, to reduce the need for and frequency of launches from Earth (Bahlmann et al., 2024). In that way, resource efficiency would be maximized and end-of-life scenarios for all related assets would be avoided. In this context, a shift in mindset is proposed, replacing the concept of end-of-life with end-of-use, giving every resource a new afterlife by design. Furthermore, utilizing in situ resources could contribute to these goals, though it remains to be seen whether such resource use can be achieved in a truly sustainable manner.

Although sunshades are designed to mitigate climate change and contribute to sustainability on Earth, they also have the potential to compromise space sustainability, a concept known as the space sustainability paradox (Wilson and Vasile, 2023). This paradox reflects the tension between the use of space-based technologies to promote sustainability on Earth while potentially polluting and harming the space environment. Key issues to consider include orbital debris and occupation, light pollution, and maintaining the ability for future space traffic and travel.

In this work, sustainability is understood in the context of the 1987 UN definition and the 2019 UNOOSA extension for space, applied to both Earth-bound and future space-based generations. It reflects the importance of ensuring that space activities, including sunshades, do not compromise the long-term sustainability of space environments while contributing to the protection of Earth.

6.1.12. SDC-12: Ethics

Like global warming, geoengineering presents unprecedented challenges and concerns that need to be addressed (Diffenbaugh and Burke, 2019; Roeser et al., 2020). The ethics criterion is often mentioned in the literature, to varying degrees (Keith, 2000; Roy, 2001; Shepherd, 2009; Kennedy et al., 2013; Corner et al., 2013; OHB System AG, 2020; Roeser et al., 2020; Roy, 2022; UNEP, 2023). It covers all ethical concerns related to geoengineering, such as moral hazard, technical fix argument, slippery slope argument, unpredictability argument, termination shock, and concerns about enhanced weather control, which will be briefly explained:

Moral hazard comes into play if the sunshade system works as expected, given concerns it could prolong mitigation and adaptation efforts and that the discussion about the implementation of such technology already shifts financial, political and intellectual resources from these efforts (Robock et al., 2008; Roy, 2022; Immega, 2022; PSF, 2023; UNEP, 2023).

The unpredictability argument translates into "we just do not know enough", which is very likely the case, as sunshades would interfere with a highly complex system. There is an urgent call for more research funding and more nations and institutions to get involved, especially the ones from the global south, who will likely suffer the most both from climate change and geoengineering. Critics mention that the effects on the environment, ecosystems, and societies are widely unknown and difficult to model. Unintended and irreversible consequences could be the outcome or the system does not have the desired effect (Keith, 2000; UNEP, 2023).

The slippery slope argument states that humanity will never stop using and advancing on geoengineering to suit the global environment needs, once implemented. This could already begin with small outdoor experiments that lead to large-scale deployment. Especially if several nations, institutions, or companies carry out deployments at the same time, it poses the risk of conflict and even war (UNEP, 2023). The literature states that, while experimental validation is required, the scale and duration of these experiments would likely need to be similar to the actual deployment to obtain reliable data on the impacts on the climate system (not only weather) (MacMynowski et al., 2011). This means that clarity about the global impacts of geoengineering deployment can only be achieved by a deployment decision (MacMartin and Kravitz, 2016). Moreover, since proponents view geoengineering as a precursor to terraforming other planets to make humanity a multi-planetary species, the slippery slope argument takes on another dimension.

The technical fix argument criticizes that, with geoengineering, a new technology would be added to counter the side effects of fossil fuel combustion instead of addressing the cause of the problem. Furthermore, geoengineering is not a long-term solution.

The termination shock problem states that geoengineering as a technical solution to combat climate change should not be turned off immediately, even if it does not work as expected. A sudden stop, due to geopolitical instabilities, manipulation, a technical or simply human error would result in a rapid temperature increase causing devastating ecological consequences, often referred to as one of the biggest risks of geoengineering (Kosugi, 2010; Parker and Irvine, 2018; UNEP, 2023).

Sunshades need to be able to impact both weather and climate (Roy, 2001), where weather refers to local, short-term conditions, and climate to long-term weather patterns in a specific region. This is necessary because the literature suggests that a global, uniform decrease in RF does not result in a globally uniform cooling effect (MacMartin et al., 2013; Sánchez and McInnes, 2015; Kravitz et al., 2016; Dai et al., 2018; Belaia et al., 2021). This discrepancy arises due to factors such as different climate seasons in the northern and southern hemispheres, the curvature of the Earth, and the fact that changes in the atmosphere, and cloud or surface albedo do not result in equivalent changes in planetary albedo (Lenton and Vaughan, 2009). As a result, no geoengineering method should be applied uniformly. Furthermore, the effects of uniformly applied SRM could counteract the intended objectives (Dai et al., 2018).

While any SRM method needs to be able to adapt to natural events that alter the Earth's RF balance, such as volcano eruptions or extreme weather events, and to counterbalance negative side effects of the method itself, it becomes evident that a deep understanding of weather control rather than "only" climate control is required for a successful implementation of SRM (Ellery, 2016; Kravitz et al., 2016). Since the underlying principle of SRM methods is the same, it also applies to sunshades (Sánchez and McInnes, 2015).

Therefore, it is very likely that this technology will need to be not only very well understood but also very precisely executed, resulting in controlled local changes on a regular basis (MacMartin et al., 2013; Sánchez and McInnes, 2015; MacMartin et al., 2016). *This would be a very powerful tool* that raises concerns about which set of design choices will allow simultaneous control of all variables in all regions (Kravitz et al., 2016). Subsequently, it opens the door to potential weaponization (Baum et al., 2022). Based on human history, it can be seriously questioned whether humanity is mature enough to use this technology for the benefit of all, if even possible.

6.1.13. SDC-13: Governance

Governance issues are of central concern and are often mentioned in the literature (Shepherd, 2009; Centers et al., 2020; Baum et al., 2022), yet no consensus has emerged. However, the UN sees itself in a position to host an inclusive panel on governance questions (UNEP, 2023).

In addition, Belaia et al. (2021) note the importance of governance as they predict the implementation of geoengineering to be likely beneficial, when carried out through a benevolent decision-making process. One of the pathways predicts an increase in global welfare compared to mitigation-adaptation scenarios, while the costs associated with climate change decrease by about 43% with limited deployment and mid term phase-out of SRM. It makes the case that good governance has the potential to positively impact the success of geoengineering (Belaia et al., 2021).

Hence, governance refers to "technical, legal, ethical, economic and other concerns" that "need to be balanced carefully in a policy (...) framework which is international in scope and remains flexible in light of fresh evidence" (Shepherd, 2009). It must be applicable to "small-scale outdoor experiments, technology development, financing (...) [,] deployment" (UNEP, 2023), operations, and phase-out.

6.1.14. SDC-14: Wording and framing

In social and communication science, wording and framing refer to "the way we describe things and the analogies we use have an influence on how facts are perceived" (OHB SE, 2022). It is a very powerful tool, but in the geoengineering context it is rarely studied, with Keith (2000); Corner et al. (2013); OHB SE (2022) providing exceptions.

Although sunshades are often described in technical terms, such as "occulting disks" (Sánchez and McInnes, 2015; Borgue and Hein, 2023), there may be more effective terminology to improve social acceptability and public perception. As demonstrated in PSF and FSC (2023), careful framing and language can play a crucial role in fostering broader public support, which in turn could help secure more research funding. Nebling stated in OHB SE (2022) that "a study showed that people are more positive about the removal of carbon dioxide from the atmosphere by technical means if you describe the method as a kind of artificial tree, i.e. use an analogy from nature, than if you try to explain the required machines in more detail."

This raises the question of whether "geoengineering" itself is an appropriate term, a point partially addressed by Keith (2000). The terminology used in this field can significantly influence public engagement, making it essential to evaluate how concepts are framed. To ensure that these aspects are properly considered, the wording and framing criterion has been included as part of the SDC framework, emphasizing the importance of clear and effective communication in advancing research and public discourse.

6.1.15. SDC-15: Public perception

Public perception serves as a foundational element in achieving social acceptability (SDC-17), as it directly influences policy decisions and industry responses to new technologies. In the context of geoengineering, public perception can be defined as "all kinds of perceived benefits, barriers, or risks associated with a specific technology" (Arning et al., 2019). Understanding public perception is crucial for guiding both the acceptance and the deployment of technologies such as sunshades.

Despite its importance, public perception is rarely explored in the geoengineering literature. Some notable studies include Arning et al. (2019) and Corner et al. (2013), and a recent contribution by Baum et al. (2024). Furthermore, (Baum et al., 2022) conducted an expert perception study focused on space-based geoengineering, and Sovacool et al. (2022, 2023) investigated expert opinions on various geoengineering strategies, including sunshades.

Given the critical role of public perception in influencing a potential sunshade deployment, this criterion was incorporated into the SDC framework to address the existing research gap and to emphasize the need for more focused studies in this area.

6.1.16. SDC-16: Energy justice

The importance of energy justice is diverse. First, like any SRM method, a sunshade would result in unequal global solar radiation reduction and will subsequently affect the Earth-bound solar energy sector. Second, the need to transition to low carbon energy production is inevitable (McCauley et al., 2019; Van Bommel and Höffken, 2021), and some sunshade concepts propose the incorporation of SBSP capabilities, as mentioned in Section 2.

Additionally, regions on Earth will have to be determined where severe weather events are more acceptable and regions that have to be specifically protected, e.g., the ones containing critical energy infrastructure such as nuclear power plants, but also wind and solar energy farms and the electrical grid itself.

Sunshades positioned at SEL_1 could have a significant impact on SBSP systems in geostationary orbit, as well as on solar arrays of satellites in Earth orbit, by reducing the amount of solar radiation reaching them. This reduction could lower the efficiency of these solar energy systems, which are critical for both space-based operations and Earth-bound energy needs, raising concerns about the broader implications for the global transition to low-carbon energy production.

Different energy justice frameworks have been introduced (Sovacool and Dworkin, 2015; McCauley et al., 2019), but in this work it is referred to "as a global energy system that fairly disseminates both the benefits and costs of energy services, and one that has representative and impartial energy decision making" (Sovacool et al., 2017).

6.1.17. SDC-17: Social acceptability

The Royal Society report highlights the importance of public acceptability as a critical criterion for assessing geoengineering projects (Shepherd, 2009). In this study, the term social acceptability is used, which is more commonly recognized in social sciences. Social acceptability cannot be quantified, but can be described as "the outcome of a collective judgment or collective opinion of a project, plan or policy" with pillars such as "participation in decision-making, trust in the promoters and institutions" and "real or perceived risks" (Gouvernement du Québec , 2023).

Achieving social acceptability for geoengineering initiatives is essential, especially given the potential scale and impact of sunshades. By fostering trust, ensuring transparency, and involving the public in decision-making processes, the likelihood of securing social acceptability for geoengineering methods increases. Hence, this criterion was added to the evaluation framework to address the complex social dynamics involved in these large-scale interventions.

6.1.18. SDC-18: Social justice

Social justice covers how risks and benefits are shared in different groups and can be defined as the "objective of creating a fair and equal society in which each individual matters, their rights are recognized and protected, and decisions are made in ways that are fair and honest" (Oxford Reference, 2023). As climate change and geoengineering will influence regions and communities differently, social justice must be a priority during all phases of the program to reduce global inequalities.

6.2. Exclusion of a cost criterion

As discussed, this work proposes cost as the economic part of side effects. Although low-cost geoengineering options are likely to increase the number of countries that would contribute to geoengineering efforts (Belaia et al., 2021), it should not be the highest priority, as it would likely lead to early resource allocation towards the most inexpensive methods – or those that claim to be. The deployment of the cheapest methods is likely associated with the acceptance of increased side effects resulting in an equally increased global inequality, which is reflected in the current bias towards SAI (Shepherd, 2009; UNEP, 2023; PSF, 2023).

Hence, a cost-focused debate could lead to the exclusion of more environmentally friendly solutions such as sunshades (Keith et al., 2020; UNEP, 2023), of which the deployment costs could likely be reduced to a more economical level if research efforts were shared equally. Furthermore, current cost estimates could have huge margin errors, which likely adds to a distorted evaluation of different methods. Instead, we should ask ourselves if a new way of assessment is appropriate, as the general pursuit of low costs and high profits brought us in today's situation.

In addition to these considerations, it is assumed that costs will be a minor issue when decision makers and residents of developed countries realize what lies ahead. That is, because an estimated annual spending of only 2% gross world product is required to implement geoengineering (SRM and CDR) to compensate for anthropogenic climate change. That equals the North Atlantic Treaty Organization contribution target, while the cost of climate change will be multiple times higher, as previously mentioned.

6.3. Criteria classification

Table 10 categorizes the SDC into technical and social dimensions, following the approach of the Royal Society (Shepherd, 2009). The classification highlights the distribution of the criteria across these two domains, illustrating their overlap and distinct characteristics.

The table demonstrates that the SDC set is relatively balanced, with multiple criteria strongly associated with both technical and social aspects. Specifically, 10 criteria fall within both dimensions, highlighting the interdisciplinary nature of sunshade development considerations, while four criteria are classified as technical and four as social. For instance, SDC-08 Technology readiness level is exclusively technical, whereas SDC-18 Social justice is purely social.

The SDC intentionally put a strong focus on sustainability. While SDC-11 Sustainability specifically addresses space and Earth-based sustainability issues and is listed as a distinct criterion, sustainability considerations are included throughout the framework. For example, SDC-05 Side effects and SDC-07 Reversibility reflect environmental sustainability by addressing unintended consequences and the ability to undo interventions. Similarly, SDC-16 Energy justice and SDC-17 Social acceptability ensure that implementation aligns with ethical and societal sustainability. This integration makes the framework a comprehensive tool for evaluating the wide-ranging aspects of sunshade deployment in order to enable discussions among researchers and policymakers in space systems, climate engineering, and sustainability governance.

Table 10
Classification of the SDC into social and technical criteria.

Nr.	Title	Criteria dimension: Technical	Social
SDC-01	Radiative forcing potential	×	×
SDC-02	Deployment time	×	×
SDC-03	Lifetime of effect	×	
SDC-04	Efficacy	×	
SDC-05	Side effects	×	×
SDC-06	Controllability	×	×
SDC-07	Reversibility	×	
SDC-08	Technology readiness level	×	
SDC-09	IPCC mitig. scen. and data	×	×
SDC-10	Integrated assessment	×	×
SDC-11	Sustainability	×	×
SDC-12	Ethics	×	×
SDC-13	Governance	×	×
SDC-14	Wording and framing		×
SDC-15	Public perception		×
SDC-16	Energy justice	×	×
SDC-17	Social acceptability		×
SDC-18	Social justice		×

7. Sunshade Development Criteria applied to sunshade literature

This section analyzes the SDC coverage within the case study literature. Fig. 5 provides a breakdown of the coverage of individual SDC, providing insight into which criteria have been prioritized within the research community. Fig. 6 highlights the cumulated coverage of SDC in different sunshade concepts and related literature from 1989 to 2025, providing insights into the progression of research focus. Both figures visualize the data provided in Table 11, and as in the previous analysis, a maximum cumulative coverage of 100% can be reached. This analysis enables the identification of gaps in the current literature and highlights areas where further research is needed to achieve a more balanced and comprehensive understanding of sunshades.

The coverage of SDC in the case study literature reveals several important trends and gaps that require attention. While Fig. 6 shows a general increase in coverage over time, two notable peaks emerge around 2009–2011 and 2020–2025. These peaks suggest concentrated efforts during these periods to address a broader range of criteria. Although the field is maturing over time, moving beyond

Table 11
SDC coverage of sunshade concepts and related literature from 1989–2025. Metric: "++" – detailed coverage; "+" – low to medium coverage; "-" – no coverage. The methodology is detailed in Section 3.

Author, year / ESA EII	SDC-01 Radiative forcing potential	SDC-02 Deployment time	SDC-03 Lifetime of effect	SDC-04 Efficacy	SDC-05 Side effects	SDC-06 Controllability	SDC-07 Reversibility	SDC-08 Technology readiness level	SDC-09 IPCC mitig. scen. and data	SDC-10 Integrated assessment	SDC-11 Sustainability	SDC-12 Ethics	SDC-13 Governance	SDC-14 Wording and framing	SDC-15 Public perception	SDC-16 Energy justice	SDC-17 Social acceptability	SDC-18 Social justice
Sunshade concepts																		
Seifritz, 1989	+	-	+	-	+	-	-	-	-	-	+	-	-	-	-	-	-	-
Early, 1989	-	+	-	-	-	+	-	-	-	-	-	+	-	-	-	-	+	+
McInnes, 2002	-	-	-	-	+	+	-	-	-	-	+	-	-	-	-	-	-	-
Angel, 2006	-	+	-	-	+	+	+	-	-	-	-	-	-	-	-	-	-	-
Kennedy et al., 2013	+	-	-	-	++	+	+	+	+	-	+	+	-	-	+	+	+	+
Sánchez, McInnes, 2015	++	++	-	++	+	++	-	-	+	-	+	-	-	-	-	+	-	-
Ellery, 2016	-	+	-	-	-	+	+	-	-	-	+	+	-	-	+	-	-	-
Fuglesang, Herreros, 2021	-	++	+	+	++	++	+	++	+	-	+	-	+	-	-	-	-	+
Roy, 2022	++	+	+	+	++	+	+	-	+	+	++	+	+	-	-	+	-	-
Borgue, Hein, 2023	-	+	-	-	+	-	-	++	+	-	-	-	-	-	-	-	-	-
IPSS contributors, 2020–2025	+	++	+	-	+	+	+	++	++	+	++	+	++	-	-	+	+	-
Related literature																		
Keith, 2000	+	+	-	+	++	+	+	-	+	+	-	++	+	++	+	-	-	+
Lenton, Vaughan, 2009	+	-	-	+	+	++	-	-	+	-	-	-	-	-	-	-	-	-
Shepherd, 2009	+	++	+	+	++	++	++	+	++	+	+	++	++	-	++	-	++	++
Kosugi, 2010	+	++	++	+	++	-	-	-	++	++	+	++	-	-	-	-	-	-
Vaughan, Lenton, 2011	++	++	++	++	++	++	++	-	++	++	+	+	+	-	+	-	+	+
Corner et al., 2013	-	-	-	-	++	+	-	-	+	+	++	++	+	++	++	-	++	++
OHB System AG, 2020	+	+	-	-	++	+	+	-	-	-	++	++	+	-	-	-	-	+
Belaia et al., 2021	+	++	+	++	++	++	-	-	-	++	-	+	-	-	-	-	-	-
Baum et al., 2022	-	+	+	+	++	++	+	-	+	+	++	+	++	-	++	+	++	+
UNEP, 2023	+	+	+	+	++	++	-	+	+	++	+	++	++	-	+	-	+	++
PSF, FSC, 2023	+	-	-	-	+	+	+	-	+	+	+	+	+	-	-	-	-	+

technical considerations, the lower coverage in the intervening years highlights the need for more consistent efforts.

In the following, three statements from the literature that have been assigned to a specific SDC are provided as an example:

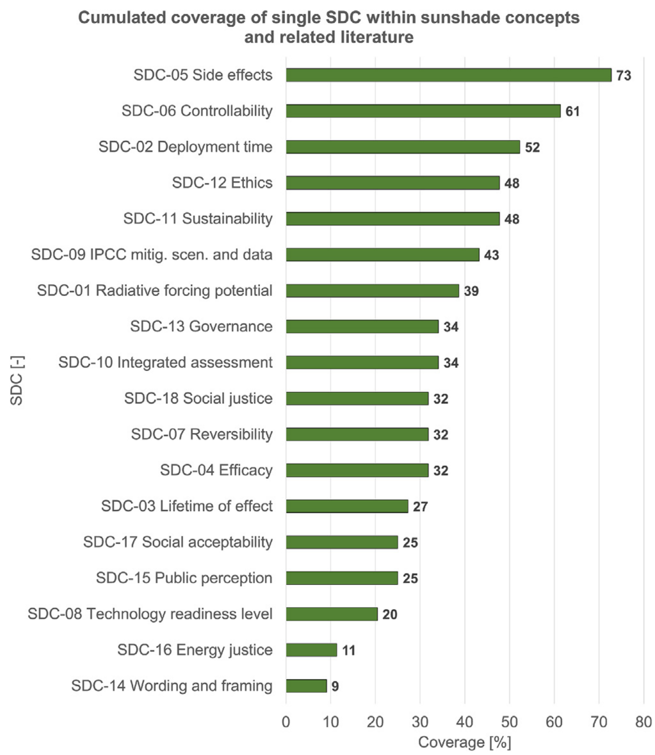

Fig. 5. Cumulated coverage of all 18 SDC in the selected literature. Here, cumulated coverage represents the extent to which an SDC is discussed within all publications. Note that while the maximum possible coverage is 100%, the x-axis limit is set to 80%. The underlying data set is provided in Table 11.

SDC-01 Radiative forcing potential:

[...] notes that solar radiation management may indeed reduce global temperatures but would probably modify, and possibly reduce global precipitation patterns. He also notes that reversing half of anthropogenic warming through radiation management techniques might actually result in precipitation patterns similar to those during pre-industrial periods. This suggests that the deployment of a solar shield must consider, in real time, unanticipated impacts on Earth 's overall climate (Roy, 2022).

SDC-07 Reversibility:

A sunshade would be scalable and reversible, with the possibility to add or remove elements to adjust the size (PSF and FSC, 2023).

SDC-12 Ethics:

This objection centers around the possibility that the solar shield approach might actually work as advertised. The fear is that this would create a ”moral hazard.” By removing the threat of global warming, some countries will choose to expend less effort in reducing emissions of greenhouse gases (Roy, 2022).

As shown in Fig. 5, there is a pronounced focus on SDC-05 Side effects with 73% coverage and SDC-06 Controllability with 61% coverage. This strong focus reflects the significant concerns surrounding unintended consequences and the need for precise control mechanisms, both of which are critical for the safe and effective use of sunshades. These criteria have received the most attention, likely because they are directly related to managing the potential risks of large-scale geoengineering.

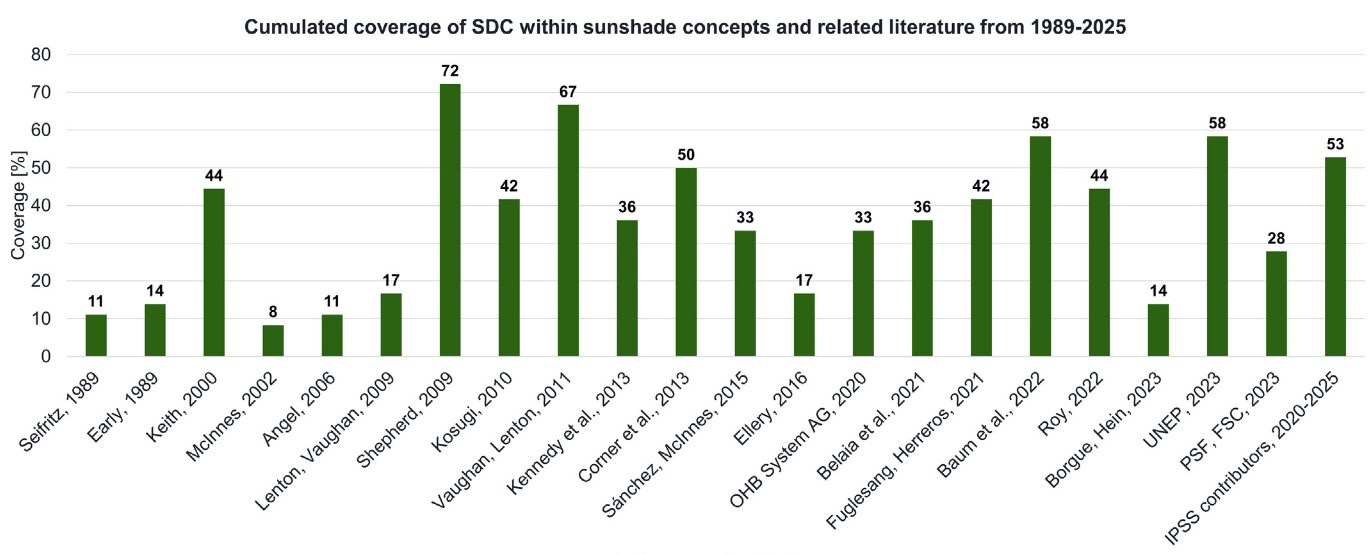

Fig. 6. Cumulated coverage of SDC in the selected literature. Here, cumulated coverage represents the extent to which the SDC are discussed within a specific publication. Note that while the maximum possible coverage is 100%, the y-axis limit is set to 80%. The underlying data set is provided in Table 11.

The SDC-12 Sustainability and SDC-13 Ethics, each with coverage of 48%, indicate a solid foundation of research in these areas, but also point to opportunities for further exploration. The result of SDC-12 Sustainability shows that while progress has been made in understanding the environmental and long-term viability of sunshades, aspects such as space debris management, the integration of circular economy principles, and the environmental impact of rocket launches and reentries remain underexplored. Similarly, the coverage of SDC-13 Ethics demonstrates that this topic is recognized, including moral hazard and geopolitical risks, but there is room for a deeper engagement with issues such as global equity, enhanced weather control, and the ethical implications of potential weaponization. Overall, the coverage is encouraging but suggests the need for continued focus on these critical areas to ensure that sunshades are developed and deployed in a sustainable and ethically responsible way.

Surprisingly, SDC-01 Radiative forcing potential has received only 39% coverage, despite being one of the most important technical criteria for assessing the impact of sunshades on solar radiation. Given its central role in determining sunshade efficacy, this gap highlights the need for further research on how sunshades can accurately reduce solar radiation with spatial and temporal precision to achieve their intended climate control goals.

Other important technical criteria, such as SDC-07 Reversibility (32%) and SDC-08 Technology readiness level (20%), show relatively low coverage. This underrepresentation reflects the current lack of practical engineering solutions and mature technologies for sunshade deployment. More research is needed to advance the technological maturity of the concept and develop strategies for the practical removal of sunshades from SEL_1.

The moderate coverage of SDC-09 IPCC mitigation scenarios and data with 43% suggests that some effort has been made to align the research on sunshades with broader climate change mitigation frameworks. However, the relatively low coverage of SDC-10 Integrated assessment with 34% indicates that further work is required to fully understand how sunshades could fit into larger climate policy, mitigation, and adaptation strategies, as well as other geoengineering concepts. More comprehensive studies are needed to assess the long-term impacts and feasibility of integrating sunshades with current and future climate interventions.

The evaluation of SDC-17 Social Acceptability and SDC-15 Public Perception, both at 25% coverage, highlights a significant gap in addressing the societal dimensions of sunshades. These aspects are critical to gaining the political and public support necessary for large-scale deployment. The low coverage of social acceptability indicates that there is insufficient exploration of how stakeholders, including the public and policymakers, might respond to sunshades, which could hinder their implementation. Similarly, the limited focus on public perception reveals a gap in understanding societal attitudes and concerns that could influence policy decisions and public engagement. Without addressing these gaps, the path to the successful deployment of sunshades could face substantial resistance, potentially compromising their long-term feasibility.

The least covered criteria, SDC-16 Energy Justice with 11% and SDC-14 Wording and Framing with 9%, continue to highlight a broader issue within the literature: the persistent lack of focus on the social, political, and ethical dimensions of sunshade deployment. These criteria are critical for shaping public perception, ensuring social acceptability, and addressing the ethical and distributive impacts of such technologies. The minimal attention to SDC-16 Energy justice raises concerns about the potential for sunshade deployment to increase global inequalities, especially in vulnerable regions that may be disproportionately affected by such interventions.

The SDC framework proves to be an effective tool for evaluating sunshades by providing a structured approach that highlights both technical and social dimensions in a (space) sustainability context. Its strength lies in its ability to systematically cover a wide range of relevant criteria, from operational performance to ethical and environmental concerns. The framework's ability to identify gaps in current research demonstrates its practical utility in guiding future studies.

8. Discussion

In a first attempt to find a comprehensive framework for evaluating the development status of sunshades, the case study literature has been analyzed for its SDG coverage. The sunshade literature focuses heavily on climate action and infrastructure, while broader socioeconomic and equity issues are underrepresented. The SDGs related to marine ecosystems, energy, water, inequalities, poverty, and hunger show low coverage, some as low as 0% to 7%. This highlights significant research gaps, particularly in assessing impacts on vulnerable populations, especially in the Global South. The lack of growth in SDG coverage since their introduction in 2016 might explain the limited recognition of the sunshade concept by major environmental bodies. To improve integration into global environmental policy, future research should address these gaps and ensure a comprehensive assessment aligned with the full spectrum of UN SDGs. The SDGs provide a useful framework for identifying the aforementioned gaps and it appears feasible to turn the results into a focused research agenda. However, the space segment, particularly the space sustainability aspect, is not reflected in the SDGs.

Hence, it was then moved to what is currently used by the European space industry to assess the environmental impact of space systems, including aspects of the space segment: the ESA EIIs. The coverage analysis of the sunshade literature reveals several critical gaps in the assessment of the environmental impacts of space-based geoengineering. Although EII-03 Human toxicity potential shows the highest coverage at 34%, even this figure indicates that a substantial portion of human health risks remains unexplored. Other indicators, such as EII-16 Mass left in space and EII-02 Ozone depletion potential, have moderate coverage with 30%, pointing to some awareness of the generation of space debris and impacts on the ozone layer. However, considering the massive scale of sunshade deployment, the comparable low coverage of mass left in space is surprising, especially given global efforts to mitigate space debris. Moreover, EII-01 Global warming potential, directly related to the primary objective of sunshades to mitigate climate change, shows only 16% coverage, highlighting a major research gap in understanding the broader environmental impacts of production and deployment. In addition, indicators related to freshwater and marine ecosystems, such as EII-06 Freshwater eutrophication potential and EII-10 Marine aquatic ecotoxicity potential, have negligible coverage, raising concerns about their oversight. Overall, while the ESA EII framework provides a comprehensive tool for assessing the environmental impact of sunshades, partly addressing the space segment, the current literature underutilizes it. Expanding research to cover these areas is critical to ensure informed decision making and sunshade development in line with sustainable environmental practices.

Furthermore, the ESA EIIs do not address the unique challenges of geoengineering, and sunshades in particular. The sustainability aspect of the future in-space ecosystem is not sufficiently visible within the indicators as well. As described in Section 4 and Section 5, there is a lack of development frameworks specifically designed to address sunshade-specific aspects, including technical, social, environmental, economic, ethical, geopolitical, scientific, and (space) sustainability perspectives. Hence, the need for a tailored development framework arises, which naturally led to the creation of the SDC.

The SDC framework has proven to be an effective tool for assessing the development status and advancing the concept of sunshades. It offers a structured approach that captures both the technical and the social dimensions of space-based geoengineering. Its ability to systematically identify and assess a wide range of criteria, from operational challenges to ethical concerns, highlights its applicability as a guiding framework. The analyzed literature showed a comprehensive coverage of critical aspects such as SDC-05 Side effects and SDC-06 Controllability, demonstrating its ability to detect the status of areas of concern in geoengineering. Additionally, the framework's identification of gaps, such as in SDC-01 Radiative forcing potential and SDC-17 Social acceptability, underlines its utility in shaping future research priorities. By revealing underexplored areas like SDC-08 Technology readiness level and SDC-07 Reversibility, the SDC framework ensures that the technical dimensions are recognized.

However, potential mistakes and biases in the literature assessment, including personal preferences, could not be entirely excluded, which may have led to bias or misinterpretation of criteria coverage. Specific types of error could include inaccuracies in interpretation, while biases may arise from selective focus or subjective judgment. To address these issues, efforts have been made to ensure a thorough and balanced review of the literature. This includes cross-checking the evaluation results within the group of authors and seeking peer feedback. Further, individual publications may not intend to cover all criteria, as technical papers naturally focus solely on technical aspects while usually neglecting social considerations, and vice versa. To address this, a broad range of literature is included in this analysis to provide a representative overview.

9. Conclusion and outlook

Examining the case study literature on the coverage of the UN SDGs and ESA EIIs led to a comprehensive set of 18 SDC. These criteria were selected and developed to reflect the overarching nature of geoengineering, incorporating aspects of sustainability while addressing space- and sunshade-specific needs. The framework is designed to evaluate the progress of the field and guide future development. It is kept sufficiently generic to (i) allow for comparison with other geoengineering proposals and (ii) to provide flexibility in addressing the criteria.

The SDC was found to consist of a balanced set of technical and social responsibility criteria. Therefore, the 18 SDC are intended to serve as a standalone evaluation and development framework. Nevertheless, it is important to acknowledge that the SDC are not fully defined or exhaustive in this context, and a certain degree of uncertainty remains in its interpretation. Hence, in the future, this framework can serve as a foundation for a more refined system, enabling a detailed and quantitative assessment, with specific design parameters derived from these criteria.

To be considered a serious complement to mitigation, adaptation, and other geoengineering methods such as SRM, it is crucial to address the identified research gaps related to sunshades. The uncovered lack of significant growth in key areas over time justifies this work. In addition to the high cost, this may also explain why sunshades have not gained widespread recognition from major environmental bodies such as UNEP, while other SRM options, such as SAI, are being investigated (UNEP, 2023). It may also have led various bodies such as the IPCC (2023), geoengineering and climate scientists (Keith et al., 2020; Sovacool et al., 2022), and the United States National Acadmies (2021) to conclude that sunshades are not a viable option. Addressing the present gaps would likely lead to greater acceptance among the public, the scientific community, and policy makers, encouraging the participation of stakeholders such as governments, the UN, and the IPCC. Although not all studies need to cover every single SDC, the summary of all related future work should. Closing these gaps will not only improve the feasibility and credibility of sunshades. It will also provide a deeper understanding of their environmental impacts, supporting more informed and balanced decision making and the potential development of sustainable space-based geoengineering practices.

While sunshades are likely to cool the Earth, they do not address atmospheric pollution. Emissions from the past 200 years have contributed to current and future warming, and merely stopping or reducing new emissions will only partially mitigate the issue. Emission reductions can help prevent further warming, but previous emissions must be removed, and sunshades provide the necessary time to address this challenge. This must be the only purpose of sunshades.

As the window for large-scale deployment of sunshades narrows, addressing research gaps through the application of the proposed SDC should be a top priority. In that context, a promising initiative is Destination Earth, a €315 million project launched by the European Commission, aimed at creating a digital twin of the Earth (European Commission, 2024). This significant advancement will allow for informed decision making through detailed modeling of mitigation, adaptation, and geoengineering efforts, as well as climate change and related socioeconomic effects.

Although the deployment of sunshades as a supplementary measure in conjunction with mitigation and adaptation efforts is an enormous challenge, the scale of the climate crisis demands solutions of comparable magnitude. Therefore, we must remain open-minded and proactive in preserving our planet and ensuring the continuation of life.

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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References

Acker, D., 2023. Parametrized Sunshade Design Study for an Evolutionary Sunshade Concept (IRS-22-S-061) Master's thesis. University of Stuttgart, Stuttgart, Germany.

Angel, R., 2006. Feasibility of cooling the earth with a cloud of small spacecraft near the inner lagrange point (L1). Proc. Nat. Acad. Sci. 103 (46), 17184–17189. https://doi.org/10.1073/pnas.0608163103.

Armstrong McKay, D.I., Staal, A., Abrams, J.F., et al., 2022. Exceeding 1.5 °C global warming could trigger multiple climate tipping points. Science 377 (6611), eabn7950. https://doi.org/10.1126/science.abn7950.

Arning, K., Offermann-van Heek, J., Linzenich, A., et al., 2019. Same or different? Insights on public perception and acceptance of carbon capture and storage or utilization in Germany. Energy Policy 125, 235–249. https://doi.org/10.1016/j.enpol.2018.10.039.

Bahlmann, J., 2023. An evaluation of space-based geoengineering approaches. Master's thesis. Technical University of Berlin, Berlin, Germany. https://doi.org/10.13140/RG.2.2.21185.88166.

Bahlmann, J., Saidani, M., Franzese, V. et al., 2024. Space and the circular economy: exploring expert perceptions. In: Proceedings of the 75th International Astronautical Congress. Milan, Italy: International Astronautical Federation. https://doi.org/10.52202/078372-0001 iAC-24,D1,1,1,x90997. https://www.researchgate.net/publication/385710397_Space_and_the_Circular_Economy_Exploring_Expert_Perceptions.

Baum, C.M., Fritz, L., Low, S. et al., 2024. Public perceptions and support of climate intervention technologies across the global north and global south. Nat. Commun., 15(1), 2060. https://www.nature.com/articles/s41467-024-46341-5.

Baum, C.M., Low, S., Sovacool, B.K., 2022. Between the Sun and Us: expert perceptions on the innovation, policy, and deep uncertainties of space-based solar geoengineering. Renew. Sustain. Energy Rev. 158, 112179. https://doi.org/10.1016/j.rser.2022.112179.

Belaia, M., Moreno-Cruz, J.B., Keith, D.W., 2021. Optimal climate policy in 3d: mitigation, carbon removal, and solar geoengineering. Clim. Change Econ. 12 (03), 2150008. https://doi.org/10.1142/S2010007821500081.

Bilbro, J.W., 2008. Using the Advancement Degree of Difficulty (AD2) as an input to risk management. https://apps.dtic.mil/sti/pdfs/ADA507591.pdf accessed on 25 August 2023.

Borgue, O., Hein, A.M., 2023. Transparent occulters: a nearly zero-radiation pressure sunshade to support climate change mitigation. Acta Astronaut. 203, 308–318. https://doi.org/10.1016/j.actaastro.2022.12.006.

Boyd, P.W., 2008. Ranking geo-engineering schemes. Nat. Geosci., 1(11), 722–724. https://www.nature.com/articles/ngeo348. Number: 11.

Boyd, P.W., 2016. Development of geopolitically relevant ranking criteria for geoengineering methods. Earth's Future 4 (11), 523–531. https://doi.org/10.1002/2016EF000447.

Brauer, U., Goodwin, M., Maheswaran, T., et al., 2023. Space-based mitigation of global warming with a planetary sunshade - limit global warming to 1.5 c and reduce the risks from climate tipping points. In: Global Conference on Climate Change (GLOC), URL: https://dl.iafastro.directory/event/GLOC-2023/paper/75031/. [Abstract].

Bromley, B.C., Khan, S.H., Kenyon, S.J., 2023. Dust as a solar shield. PLOS Clim. 2 (2). https://doi.org/10.1371/journal.pclm.0000133, e0000133.

Burton, R., Coverstone, V., Hargens-Rysanek, J., et al., 2005. UltraSail - Ultra-Lightweight Solar Sail Concept. In: In 41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit. American Institute of Aeronautics and Astronautics (AIAA), Tucson, Arizona, p. 4117. https://doi.org/10.2514/6.2005-4117.

Carlson, C.J., Colwell, R., Hossain, M.S., et al., 2022. Solar geoengineering could redistribute malaria risk in developing countries. Nat. Commun. 13 (1), 2150. https://doi.org/10.1038/s41467-022-29613-w.

Centers, R., Schertz, J., Scott, E. et al., 2020. Space resources to stop global warming: a planetary sunshade. In: 71st International Astronautical Congress (IAC) (pp. IAC–20–D3.1.8x60718). CyberSpace Edition: International Astronautical Federation (IAF). https://static1.squarespace.com/static/60d495bac7a14f7e7507d20b/t/60ef1584cf39e16310db0357/1626281349454/IAC+Planetary+Sunshade.pdf.

Chesley, B., Matonti, C.L., Sonty, S.S. et al., 2023. A conceptual framework for climate change mitigation actions employing in-space geoengineering. Baku, Azerbaijan: International Astronautical

Federation (IAF). https://scholar.google.com/scholar_lookup?title=A%20conceptual%20framework%20for%20climate%20change%20mitigation%20actions%20employing%20in-space%20geoengineering&publication_year=2023&author=B.%20Chesley&author=C.L.%20Matonti&author=S.S.%20Sonty&author=M.%20Gutowska&author=M.%20Romano.

Coco, M., Matonti, C.L., Cappelletti, C. et al., 2025. Planetary sunshade for solar geoengineering: Preliminary design of a precursor system and mission. Acta Astronaut., 235, 452–462. https://doi.org/10.1016/j.actaastro.2025.05.031.

Corner, A., Parkhill, K., Pidgeon, N., et al., 2013. Messing with nature? Exploring public perceptions of geoengineering in the UK. Global Environ. Change 23 (5), 938–947. https://doi.org/10.1016/j.gloenvcha.2013.06.002.

Crossan, M.M., Apaydin, M., 2010. A multi-dimensional framework of organizational innovation: a systematic review of the literature. J. Manage. Stud. 47 (6), 1154–1191. https://doi.org/10.1111/j.1467-6486.2009.00880.x.

Cunff, A.L., 2020. The difference between efficacy, effectiveness and efficiency. https://nesslabs.com/efficacy-effectiveness-efficiency accessed on 23 August 2023.

Dai, Z., Weisenstein, D.K., Keith, D.W., 2018. Tailoring meridional and seasonal radiative forcing by sulfate aerosol solar geoengineering. Geophys. Res. Lett. 45 (2), 1030–1039. https://doi.org/10.1002/2017GL076472.

Deloitte, 2022. Deloitte Research Reveals Inaction On Climate Change Could Cost The World's Economy US$178 Trillion By 2070. https://www.deloitte.com/global/en/about/press-room/deloitte-research-reveals-inaction-on-climate-change-could-cost-the-world-economy-us-dollar-178-trillion-by-2070.html accessed on 05 August 2023.

Diffenbaugh, N.S., Burke, M., 2019. Global warming has increased global economic inequality. Proc. Nat. Acad. Sci. 116 (20), 9808–9813. https://doi.org/10.1073/pnas.1816020116.

Early, J.T., 1989. Space-based solar shield to offset greenhouse effect. J. Brit. Interplanet. Soc. 42, 567–569, URL: https://ui.adsabs.harvard.edu/abs/1989JBIS...42..567E.

Ellery, A., 2016. Low-cost space-based geoengineering: an assessment based on self-replicating manufacturing of in-situ resources on the moon. Int. J. Environ. Ecol. Eng. 10 (2), 278–285. https://doi.org/10.5281/ZENODO.1129952.

Elo, S., Kyngäs, H., 2008. The qualitative content analysis process. J. Adv. Nurs. 62 (1), 107–115. https://doi.org/10.1111/j.1365-2648.2007.04569.x.

Enrique, B., Marta, B., 2020. Efficacy, effectiveness and efficiency in the health care: the need for an agreement to clarify its meaning. Int. Arch. Public Health Commun. Med. 4 (1). https://doi.org/10.23937/2643-4512/1710035.

ESA, 2016. Space System LCA Guidelines. ESSB-HB-U-005. ESA.

European Commission, 2024. Commission launches destination earth system in Finland. https://ec.europa.eu/commission/presscorner/detail/en/ip_24_3181 accessed on 24 September 2024.

European Environment Agency, 2023. Trends and projections in Europe 2023. LU: Publications Office. https://data.europa.eu/doi/10.2800/595102.

Fix, S., 2021. Feasibility Study of a Sunshade in the Vicinity of the Sun Earth L1 Lagrange Point (IRS-21-S-006). Master's thesis. University of Stuttgart, Stuttgart, Germany. https://static1.squarespace.com/static/60d495bac7a14f7e7507d20b/t/610862ec0ef29060d75365dc/1627939568010/Fix-2021.pdf.

Fuglesang, C., De Herreros Miciano, M.G., 2021. Realistic sunshade system at l1 for global temperature control. Acta Astronaut. 186, 269–279. https://doi.org/10.1016/j.actaastro.2021.04.035.

Ganzmann, J., 2023. Development of a Modular Logistics Concept Enabling the Deployment of the IPSS System (IRS-23-S-045). Master's thesis. University of Stuttgart, Stuttgart, Germany.

Gouvernement du Québec, 2023. Social acceptability. https://www.quebec.ca/en/government/policies-orientations/social-acceptability accessed on 25 August 2023.

Horowitz, C.A., 2016. Paris agreement. Int. Legal Mater. 55 (4), 740–755. https://doi.org/10.1017/S0020782900004253.

Immega, G., 2022. Mass Launch System for L1 Solar Geoengineering. https://static1.squarespace.com/static/60d495bac7a14f7e7507d20b/t/6201a4d09426aa1a6123b28d/1644274897323/immega-2022.pdf.

IPCC, 2015. Climate Change 2014: Synthesis Report. Working Groups I, II and III Contribution to the Fifth Assessment Report (AR5) of the IPCC. A Report of the IPCC (IPCC) Geneva, Switzerland. https://www.ipcc.ch/site/assets/uploads/2018/02/SYR_AR5_FINAL_full.pdf.

IPCC, 2021. Climate Change 2021 – The Physical Science Basis: Working Group (WG) I Contribution to the Sixth Assessment Report (AR6) of the IPCC. (1st ed.). Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press. https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_FullReport_small.pdf.

IPCC, 2022a. Summary for Policymakers. In Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report (AR6) of the IPCC. A Report of the IPCC IPCC Cambridge, United Kingdom and New York, NY, USA. https://www.ipcc.ch/report/ar6/wg2/downloads/report/IPCC_AR6_WGII_SummaryForPolicymakers.pdf.

IPCC, 2022b. Summary for Policymakers. In Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report (AR6) of the IPCC. A Report of the IPCC IPCC Cambridge, United Kingdom and New York, NY, USA. https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_SummaryForPolicymakers.pdf.

IPCC, 2023. Summary for Policymakers. In Climate Change 2023: Synthesis Report. Working Groups I, II and III Contribution to the Sixth Assessment Report (AR6) of the IPCC. A Report of the IPCC IPCC Geneva, Switzerland. https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_SPM.pdf.

Jehle, A., Scott, E., Centers, R., 2020. A planetary sunshade built from space resources. In: In ASCEND 2020 (p. NA). Virtual Event: American Institute of Aeronautics and Astronautics (AIAA). https://doi.org/10.2514/6.2020-4077.

Keith, D.W., 2000. Geoengineering the climate: history and prospect. Annu. Rev. Energy Env. 25 (1), 245–284. https://doi.org/10.1146/annurev.energy.25.1.245.

Keith, D.W., 2019. D.W. Keith. Solar Geoengineering: Public Policy and Geopolitical Considerations. https://youtu.be/Q76t47E1FUA Institute of International and European Affairs (IIEA). Accessed on 21 July 2023.

Keith, D.W., Morton, O., Shyur, Y. et al., 2020. Reflections on a Meeting about Space-Based Solar Geoengineering. https://geoengineering.environment.harvard.edu/blog/reflections-meeting-about-space-based-solar-geoengineering accessed on 13 July 2023.

Kennedy, R.G., Roy, K.I., Fields, D.E., 2013. Dyson dots: changing the solar constant to a variable with photovoltaic lightsails. Acta Astronaut. 82 (2), 225–237. https://doi.org/10.1016/j.actaastro.2012.10.022.

Kosugi, T., 2010. Role of sunshades in space as a climate control option. Acta Astronaut. 67 (1), 241–253. https://doi.org/10.1016/j.actaastro.2010.02.009.

Kravitz, B., MacMartin, D.G., Wang, H., et al., 2016. Geoengineering as a design problem. Earth Syst. Dynam. 7 (2), 469–497. https://doi.org/10.5194/esd-7-469-2016.

Krippendorff, K., 2019. Content analysis: an introduction to its methodology. 2455 Teller Road, Thousand Oaks California 91320: SAGE Publications, Inc. https://doi.org/10.4135/9781071878781.

Lan, X., Tans, P., Thoning, K. et al., 2025. Trends in globally-averaged CO2 determined from NOAA Global Monitoring Laboratory measurements. https://doi.org/10.15138/9N0H-ZH07 accessed on 14 February 2025.

Lenton, T.M., Held, H., Kriegler, E., et al., 2008. Tipping elements in the Earth's climate system. Proc. Nat. Acad. Sci. 105 (6), 1786–1793. https://doi.org/10.1073/pnas.0705414105.

Lenton, T.M., Rockström, J., Gaffney, O., et al., 2019. Climate tipping points - too risky to bet against. Nature 575 (7784), 592–595. https://doi.org/10.1038/d41586-019-03595-0.

Lenton, T.M., Vaughan, N.E., 2009. The radiative forcing potential of different climate geoengineering options. Atmos. Chem. Phys. 9 (15), 5539–5561. https://doi.org/10.5194/acp-9-5539-2009.

Lunt, D.J., Ridgwell, A., Valdes, P.J., et al., 2008. "sunshade world": A fully coupled GCM evaluation of the climatic impacts of geoengineering. Geophys. Res. Lett. 35 (12). https://doi.org/10.1029/2008GL033674.

MacMartin, D.G., Keith, D.W., Kravitz, B., et al., 2013. Management of trade-offs in geoengineering through optimal choice of non-uniform radiative forcing. Nat. Clim. Change 3 (4), 365–368. https://doi.org/10.1038/nclimate1722.

MacMartin, D.G., Kravitz, B., 2016. Dynamic climate emulators for solar geoengineering. Atmos. Chem. Phys. 16 (24), 15789–15799. https://doi.org/10.5194/acp-16-15789-2016.

MacMartin, D.G., Kravitz, B., Long, J.C.S., et al., 2016. Geoengineering with stratospheric aerosols: what do we not know after a decade of research? Earth's Future 4 (11), 543–548. https://doi.org/10.1002/2016EF000418.

MacMynowski, D.G., Keith, D.W., Caldeira, K., et al., 2011. Can we test geoengineering? Energy Environ. Sci. 4 (12), 5044. https://doi.org/10.1039/c1ee01256h.

Maheswaran, T., 2021. Analysis of Logistical Construction Aspects of a Sunshade Concept in the Vicinity of the Sun Earth L1 Lagrange Point (IRS-21-S-017). Master's thesis. University of Stuttgart, Stuttgart, Germany. https://static1.squarespace.com/static/60d495bac7a14f7e7507d20b/t/610864efcafd097facb27619/1627940087704/Maheswaran-2021.pdf.

Maheswaran, T., Acker, D., Fasoulas, S., 2023. The International Planetary Sunshade System - An Umbrella Project Combining Sustainable Energy Supply with Mitigation of Global Warming. In: In 17th International Conference on Space Operations (SpaceOps). Mohammed Bin Rashid Space Centre (MBRSC), Dubai, United Arab Emirates, p. ID555, URL: https://www.researchgate.net/publication/371987573_The_International_Planetary_Sunshade_System_-An_Umbrella_Project_Combining_Sustainable_Energy_Supply_with_Mitigation_of_Global_Warming.

Maheswaran, T., Acker, D., Fasoulas, S. et al., 2022. The International Planetary Sunshade - An Umbrella Project to Foster International Collaboration to Mitigate Global Warming. In 73rd International Astronautical Congress (IAC) (pp. IAC–22B1611x69565). Paris, France: International Astronautical Federation (IAF). https://www.researchgate.net/publication/364153880_The_International_Planetary_Sunshade_-_An_Umbrella_Project_to_Foster_International_Collaboration_to_Mitigate_Global_Warming.

Maheswaran, T., Fix, S., 2021. Roadmap for an International Planetary Sunshade (IPSS). In: 72nd International Astronautical Congress (IAC) (pp. IAC–21, D4,1,6, x64164). Dubai, United Arab Emirates: International Astronautical Federation (IAF). URL: https://iafastro.directory/iac/archive/browse/IAC-21/D4/1/64164/.

Maheswaran, T., Ganzmann, J., Acker, D. et al., 2023b. The International Planetary Sunshade - A Space-Based Climate Mitigation Concept Combining In-Space Manufacturing and Assembly with the Integration of Space Resources. https://gloc2023-iaf.ipostersessions.com/default.aspx?s=7E-B6-DE-26-84-B7-5D-F7-34-A0-5A-29-B2-E1-8E-75&guestview=true Global Space Conference on Climate Change (GLOC), Oslo, Norway; Interactive Poster Presentation.

Maheswaran, T., Ganzmann, J., Acker, D. et al., 2023c. Logistical Infrastructure for an ISRU-Based Sunshade Concept to Support Climate Action. Space Ressources Week (SRW), 2023, Luxembourg, Luxembourg; Interactive Poster Presentation.

Maheswaran, T., Mindermann, P., Acker, D., et al., 2023. International planetary sunshade concept with a function-integrated and scalable support structure based on coreless filament winding. J. Phys: Conf. Ser. 2526 (1), 012113. https://doi.org/10.1088/1742-6596/2526/1/012113.

McCauley, D., Ramasar, V., Heffron, R.J., et al., 2019. Energy justice in the transition to low carbon energy systems: Exploring key themes in interdisciplinary research. Appl. Energy 233–234, 916–921. https://doi.org/10.1016/j.apenergy.2018.10.005.

McInnes, C.R., 2002. Minimum mass solar shield for terrestrial climate control. J. Brit. Interplanet. Soc. 55 (9–10), 307–311, URL: https://www.scopus.com/pages/publications/2642539703.

Mindermann, P., Acker, D., Wegner, R., et al., 2024. Long-span fiber composite truss made by coreless filament winding for large-scale satellite structural systems demonstrated on a planetary sunshade concept. Scient. Rep. 14 (1), 8190. https://doi.org/10.1038/s41598-024-58513-w.

NOAA, 2023. Annual 2022 Global Climate Report. https://www.ncei.noaa.gov/access/monitoring/monthly-report/global/202213 accesssed on 20 July 2023.

OHB SE, 2022. #EngineeringOurEarth Part 6: Why Framing Matters When Communicating About Geoengineering. URL: https://www.ohb.de/en/magazine/engineeringourearth-part-6-why-framing-matters-when-communicating-about-geoengineering.

OHB System AG, 2020. Solar Radiation Management: Detailed SRM Study Report. Report OHB System AG Bremen, Germany. [Limited Access: Pages 7–8, 17–21 of 81].

Oxford Reference, n.d.. Social Justice. https://www.oxfordreference.com/display/10.1093/oi/authority.20110803100515279 accessed on 25 August 2023.

Parker, A., Irvine, P.J., 2018. The risk of termination shock from solar geoengineering. Earth's Future 6 (3), 456–467. https://doi.org/10.1002/2017EF000735.

Planetary Sunshade Foundation, 2023. State of Space-Based Solar Radiation Management. https://static1.squarespace.com/static/60d495bac7a14f7e7507d20b/t/640f43622e4d792d408acfee/1678721894552/PSF+-+State+of+Space+-+Print+Version.pdf.

Planetary Sunshade Foundation, & Fuglesang Space Center, 2023. State of Space-Based Solar Radiation Modification. https://static1.squarespace.com/static/60d495bac7a14f7e7507d20b/t/652748130cbd8953145fc79b/1697073173301/PSF+-+State+of+Space+Intl+-+Print+Version.pdf.

Robock, A., Jerch, K., Bunzl, M., 2008. 20 Reasons why geoengineering may be a bad idea. Bull. Atom. Scient. 64 (2), 14–59. https://doi.org/10.1080/00963402.2008.11461140.

Roeser, S., Taebi, B., Doorn, N., 2020. Geoengineering the climate and ethical challenges: what we can learn from moral emotions and art. Crit. Rev. Int. Soc. Polit. Philos. 23 (5), 641–658. https://doi.org/10.1080/13698230.2020.1694225.

Romano, M., Chesley, B., Matonti, C.L. et al., 2023. Survey and comparison of in-space and in-atmosphere geoengineering concepts for climate change mitigation. https://gloc2023-iaf.ipostersessions.com/Default.aspx?s=68-81-57-F9-30-9A-B7-03-F4-27-71-57-56-05-3C-34 Global Space Conference on Climate Change (GLOC), 2023, Oslo, Norway, [Interactive Poster Presentation].

Roy, K., 2022. The solar shield concept: current status and future possibilities. Acta Astronaut. 197, 368–374. https://doi.org/10.1016/j.actaastro.2022.02.022.

Roy, K.I., 2001. Solar sails: An answer to global warming? In AIP Conference Proceedings (pp. 413–418). AIP volume 552. URL: https://doi.org/10.1063/1.1357956 ISSN: 0094243X.

Sánchez, J.-P., McInnes, C.R., 2015. Optimal sunshade configurations for space-based geoengineering near the Sun-Earth L1 Point. PLOS ONE 10 (8), e0136648. https://doi.org/10.1371/journal.pone.0136648.

Schreier, M., 2012. Qualitative content analysis in practice. Los Angeles London New Dehli Singapore Washington DC: SAGE, http://refhub.elsevier.com/S0273-1177(25)01155-X/h0425.

Seifritz, W., 1989. Mirrors to halt global warming?. Nature 340 (6235). https://doi.org/10.1038/340603a0, 603–603.

Shepherd, J.G., 2009. Geoengineering the Climate: Science, Governance and Uncertainty. 10/29. The Royal Society, URL: https://eprints.soton.ac.uk/156647/.

Shyur, Y., Keith, D., 2019. Annotated bibliography on space-based geoengineering. https://static1.squarespace.com/static/60d495bac7a14f7e7507d20b/t/60ef1773734ecf541e83d4c2/1626281844080/Annotated+bibliography+on+space-based+Geoengineering+-+Shyur+%282020%29.pdf.

Sovacool, B.K., Baum, C.M., Low, S., 2022. Determining our climate policy future: expert opinions about negative emissions and solar radiation management pathways. Mitig. Adapt. Strat. Glob. Change 27 (8), 58. https://doi.org/10.1007/s11027-022-10030-9.

Sovacool, B.K., Baum, C.M., Low, S., 2023. Risk–risk governance in a low-carbon future: Exploring institutional, technological, and behavioral tradeoffs in climate geoengineering pathways. Risk Anal. 43 (4), 838–859. https://doi.org/10.1111/risa.13932.

Sovacool, B.K., Burke, M., Baker, L., et al., 2017. New frontiers and conceptual frameworks for energy justice. Energy Policy 105, 677–691. https://doi.org/10.1016/j.enpol.2017.03.005.

Sovacool, B.K., Dworkin, M.H., 2015. Energy Justice: Conceptual Insights and Practical Applications. Appl. Energy 142, 435–444. https://doi.org/10.1016/j.apenergy.2015.01.002.

Szapudi, I., 2023. Solar radiation management with a tethered sun shield. Proc. Nat. Acad. Sci. 120 (32). https://doi.org/10.1073/pnas.2307434120, e2307434120.

Town, J., Pushparaj, N., Cappelletti, C., 2025. Preliminary structural system design for planetary sunshade. Aerospace, 12(9), 785. https://doi.org/10.3390/aerospace12090785. Publisher: Multidisciplinary Digital Publishing Institute.

Tzinis, I., 2021. Technology Readiness Level. http://www.nasa.gov/directorates/heo/scan/engineering/technology/technology_readiness_level accessed on 25 August 2023.

UN, 2016. The 17 Goals — Sustainable Development. https://sdgs.un.org/goals accessed on 22 August 2023.

UN, 2023. Sustainability. https://www.un.org/en/academic-impact/sustainability accessed on 27 August 2023.

UNEP, 2023. One Atmosphere: An Independent Expert Review on Solar Radiation Modification Research and Deployment. Nairobi, Kenya: UNEP. https://wedocs.unep.org/bitstream/handle/20.500.11822/41903/one_atmosphere.pdf?sequence=3&isAllowed=y.

United States National Acadmies, 2021. Reflecting Sunlight: Recommendations for Solar Geoengineering Research and Research Governance. National Academies Press. https://doi.org/10.17226/25762 pages: 25762.

UNOOSA, 2021. Guidelines for the Long-term Sustainability of Outer Space Activities of the Committee on the Peaceful Uses of Outer Space. Vienna, Austria: United Nations (UN). URL: https://www.unoosa.org/documents/pdf/PromotingSpaceSustainability/Publication_Final_English_June2021.pdf.

Van Bommel, N., Höffken, J.I., 2021. Energy Justice within, between and beyond European Community Energy Initiatives: a review. Energy Res. Soc. Sci. 79, 102157. https://doi.org/10.1016/j.erss.2021.102157.

Vaughan, N.E., Lenton, T.M., 2011. A review of climate geoengineering proposals. Clim. Change 109 (3–4), 745–790. https://doi.org/10.1007/s10584-011-0027-7.

Wigley, T.M.L., 2006. A combined mitigation/geoengineering approach to climate stabilization. Science 314 (5798), 452–454. https://doi.org/10.1126/science.1131728.

Wilson, A.R., Vasile, M., 2023. The space sustainability paradox. J. Clean. Prod., 423, 138869. https://doi.org/10.1016/j.jclepro.2023.138869.

Wohlin, C., 2014. Guidelines for snowballing in systematic literature studies and a replication in software engineering. In: Proceedings of the 18th International Conference on Evaluation and Assessment in Software Engineering (pp. 1–10). ACM. https://dl.acm.org/doi/10.1145/2601248.2601268.