An Evaluation of Space-Based Geoengineering Approaches

Master of Science Thesis by

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Abstract

Space-based geoengineering has been proposed as a lower-risk but higher-cost alternative to terrestrial solar irradiation management approaches such as stratospheric aerosol injection. However, due to its high mass and therefore high number of required rocket launches, existing approaches have not been considered as serious alternatives. Emerging alternatives such as ultra-low mass sunshade designs and in-space manufacturing using in-situ resources might change this verdict. Hence, the objective of this MSc. thesis is to evaluate emerging approaches. To this end, an extensive literature review identified 18 geoengineering evaluation criteria and two sustainability frameworks, revealing several research gaps, such as the global warming potential of the high number of rocket launches, which was subsequently addressed. Due to the added complexity of in-space manufacturing using in-situ resources at scale, and increased overall weight of in-space resource-based space systems, it is concluded that an advanced Earth-manufactured concept such as the *Realistic Sunshade System* seems more feasible and rational short- and midterm.

Zusammenfassung

Weltraumbasiertes Geoengineering wird als risikoärmere, aber kostenintensivere Alternative zu erdbasierten Methoden zur Beeinflussung der Sonneneinstrahlung, wie z. B. der Injektion von Aerosolen in die Stratosphäre, eingeschätzt. Aufgrund der hohen Masse und der damit verbundenen hohen Anzahl an erforderlichen Raketenstarts wurden die bisherigen Konzepte jedoch nicht als ernsthafte Alternativen betrachtet. Aufkommende Alternativen wie *sunshades* mit extrem geringer Masse und die Herstellung im Weltraum unter Verwendung von in-situ-Ressourcen könnten diese Einschätzung ändern. Ziel dieser Masterarbeit ist es daher, die neuen Ansätze zu bewerten. Zu diesem Zweck wurden im Rahmen einer umfassenden Literaturrecherche 18 Bewertungskriterien für Geoengineering und zwei Nachhaltigkeitsframeworks ermittelt, wobei mehrere Forschungslücken zutage traten, wie z. B. das *global warming potential* der hohen Anzahl von Raketenstarts, das untersucht wurde. Aufgrund der zusätzlichen Komplexität der Herstellung im Weltraum unter Verwendung von in-situ-Ressourcen in großem Maßstab und des höheren Gesamtgewichts von auf in-situ-Ressourcen basierenden Weltraumsystemen wird geschlussfolgert, dass ein fortschrittliches, auf der Erde hergestelltes Konzept wie das *Realistic Sunshade System* kurz- und mittelfristig realistischer und ausgewogener erscheint.

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Symbols

Latin Symbols

A_{Sh}	$[\mathrm{m}^2]$	Sunshade Surface Area
B_{ISRU}	$[-]$	ISRU Bootstrapping Factor
f	$[-]$	Relative Solar Radiation Reduction
M_{Infra}	[kg]	Space Infrastructure Mass
M_{Sh}	[kg]	Sunshade Mass
P_G	[W]	Generated Power by Solar Cells
Q	$[-]$	Sail Efficiency Factor, equal to κ
RF	$[\frac{\mathrm{W}}{\mathrm{m}^2}]$	Radiative Forcing
r_{Sh}	[m]	Distance Sunshade to Earth
S	$[\frac{\mathrm{W}}{\mathrm{m}^2}]$	Annual Global Mean Flux of Solar Radiation at TOA
ΔRF	$[\frac{\mathrm{W}}{\mathrm{m}^2}]$	Change in Radiative Forcing
ΔS	$[\frac{\mathrm{W}}{\mathrm{m}^2}]$	Change in Solar Radiation
ΔT	[K]	Change in Earth Global Mean Temperature

Greek Symbols

α_p	$[-]$	Planetary Albedo
κ	$[-]$	Optical Surface Property Factor, equal to Q
λ	$[\frac{\mathrm{W}}{\mathrm{m}^2\,\mathrm{K}}]$	Climate Sensitivity
ρ_{Sh}	$[\frac{\mathrm{kg}}{\mathrm{m}^2}]$	Average Areal Sunshade Density

Constants

AU	1.49598×10^{11}	[m]	Astronomical Unit
S_0	1371	$[\frac{\mathrm{W}}{\mathrm{m}^2}]$	Average Solar Constant at 1 AU

Abbreviations & Acronyms

AD^2	Advancement Degree of Difficulty
AL_2O_3	Aluminium Oxide
AR5	Fifth Assessment Report of the IPCC
AR6	Sixth Assessment Report of the IPCC
Bq	Becquerel
CDR	Carbon Dioxide Removal
CFC	Chlorofluorocarbon
CH_4	Methane
CO_2	Carbon Dioxide
CTUe	Comparative Toxic Unit for Aquatic Ecotoxicity Impacts
CTUh	Comparative Toxic Unit for Human
COP26	26^{th} United Nations Climate Change Conference of the Parties
CTP	Climate Tipping Point
DB	Dichlorobenzene
EII	ESA Space System LCA Environmental Impact Indicator
ESA	European Space Agency
eq	Equivalent
FAA	US Federal Aviation Administration
GEC	Geoengineering Evaluation Criteria
GDP	Gross Domestic Product
GHG	Green House Gas
GMT	Global Mean Temperature
GWP	Global Warming Potential
GWP_{100}	Global Warming Potential over 100 Years

IPCC	Intergovernmental Panel on Climate Change
IPSS	International Planetary Sunshade
ISMA	In-Space Manufacturing
ISRU	In-Situ Resource Utilization
L	Lagrange Point, here SEL
LCA	Life Cycle Assessment
LEO	Low Earth Orbit
MAG	Mitigation, Adaptation, and Geoengineering
MAGS	Mitigation-Adaptation-Geoengineering Strategy
MCB	Marine Cloud Brightening
N	Nitrogen
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organization
NDC	Nationally Determined Contributions
NMVOC	Non-Methane Volatile Organic Compound
NO	Nitric Oxide (Nitrogen Oxide or Nitrogen Monoxide)
NOAA	National Oceanic and Atmospheric Administration
NO_x	Nitrogen Oxides
NO_2	Nitrogen Dioxide
N_2O	Nitrous Oxide
ODS	Ozone-Depleting Substances
OHB	OHB System AG
P	Phosphorus
Param.	Parameter
PEA	Programmatic Environmental Assessment
PSF	Planetary Sunshade Foundation
RCP	Representative Concentration Pathway
RSS	Realistic Sunshade System
SAI	Stratospheric Aerosol Injection
SBSP	Space-Based Solar Power
SDG	Sustainable Development Goal of the UN

SEL	Sun-Earth Lagrange Point
SG	Solar Geoengineering, equal to SRM
SO_2	Sulfur Dioxide
SSP	Shared Socio-Economic Pathway
SRM	Solar Radiation Management, equal to SG
SRP	Solar Radiation Pressure
TOA	Top of the Atmosphere
TRL	Technology Readiness Level
U	Uranium
UK	United Kingdom
UN	The United Nations
UNEP	United Nations Environmental Programme
UNFCCC	United Nations Framework Convention on Climate Change
US	United States of America
USA	United States of America
VOC	Volatile Organic Compound

Chapter 1

Introduction

"Climate change is one of the biggest challenges of our times" [1]. We are surrounded by comparable headlines, yet in 2022 greenhouse gas (GHG) emissions continued their historically high rates of growth [2]. In that context, the Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) predicts the 2015 Paris Agreement, whose overarching goal is to limit the increase in global mean temperature (GMT) to well below 2°C and preferably to 1.5°C, unlikely to be achieved [3, 4]. A 1.5°C increase seems small, but given the fact, that the GMT in 2022 was around 15°C, it takes on a new perspective [5]. Compared to the pre-industrial temperature levels of 1850–1900, we currently face a warming of 1.1°C [3] and it is likely that we reach a global warming of 1.5°C in the 2030s [6].

Moreover, the current warming already touches the lower end of climate tipping points (CTPs), such as the melting of major ice sheets [7]. A tipping point is defined as *"a critical threshold at which a tiny perturbation can qualitatively alter the state or development of a system"* [8]. In the climate context, it is a critical threshold which, if exceeded, leads to major and irreversible changes in the climate system [9]. It is important to highlight that even in the range of the Paris Agreement several CTPs are expected to be triggered and many more will follow in the range of 2.2°C to 3.5°C of warming, which is expected to be a likely scenario based on the implementation of current climate policies [3, 7, 9].

1.1 Motivation

To reach the 1.5°C goal, global emissions must peak in 2025 and decline 43% by 2030 [10]. At best, this can be seen as a very optimistic case. Within this frame of reference, geoengineering as the intentional large-scale manipulation of the environment has been discussed as a *complement* to GHG mitigation and climate change adaptation efforts [11, 12, 13, 14, 15]. In an ideal scenario, geoengineering would *temporarily* be used to buy enough time to let us transform our world into a net-zero or even negative-emission-one, bringing atmospheric GHG levels back to the pre-industrial state, while keeping the near-future warming below the Paris Agreement levels to prevent CTPs from being reached. At the one hand promising, geoengineering methods such as Solar Radiation Management (SRM) and Carbon Dioxide Removal (CDR) come with major risks and challenges.

Geoengineering is by no means a permanent or sole solution. Even the most optimistic scenarios show that no realistic geoengineering method is able to mitigate anthropogenic climate change alone, therefore only a combined mitigation-adaptation-geoengineering strategy (MAG, MAGS) is likely to tackle the problem sufficiently [14]. As one of the SRM methods, space-based geoengineering has been proposed as a lower-risk but higher-cost alternative to terrestrial geoengineering approaches such as Stratospheric Aerosol Injection (SAI).

However, due to its high mass and therefore amount of required launches, existing approaches have not been considered as serious alternatives. Emerging alternatives such as ultra-low mass sunshade designs and in-space manufacturing using in-situ resources might change this verdict [16, 17, 18, 19]. Therefore, emerging space-based approaches must be investigated and evaluated.

1.2 Objectives and Outline

The evaluation of selected space-based geoengineering approaches shall be done by using a set of evaluation criteria, including sustainability aspects. Subsequently, a parametric model shall be developed for space-based geoengineering alternatives, notably Earth-launch and in-space manufactured sunshades. That will allow the exploration and characterization of the trade-space of the selected approaches.

In chapter 2, the scientific background about climate change and the three main pillars for tackling the issue, namely mitigation, adaptation and geoengineering will be covered. Chapter 3 will contain a twofold literature survey. First, a wide literature study will be conducted to select appropriate criteria for the geoengineering concept evaluation. Second, the chosen criteria will then be used to analyse another selection of more specific geoengineering literature regarding how much they cover the given criteria.

Therefore, a clear picture of the current state of the literature will be derived, allowing for data-based evaluation of which space-based geoengineering approaches are most suitable for an evaluation and what are the research gaps that needs to be addressed. Chapter 4 will focus on the description of selected space-based approaches while in chapter 5 the evaluation of concepts using a selection of criteria or parameter, respectively a research gap, will be examined. To conclude the thesis, chapter 6 will summarize the results and chapter 7 presents an outlook.

Chapter 2

Background

The following chapter provides an overview of the current climate change situation and three different ways to approach the problem, namely mitigation, adaptation and geoengineering. Geoengineering can be divided into Solar Radiation Management and Carbon Dioxide Removal, which will be explained further. The chapter ends dealing with the ethical implications of geoengineering.

2.1 Climate Change

Climate change can be described as a significant variation in the average weather conditions while climate is the long-term pattern of weather in a particular area [20, 21]. In that context, long-term stands for at least 30 days [20]. In a simpler approach, climate change can also be translated simply as cumulative emissions in the Earth's atmosphere [22]. There have always been natural changes in climate, but there is strong evidence that the human activities since 1800 contributed significantly to the warming of our planet, mainly through emitting GHGs into the Earth's atmosphere [3]. The global anthropogenic emissions have continued to rise across all major groups of GHGs and so is their influence on global warming and the so called green house effect, which is when GHGs trap the solar radiation in the Earth's atmosphere [23, 24].

2.1.1 Influence of Anthropogenic Green House Gases

In 2019, the major contributors to the anthropogenic greenhouse effect are Carbon Dioxide (CO_2) with 75%, Methane (CH_4) with 18% and Nitrous Oxide (N_2O), which is responsible for 4% of the total GHG emissions, as can be seen in figure 2.1

[23, 2, 25, 26]. While CO_2 emissions mainly come from land use and burning fossil fuels, CH_4 emissions primarily stem from agriculture, oil and gas operations and a combination of the previous mentioned mainly contributes to N_2O emissions [23, 27].

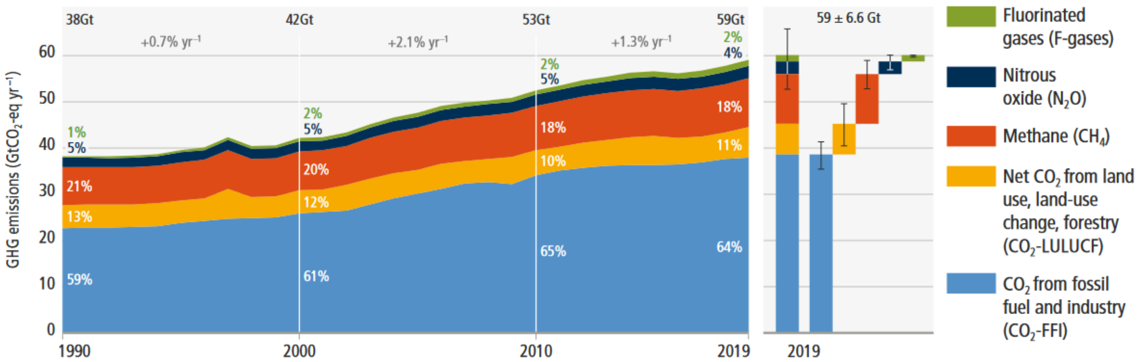

Figure 2.1: Annual global anthropogenic GHG emissions on a rise from 1990–2019 [23].

In that context, it is important to introduce the global warming potential GWP of GHGs, as they differ in how strong they contribute to the global warming, after being released into the atmosphere. The GWP estimates for each gas include the ability to absorb energy and their lifetime in the atmosphere, using CO_2 as a reference [28]. Most commonly, the GWP over 100 years is used (GWP_{100}) to compare the gases' influence. Even though the different lifetimes of GHGs are reflected by GWP_{100}, there is a rising discussion to develop a new metric, as short-lived gases, such as CH_4, are still misrepresented in terms of their influence on global temperature [29].

The GWP estimates vary slightly depending on how they have been calculated and therefore different ranges can be found depending on author and year of publication. An overview of GWP_{100} values and their global mean lifetime in the atmosphere is presented in table 2.1. These values will be applied to this thesis, primarily in chapter 5, as they stem from AR6, the scientifically most comprehensive work.

In addition to the latest IPCC report, the United States (US) National Oceanic and Atmospheric Administration (NOAA) publishes average global GHG measurements every year, including the data covering 2020–2022, which is missing in figure 2.1. These results are shown in figure 1 in the appendix. The clear trend, that the accumulation of GHG in the Earth's atmosphere is *still on a rise*, can be seen [2].

Table 2.1: Overview of major GHGs: GWP_{100} and global mean atmospheric lifetime relative to CO_2 [30].

Greenhouse Gas	**Chemical Formula**	**GWP_{100}**	**Atmospheric Lifetime [y]**
Carbon Dioxide	CO_2	1	#[a]
Methane[b]	CH_4	29.8 ± 11	11.8 ± 1.8
Nitrous Oxide	N_2O	273 ± 130	109 ± 10

[a] There is no specific lifetime for CO_2 as it is continuously cycled between the atmosphere, oceans and land biosphere [30].
[b] Fossil-based, non fossil-based Methane shares the same atmospheric lifetime but has a lower GWP_{100} of 27.0 ± 11 [30].

2.1.2 The Paris Agreement Seems Out of Reach

As mentioned in chapter 1, the international community agreed in the 2015 Paris Agreement to limit global warming to below 2°C and preferably to 1.5°C [4], while the lower goal would still be an average GMT increase of 10% [5]. It is important to highlight, that the effects of global warming on our climate system are not linear, so the effects of a 2°C warming are much worse than those of 1.5°C. Additionally, it is unlikely that there is a *"global warming safe zone"*. So far, the 1.5°C goal is a pure political threshold and does not reflect the warnings of the scientific community as it would still cause severe issues, which will be covered in section 2.1.4 [22].

Even though the Paris Agreement is or was the first-ever global and legally binding climate change agreement – based on the current implemented policies – it's goal seems *out of reach*, as figure 2.2 visualizes [3]. More into detail, the figure shows global net GHG emissions from 2000–2015 and projections of annual GHG emissions until 2100 using the Nationally Determined Contributions (NDCs) as a baseline scenario. The NDCs were announced prior to the 26th United Nations Climate Change Conference of the Parties (UN, COP26), which took place in Glasgow, United Kingdom in 2021. They determine efforts by each of the 193 signing countries of the Paris Agreement to reduce national emissions [31].

Based on these efforts, a warming of 3.2°C is projected, ranging from 2.2°C to 3.5°C with medium confidence. Furthermore, figure 2.2 shows that only rapid, deep and immediate GHG reductions can limit warming to 1.5°C or 2°C while targeting net-zero or even net-negative emissions by 2100.

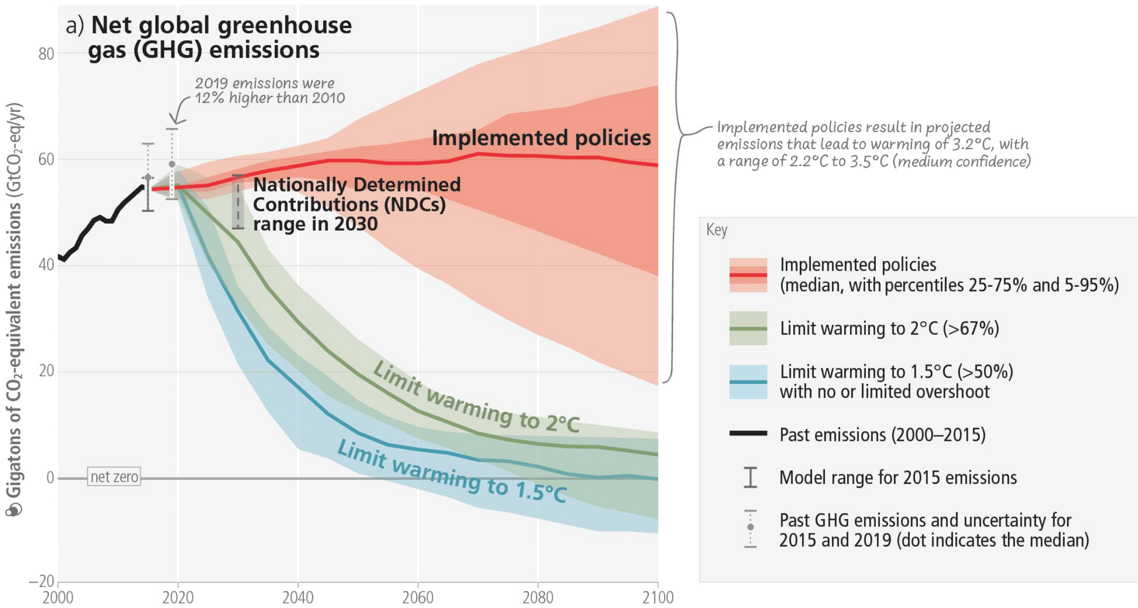

Figure 2.2: Annual global anthropogenic GHG emission of modelled pathways consistent with implemented policies and mitigation strategies from 2000–2100 [3].

2.1.3 The IPCC's Climate Pathways

The Fifth Assessment Report (AR5) of the IPCC, on which the Paris Agreement is based, introduced four Representative Concentration Pathways (RCPs), that assume 0.85°C warming relative to pre-industrial levels as a starting point. Each scenario, namely RCP2.6, RCP4.5, RCP6.0 and RCP8.5, predicts annual GHG emissions until 2100, while providing a corresponding radiative forcing RF as part of their label [32]. While RF is given in $[\frac{\mathrm{W}}{\mathrm{m}^2}]$, it *"describes any imbalance in the Earth's radiative budget caused by human or natural interference with the climate system"* [33]. Based on this scientific concept, a change in GMT can be derived, which will be shown in chapter 5.

AR6 presented a new set of pathways, called Shared Socio-Economic Pathways (SSPs). As it is the latest IPCC report, it represents the current situation while assuming 1.1°C warming relative to pre-industrial levels as a starting point for each SSP. The SSPs show a wider range of GHG, land use and air pollutant future and additionally include changes in population, gross domestic product (GDP), education, urbanisation and rate of technological development, which is the first time this has been done in an IPCC assessment report.

A classification of the five SSPs in terms of socio-economic challenges related to adaptation and mitigation can be seen in figure 2.3 [34]. For SSP1, the chart shows low challenges in terms of mitigation and adaptation, which requires a rapid GHG reduction and high global resource efficiency, and is therefore the most sustainable pathway. SSP2 represents a balanced scenario with intermediate challenges while SSP3 shows high challenges for mitigation and adaptation, which translates into an arduous implementation of regional energy and land policies and an overall very slow development.

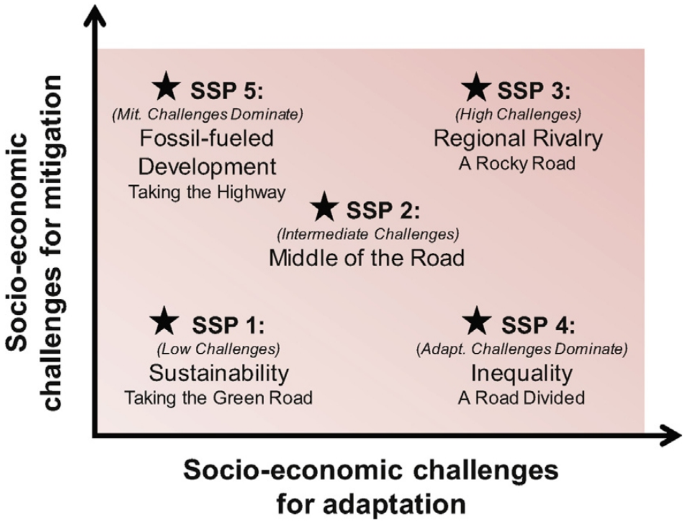

Figure 2.3: The IPCCs five SSPs representing different combinations of challenges to mitigation and adaptation [34].

However, SSP4 stands for low mitigation and high adaptation challenges, which means the existence of a global high-tech economy with regional low-tech economies and leads to global inequality. Lastly, SSP5 represents high mitigation challenges, which equals a resource and fossil fuel intensive economy while having a rapid development and therefore low adaptation challenges [34, 35]. It is worth nothing that the AR6 did not estimate likelihoods of the SSPs and that the SSP4 – *"Inequality - A Road Divided"* – was not taken into account for the IPCC reports [30, 35]. The SSPs are complex scenarios, with a scope reaching far beyond what can be presented in this thesis. Nevertheless, to provide some more background information of each SSP scenario, a summary of the SSP narratives can be found in table 1 in the appendix [35].

An illustrative set of five SSPs scenarios was selected for AR6 and coupled with RF values representing expected outcomes by each SSP scenario through 2100 [30]. Table 2.2 shows the estimated RF values by the end of the century coupled with near- and long-term GMT increase. It is remarkable that only the first SSP1 scenario,

Table 2.2: Overview of the SSPs of the IPCC's AR6 [30].

SSP	**RF** $[\frac{W}{m^2}]^{a}$	**Near-Term (2021–2040) GMT Increase** [°C][b, c]	**Long-Term (2081–2100) GMT Increase** [°C][b, c]
SSP1-1.9	1.9	1.2 to 1.7	1.0 to 1.8
SSP1-2.6	2.6	1.2 to 1.8	1.3 to 2.4
SSP2-4.5	4.5	1.2 to 1.8	2.1 to 3.5
SSP3-7.0	7.0	1.2 to 1.8	2.8 to 4.6
SSP5-8.0	8.0	1.3 to 1.9	3.3 to 5.7

[a] By the year 2100.
[b] Likelihood: Very likely (90–100% probability).
[c] Temperature differences relative to the GMT of the period 1850–1900.

which is most optimistic, allows for reaching the Paris Agreement as a very likely outcome while the scenario itself is expected to be the most unlikely one [30, 36].

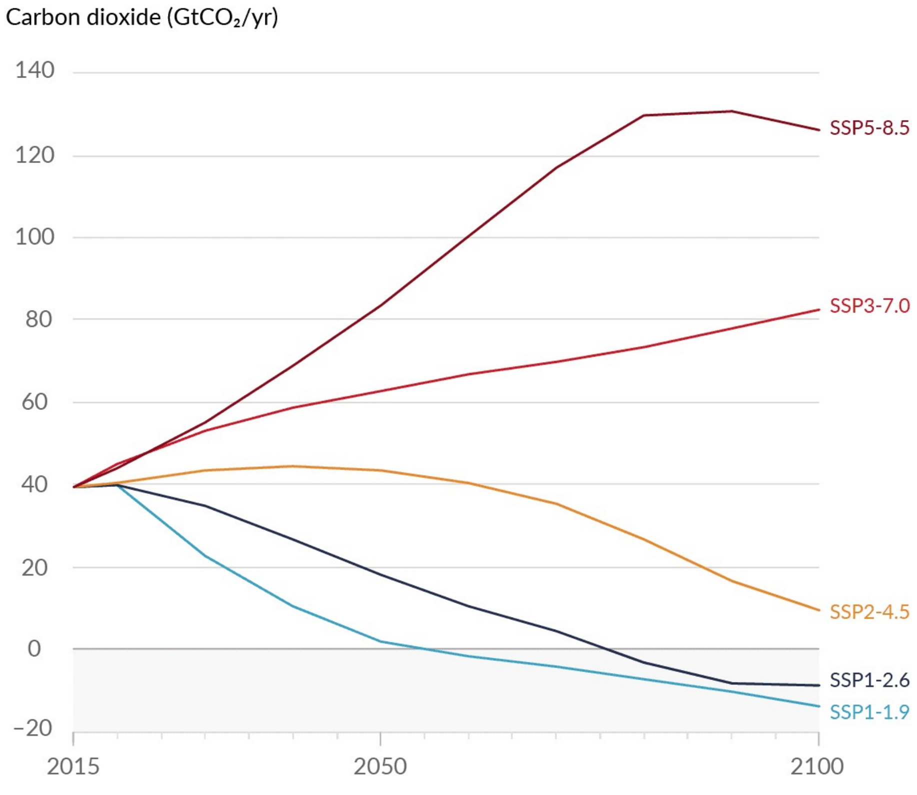

Figure 2.4: Future global CO_2 emissions across the illustrative set of five SSP scenarios of the IPCC's AR6 [30].

Furthermore, the second SSP1 scenario, which still can be considered as very optimistic, predicts a very likely temperature increase of 1.3°C to 2.4°C. This already involves missing the Paris Agreement, while the SSP2-4.5, SSP3-7.0 and SSP5-8.0 scenarios go far beyond. To underline that, figure 2.4 shows the need for rapid and drastic CO_2 emission reduction, as we have to achieve net-zero emission by 2055 and 2075, and net-negative emissions from there, to either reach and sustain the SSP1-1.9 or SSP1-2.6 scenario.

Comparing the possible outcomes of these scenarios with the RCP scenarios of AR5, it can be observed that a warming of 2°C is *much more likely*, as AR6 predicts a very likely temperature increase of 2°C to 5°C and no slowing down in emitting GHGs into the atmosphere could be observed during the past decade [30, 32].

2.1.4 Global Warming Effects Earth and Future Climate

Human influence has contributed to global warming at a rate that is unprecedented in at least the last 2000 years. The likely range of total human-caused GMT increase from pre-industrial levels to 2010–2019 is 0.8°C to 1.3°C [30]. This trend seems to continue, as describes in the previous sections, which will effect our future climate and therefore all aspects of life on Earth. The effects are far too extensive to be adequately covered in this thesis, as the AR6 comprises nearly 8000 pages.

However, the report shows strong evidence that the concentration of CO_2 is unmatched for 2 million years, the last decade was warmer than any period for 125,000 years, the sea level rise proceeds faster than any prior century for 3000 years, the summer arctic ice coverage is smaller than anytime in previous 1000 years while the glacial retreat is unmatched for at least 2000 years. All this, while the ocean warming and increase in acidification occurs more rapid than at any time since end of the last ice age, which lasted until 25,000 years ago [3, 23, 30, 37, 36].

The warmer the atmosphere becomes, the more water it can absorb and thus, in turn, more heat energy. The increase in absorbed water leads to a higher risk of heavy precipitation events causing floods, while the proportion of intense tropical cyclones will rise as well. On the other hand, heatwaves, droughts, and fires are also expected to increase in frequency and intensity, associated with the loss of 99% of coral reefs in a 2°C warming scenario and 29% biodiversity loss in a 3°C warming scenario, which can be seen in figure 2.5 [37].

The figure, based on the results of AR6, also shows that the risks of 2°C and 3°C warming are much worse compared to 1.5°C warming, as noted earlier in section 2.1.2. It is important to mention that each region of the world will experience a specific combination of various changes while future risks will increase rapidly with every fraction of a GMT increase, requiring re-settlements on a global scale [30, 37].

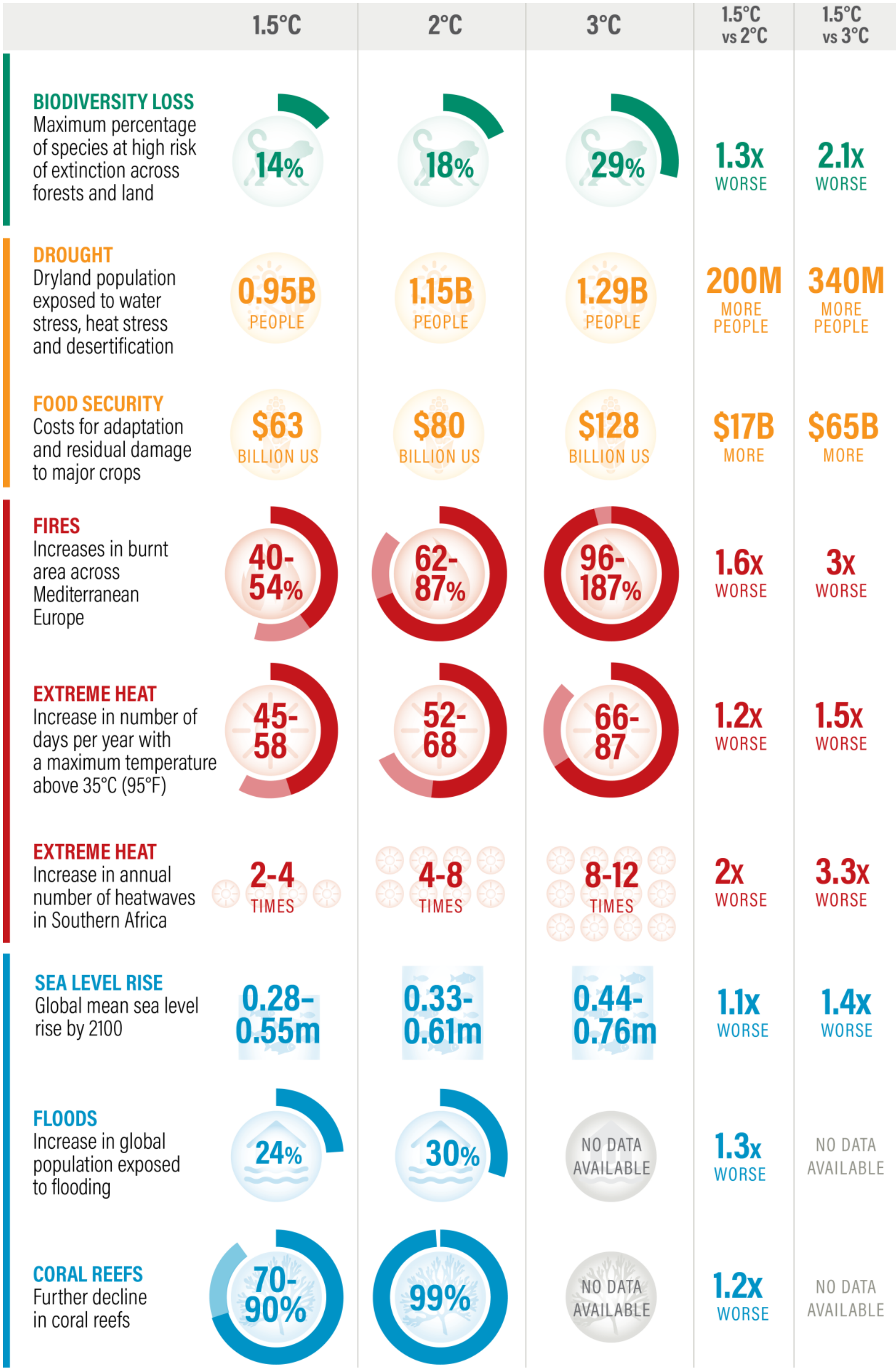

Figure 2.5: Risks from rising GMT based on the IPCC's AR6 [37].

The effects of global warming will also cause severe economical damage. The results of AR6 presented in figure 2.5 estimate 63 US$ billion to 128 US$ billion per year to ensure food security. A recent study estimated that an unchecked climate change can cost US$178 trillion by 2070 [38]. It is estimated by the study that it will be less costly to transform the global economy to net-zero and below. At which scale this has to happen will be covered in the next section.

2.2 Mitigation

Most important and effective against climate change is tackling it's cause. Therefore mitigating GHG emissions is the only sustainable pathway and long-term solution that leads out of the crisis. As stated in section 2.1.2, the trend from implemented policies, which are the NDCs announced prior to COP26, does not reflect the Paris Agreement's goal. Panel a) of figure 2.6 reflects that, while even predicting rising global emissions until 2050 [36].

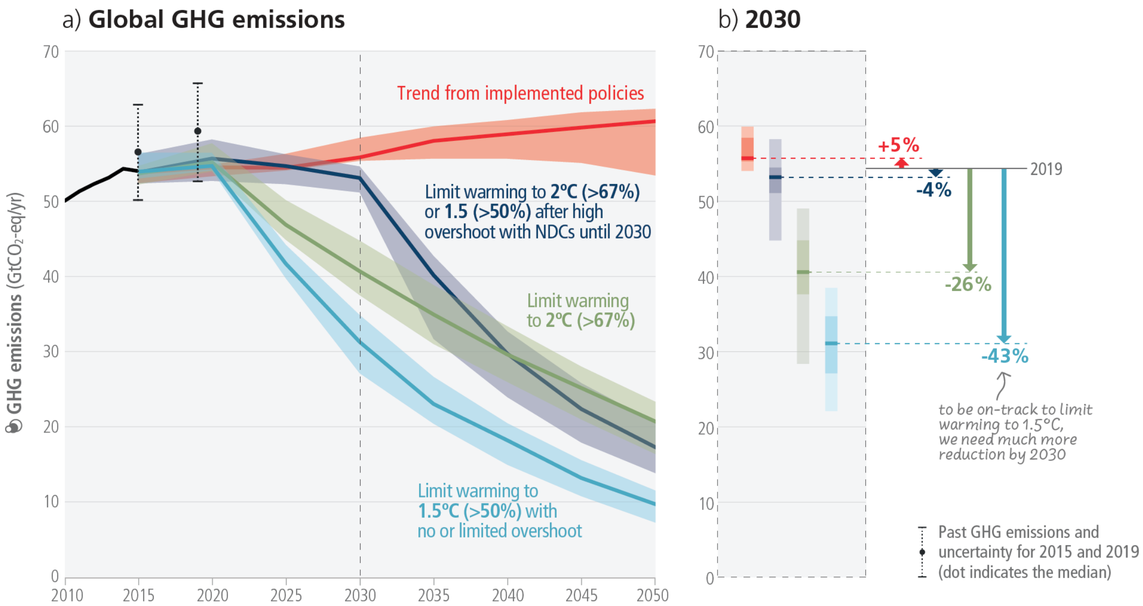

Figure 2.6: Annual global GHG emissions of modelled pathways from 2010–2050 (panel a), and projected emission outcomes from near-term policy assessments for 2030, including required emission cuts to meet the Paris Agreement goals (panel b) [36].

The three mitigation pathways shown assume immediate action after 2020, which we already know was not the case, as figure 1 in the appendix shows. Figure 2.6 further shows that 2030 is the critical inflection point where after a high overshoot in GHG emissions followed by a drastic cut a pathway towards 2°C warming could still be achievable.

Panel b) of figure 2.6 illustrates how much emission reduction is required by 2030 to achieve either 1.5°C or 2°C warming by 2100. In detail, a global emission reduction of 43% is required for 1.5°C warming and 26% is required for 2°C warming, while a reduction of 4% is given for the overshooting scenario and an emissions increase of 5% is estimated by 2030 based on implemented policies [36]. Reaching a global emission reduction of 43% or 26% by 2030 would still be just the beginning of a much more ambitious roadmap toward net-zero emissions by 2050 and net-negative afterwards to comply with the Paris Agreement, as discussed in sections 2.1.2 and 2.1.3.

It can seriously be questioned if the tremendous gap between reality and estimated climate pathways can be closed, therefore it is important to prepare humanity for drastic changes which leads to the next section.

2.3 Adaptation

In a climate context, the IPCC defines adaptation in human systems *"as the process of adjustment to actual or expected climate and its effects in order to moderate harm or take advantage of beneficial opportunities"* and in natural systems as *"the process of adjustment to actual climate and its effects"* while *"human intervention may facilitate this"* [39]. The goal of adaptation is to achieve ecosystem and planetary health, while a climate resilient development shall ensure human health and well-being, equity, and justice. For this purpose, the IPCC links to the UN's Sustainable Development Goals (SDGs), which will be explained more in detail in chapter 3 [39].

Beyond these definitions and frameworks, the IPCC finds that global adaptation efforts are largely reactive and small-scale and most of the 170 countries that included adaptation into their national policies are still planning for implementation while mainly focusing on current threats and near-term risks such as temperature increase in cities [39, 40]. The blocking point for moving forward is sufficient funding. Let alone industrialized countries, the IPCC estimates adaptation needs for developing countries will reach US$127 billion by 2030 and US$295 billion per year by 2050. Currently, adaptation accounts for only 4% to 8% of tracked climate finance, which amounted to US$579 billion in 2017–2018 [39, 40].

The IPCC presents three adaptation strategies, namely social programs to improve equity and justice (i), ecosystem-based adaptation (ii), and new technologies and infrastructure (iii). Strategy (i) propose actions ranging from reorganizing access to clean water, sanitation, and healthcare to partnerships among governments, civil society organizations, and the private sector while ensuring locally led decision-making processes. Under (ii), ecosystem protection, restoration, and sustainable management are proposed, for example through more sustainable agricultural practices such as integrating trees into farms, increasing crop diversity, and planting trees in pastures, while under (iii), the IPCC suggests that combining nature-based solutions with engineered options such as flood control channels can contribute to reducing water- and coastal-related risks. Access to better technologies such as more resilient crop varieties, improved livestock production, or green energy production utilizing solar and wind energy can also help increase climate change resilience. [39, 40].

On the other hand, the reality unfolds the truth that there are already severe impacts of climate change for which it is already too late to adapt. This is when people have already lost their source of income, such as coastal communities due to the loss of coral reefs, or people losing their homes due to the increase in fire, drought, and flood events worldwide, as described in section 2.1.4.

A recent example shows that severe heat waves can occur in southern Europe during the summer, leaving open the question of whether adaptation is even possible, as the magnitude of the heat will be unprecedented and is expected to be the new future normal, leaving no room for recovery [30, 36, 39, 40, 41].

In summary, AR6 offers an even more devastating outlook on the short-, medium-, and long-term future of planet Earth than AR5. At this point, as a complement to mitigation and adaptation efforts, we discuss geoengineering as a method of artificially cooling the planet, which will be discussed in subsequent sections and chapters.

2.4 Geoengineering

Geoengineering refers to large-scale interventions in the Earth's natural systems to counter the effects of climate change and can be categorized into SRM and CDR [11, 13, 33, 42]. As discussed in previous sections, humanity appears unable to respond in a timely manner to self-inflicted climate change while the lower band of first tipping points are reached. In this context, it is discussed whether it is either already too late for mitigation-only scenarios or whether a scenario in which we not achieve net-zero or even net-negative emissions by 2050 becomes more likely with each passing day.

The debate centers on if a point has already been reached where only a combination of rapid and deep emissions cuts, tremendous adaptation efforts, and geoengineering can be the only solution to mitigate climate change sufficiently. In that three-part scenario, it is furthermore discussed if in terms of geoengineering only a combination of different SRM and CDR methods are able to tackle the problem sufficiently as their effectiveness and timeliness differ enormously and therefore cannot indefinitely be scaled-up due to costs, side-effects and feasibility [14].

Even though those integrated assessments are very likely to be the only solution to the scale of the problem, those are rarely covered in literature – and space-based solutions are usually left out [12, 14]. In that context, it is important to note that geoengineering can only be a complement to, not a substitute for, mitigation and adaptation. Recent evidence has made it clear that geoengineering methods such as SAI are very likely to have severe negative side effects and therefore should not and cannot be expanded indefinitely [11, 14].

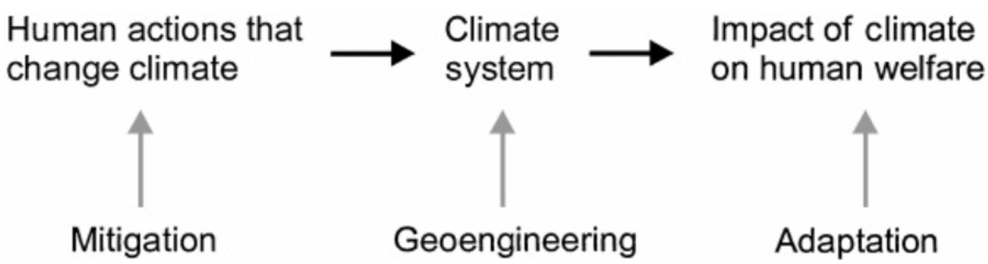

Figure 2.7: Geoengineering directly affects the climate system and, together with mitigation and adaptation, forms the three-part solution to the climate problem [11].

Figures 2.7 presents geoengineering in a context where it is the only response strategy that directly affects the climate system and, together with mitigation and adaptation, forms the three-part solution to climate change. The horizontal arrows show the causal chain of the anthropogenic climate problem while the vertical arrows, together with the bottom row, define the different ways of intervention.

The figure also shows that while mitigation affects all aspects of the causal chain, adaptation is the least effective strategy solution-wise, as it has no impact on the cause of anthropogenic climate change and the climate system itself. Therefore, it is critical to balance efforts, and it is still an unresolved question if, and to what extent geoengineering can and should be used.

There is a variety of different geoengineering approaches [11, 13, 33, 43, 44]. SRM focuses on reducing net incoming short-wave solar radiation, either through deflecting sunlight before it reaches the Earth or by increasing the albedo (reflectivity) of the Earth's surface, atmosphere or even clouds.

This illustrates that SRM aims at lowering the Earth's temperature and is not able to reduce GHG emissions with all their negative side effects such as ocean acidification, and therefore can only be seen as a rather short-term solution to prevent reaching tipping points while the world moves to net negative emissions. The main positive aspect about SRM is, that there is an immediate effect on the climate system effect after deployment. Section 2.4.1 will cover different approaches more into detail.

CDR approaches such as afforestation and reforestation, Direct Air Carbon Capture and Storage (DACCS), and ocean fertilisation aim to reduce the CO_2 levels in the atmosphere to allow outgoing long-wave heat radiation to escape the Earth's atmosphere more easily. It misses on other GHGs, but can theorethicaly be adapted to, and as long-lived CO_2 is the main driver of climate change, it is the only method next to mitigation contributing to achieve a net-zero world [45].

CDR methods are rather long-term solutions, as it takes decades to centuries to scale them up while it takes time till they effect the climate and the captured CO_2 needs to be stored, in terms of humanity we are talking infinity scale [46, 47, 48]. While this technology will likely be a central part of our future operations – it is no solution to our current climate crisis.

This can be seen as rather irrational, but if the goal is to achieve pre-industrial temperatures, pre-industrial CO_2 levels are required. This means, even if the transition to a net-zero world has been achieved it just stops making the situation worse. That means, that even in a net-zero world the heating will still continue because of the fact, that the GHG emissions since 1850–1900 are still in the atmosphere (past cumulative emissions, which will continue to heat up the planet) [22].

In that context, it becomes clear that a net-zero world is just an intermediate stept and by no means a solution to the long-term climate problem. It took humanity almost 200 years to reach current CO_2 levels and based on most optimistic CDR timelines it will take centuries to reach this levels again, the implementation of infinite storage solutions presumed while finding a solution for the mostly energy-hungry capture- or deployment technologies, not mentioning a wide range of side-effects as many solutions interfere with natural processes such as increasing alkalinity or conflicts of land use as the low efficiencies of CDR methods require global deployment [22, 14, 46, 47].

Natural CDR solutions such as afforestation and restoring wetlands should always be of highest priority. In respect to the century-, even millenial scale of the required efforts the lifetime of carbon stored in these systems are a very important criteria. The efficiency depends on future policy choices and on how climate changes evolves as warming increases the flux back to the atmosphere.

Therefore, it is discussed to call these methods *"carbon banking"* or *"delayed emissions"* [14]. It becomes clear that not only mitigation and adaptation, but also CDR as the only geoengineering option that aims to reduce the atmospheric GHGs comes with massive challenges and is no short term solution. For this reason, this work will focus on SRM from here.

Until today, geoengineering research has been focusing on what will geoengineering do, but as research proceeds and climate change evolves, there is a rising need to address outstanding engineering, governance and design questions. The scientific community should focus on answering the question if geoengineering can do what we want it to do, and at what confidence. Therefore it is important to understand the potential risks and benefits of these methods in order to make informed decisions about whether and how they can be used while considering the ethical implications, which will be covered in section 2.5.

2.4.1 Solar Radiation Management Approaches

SRM approaches can be divided into Earth-based methods such as surface albedo enhancement, Marine Cloud Brightening MCB, or Cirrus Cloud Thinning CCT and space-based methods such as dust clouds of lunar or asteroidal material, placed between the Sun and Earth, or constructed megaconstellations, usually in the vicinity of the Sun-Earth Lagrange Point 1 (SEL_1), and henceforth referred to as *"sun-*

shades" [13, 49]. In any two-body system in space, there are five Lagrange points where gravitational forces balance – a desirable location for space-based geoengineering.

While Figure 2.8 provides an overview of the different SRM approaches and their location, it also illustrates that all methods have in common that they aim to alter the Earth's energy balance in order to cool the planet. The SRM approaches presented will be briefly described in the next sections.

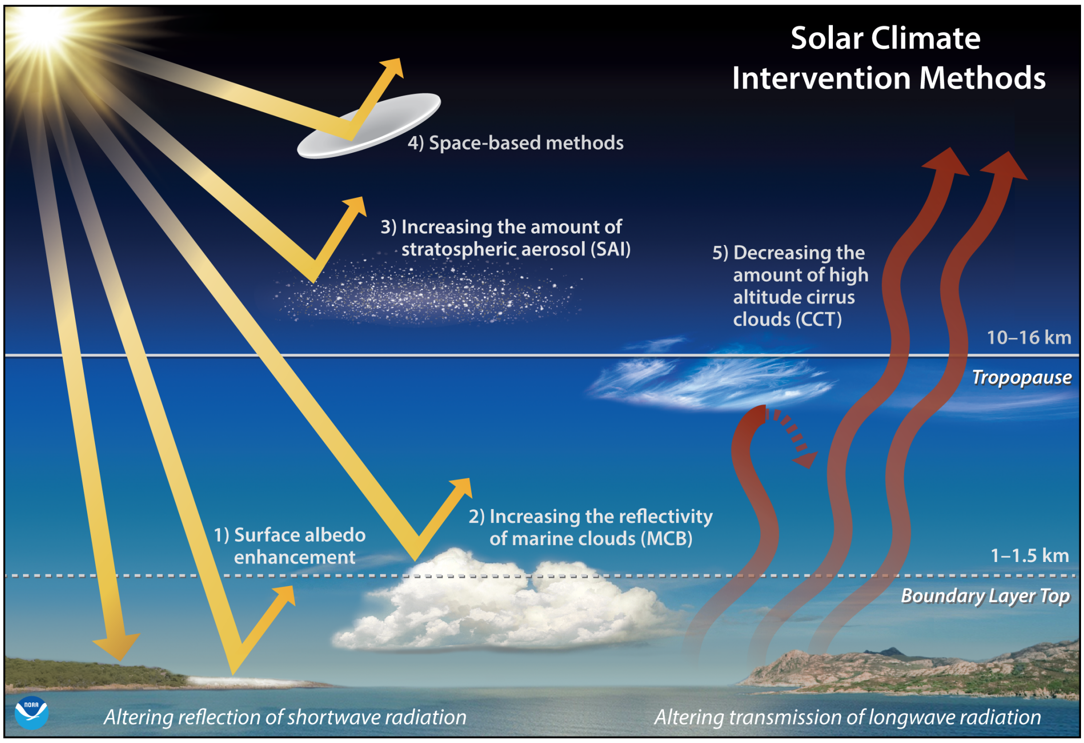

Figure 2.8: Overview of SRM approaches that either alter reflection of shortwave radiation or transmission of longwave radiation [50].

Earth-Based Concepts

SAI as the most studied SRM approach aims to reduce the amount of solar radiation that reaches the Earth's surface by injecting aerosols into the stratosphere (more than 20 km above the Earth's surface), while the particles reflect some of the incoming solar radiation back into space. Mainly discussed is the injection of SO_2 particles, which can be done with hundreds to thousands of aircraft at high altitude. Although this technology still needs to be developed (these aircraft need to fly higher than the SR-71 Blackbird), it seems like a feasible task, while deployment with any other vehicle one can think of, such as the more environmentally friendly deployment by high-altitude balloons, is possible [13, 15, 51].

The idea of SAI is adapted from volcano eruptions. Observations showed that ejected SO_2 particles cooled the Earth in a certain area by 0.6°C for about 15 months [52]. However, the literature also cites enormous research gaps and unknowns, e.g., differences between impulsive (volcanic) and continuous (SAI) injection [53, 54], and largely unknown side effects of changing the chemical composition of the atmosphere, although large amounts of SO_2 are already in the atmosphere, the execution of the proposed concept certainly results in new concentration levels [11, 14, 46, 54].

Further study is also needed to determine whether the increased atmospheric particle density could reach a level where spacecraft reentry becomes more challenging as heat shields could wear out faster – just to show one of several challenges that are not often thought of in connection with SAI.

Surface albedo enhancement can be applied to oceans or land. The goal is to increase the reflectance of the surface, e.g., by adding particles to water, genetically manipulating plants, or altering the roof of buildings. MCB aims to increase atmospheric reflectance by artificially creating stratocumulus clouds and increasing the concentration of cloud droplets over the ocean by introducing a fine salt mist derived from seawater by ships crossing the ocean. CCT aims to reduce the number of high-altitude cirrus clouds by seeding them with aerosols. Although this method aims to allow longwave radiation to escape from the Earth more easily, it belongs to the SRM approaches.

Even in best-case scenarios and when applied globally, while taking into account feasibility, surface albedo enhancement, MCB, and CCT are unlikely to reach the required scale, while SAI does [13, 33]. Moreover, Earth-based SRM approaches largely interfere with nature and human needs such as land use interests, and aim to intensively alter the Earth's atmosphere. This is where space-based geoengineering approaches brought to the discussion, as they only alter one variable, which is incoming solar radiation, with no chemical interactions. These approaches which will be covered in the next section.

Space-Based Concepts

Space-based geoengineering approaches use structures or materials in space to block or reflect incoming solar radiation. They are considered to be more expensive and technically challenging, but considered to be one of the most efficient SRM technology in terms of potential cooling in relation to RF, which is comparable to the efficiency of SAI) [33, 55].

Furthermore, they are the least invasive method, as they alter the solar constant in clean way. This leads to more predictable effects and, simultaneously, side effects are expected to be less significant compared to other geoengineering approaches. Additionally, the effects can be steered and, if necessary, eliminated at will as without corrections at SEL_1 any placed mass will disappear in a matter of weeks through the influence of solar radiation pressure SRP [11, 55, 56].

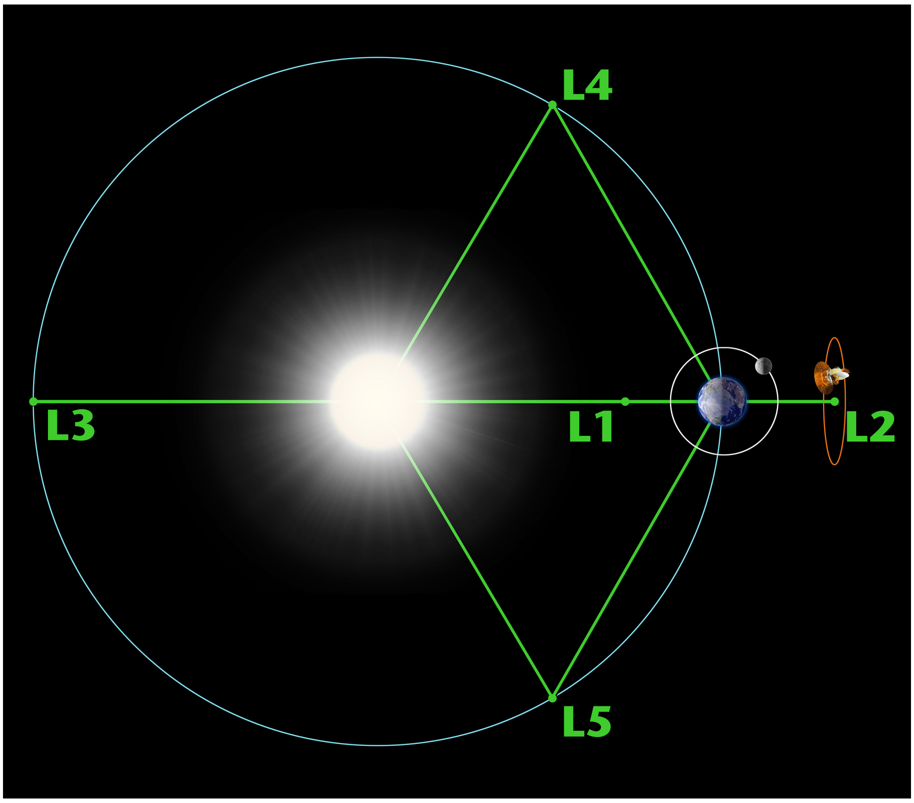

Figure 2.9: The five Lagrange Points of the Sun-Earth system, usually referred to as L1 to L5 or SEL_1 to SEL_5 [57]. The illustration is not to scale, as SEL_1 is 1.5 million km away from Earth, which corresponds to about 1% of the Earth-Sun distance.

It is also important to consider that space-based solutions, once established, are not subject to extreme weather events. The number and intensity of those events will most likely increase over the next decade, as previously discussed, which in turn may greatly influence strategic decisions about implementing Earth-based solutions, such as CDR. This could lead to even more future land use conflicts.

First sunshade concepts were independently brought up by Seifritz [58] and Early [56] in 1989. Seifritz proposed large mirrors mounted on satellites at SEL_1, while also considering SEL_2 and SEL_3, and Early suggested a thin reflecting or refracting glass shield at SEL_1. The different SEL positions can be seen in figure 2.9. McInnes presented a concept of a large solar shield at SEL_1 in 2002 [59], while Angel proposed a cloud of trillions of smaller "flyers" at the same location [60].

Moving forward, Kennedy et al. introduced their concept of "Dyson Dots" in 2013, consisting of a swarm of solar energy collecting sails with a total size of Texas, bringing a potential use case to the sunshade as the the concept would be able to capture and beam enough solar energy to Earth to meet present and future energy needs [61].

Sánchez and McInnes stated in 2015, that non-uniform shading is required to achieve a uniform cooling effect and presented dedicated orbits and techniques to do so [55]. A year later, Ellery 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. All concepts mentioned in this paragraph aim for a shunshade position in the vicinity of SEL_1.

In respect to progressing climate change, SEL_1 concepts matured to more holistic approaches as they tackle, e.g., more engineering challenges than previous work. Fuglesang and Herreros published their concept of a *Realistic Sunshade System* (RSS) in 2021. While this is an advanced Earth-launch concept, they aim for a possible start of deployment within two decades, which seems feasible if technology development starts now [16].

In 2020, the *"Planetary Sunshade"* concept build from space resources was published by Centers et al. [62] and Jehle et al. [63] and a visualization can be seen in figure 2.10. The concept was then – in collaboration – further developed into the *International Planetary Sunshade* (IPSS) by another group of authors such as Fix

[17] and Maheswaran [19, 64]. It is being further developed by Maheswaran et al. and Brauer [65, 66, 67, 68, 69] while Ganzmann and Acker will publish their work focusing on space logistics and evolutionary sunshade designs in 2023. Within it's variants, the IPSS aims for delivering space-based solar power (SBSP) from SEL_1 to Earth to cover global energy needs. Both the RSS and IPSS will be explained more into detail in chapters 3, 4 and 5.

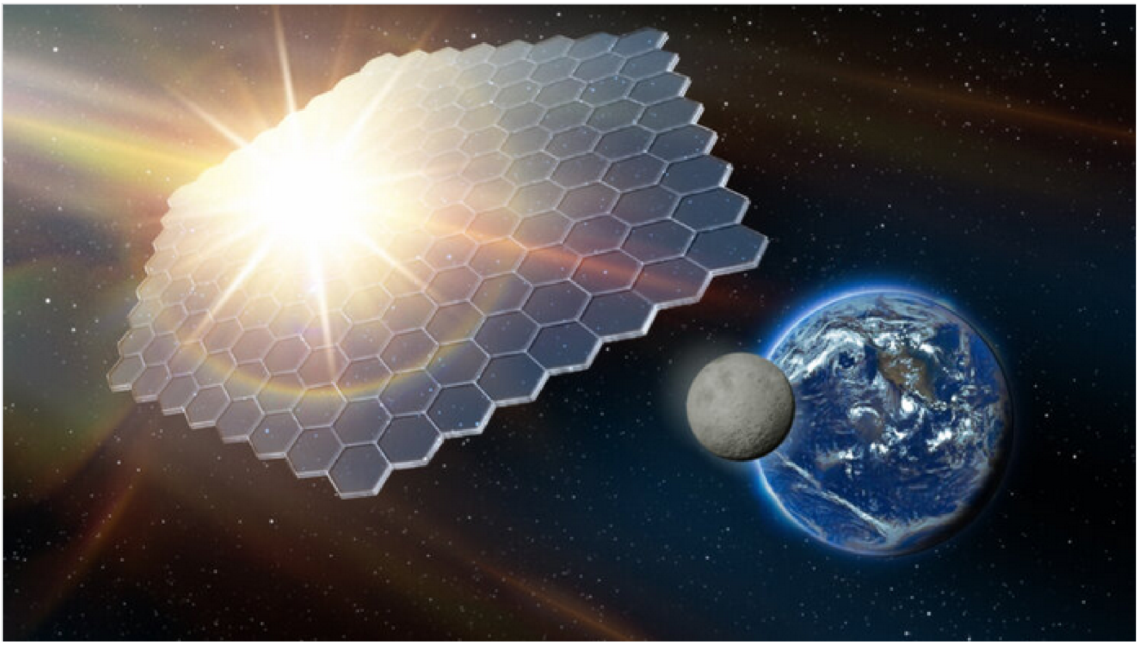

Figure 2.10: Illustration of the *Planetary Sunshade* concept at SEL_1 [62].

Borgue and Hein proposed an ultra-lightweight and near-zero SRP sunshade design in 2023 [18] utilizing advanced solar sail concepts of NASA [70]. The Earth-launch concept aims to reduce the required launch mass by factor 10^2 to 10^3. However, as a near-zero SRP design is unlikely to reach SEL_1 by solar sailing, a final sunshade concept would require an additional, disposable membrane layer (as suggested by the authors), or any form of space propulsion and possibly containment for transportation which has to be added to the launch mass calculations.

The lightest sunshade concept to date was published by Szapudi in 2023 [71]. Szapudi's tethered shield concept aims to require only 1% of the total mass to be launched from Earth. The fully Earth-manufactured sunshade would utilize lightweight tethers to be attached to a balancing mass (stemming from lunar dust or an asteroid) placed toward the sun. The 37.000 tonnes shield could therefore be placed close to Earth resulting in a relatively small sunshade surface area A_{Sh}, 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 accounts for the required infrastructure for an asteroid orbit manipulation or lunar mining activities as well as transporting the latter to SEL_1, which is important when comparing it to holistic approaches, such as RSS and IPSS.

As well in 2023, the concept of using lunar dust as a solar shield, previously researched by Struck in 2007 [72] and Bewick et al. in 2012 [73] has been taken up and advanced by Bromley et al. through the use of novel Earth-Sun intercept orbits and an analysis on particle properties and their scattering abilities [74].

Most concepts aim for a GMT decrease of 1°C to 2°C, resulting in a permanent sunlight attenuation of 0.5% to 1.8%, while 1.8% equals six days of the year of an obscured sun [74]. They mostly differ in the optical surface property factor κ (or Q), average areal density ρ_{Sh}, size and number of sunshades or objects and if they are either manufactured on Earth and launched by chemical or electrical propulsion or if they mostly or partly rely on in-situ resource utilization (ISRU) and in-space manufacturing (ISMA). ISRU focuses on using lunar regolith or even asteroidal materials aiming to minimize the environmental influence through the high number of required rocket launches to and to keep precious materials on Earth.

Any sunshade project scale would be unprecedented, newer concepts weight ranges from tens to hundreds of million tonnes, spanning low single-digit million km^2 [16, 17, 49]. Production of sunshades would therefore require an Earth- and/or space-based industry comparable to global phone or car industry.

Considering the scale, lowering maintenance frequency at SEL_1 is important as a single sunshade unit would have a limited lifetime and deployment of the whole system would take decades. Literature states that lifetime of a sunshade unit should reach 50 years, which is challenging to achieve as to increase lifetime on a decade scale primarily shielding of electronics, which is mass-intense, is necessary. A more robust but lightweight sunshade systems has to be developed while maintenance based on ISRU and ISMA would be the long term goal. If lifetime does not reach required levels in a timely manner, it is likely that maintenance would consume notable launch capacity before deployment is completed, therefore delaying deployment significantly.

In that context, a full Life Cycle Assessment (LCA), e.g., exploring environmental influence of development, production, deployment, maintenance and disposal has to be executed, as it is rarely covered in literature [16, 18, 75].

As time is a very critical factor, LCA has to be done simultaneously to development efforts. Understanding how the implementation of mitigation technology would contribute to global warming is not only a critical criterion to the systems efficiency, but also of utmost importance in terms of the purpose of this *emergency technology*, which is to buy time to transform global operations to net-negative emissions to counteract anthropogenic climate change. The latter aspect already contains an ethical dimension, which leads to the next section.

2.5 Ethical Implications of Geoengineering

Like Global warming, geoengineering comes with unprecedented challenges and concerns, that need to be addressed [76, 77]. A reduction in GMT does not necessarily mean improved living conditions for all countries and communities. It is likely that some regions benefit greatly while others suffer more and therefore raise the global inequality [15, 55]. Next to the question of governance, there is also a debate about whether humanity should intentionally intervene with nature on a global scale, while advocates point out that we have long done so through emitting GHGs into the atmosphere and would simply undo it.

Critics usually cite this as an argument against geoengineering because humanity has already proven that it can develop technology, but lacks the development of a society on the same scale, which often leads to misuse of technology. The topic has to be discussed among the general public, but studies on public or even expert perception has been very limited [43, 49]. On the other hand the UN promotes itself as well positioned to lead a globally inclusive conversation on SRM in its 2023 Environment Programme (UNEP) report [15]. Overall, the discussion brought up major concerns which will be discussed in the following sections.

2.5.1 Moral Hazard

Moral hazard comes into play if geoengineering works as expected, given concerns it could prolong mitigation and adaptation efforts and that the discussion about the implementation of such technology already shift financial, political and intellectual resources from these efforts [15, 78, 79, 80, 81].

One could also argue that on the same timescale the shift from a fossil fuel based economy towards a net zero economy is inevitable as fossil fuel reservoirs will come to an end. It is expected that the forced phase-out of gas is in 49 years, oil in 57 years and coal in 139 years due to limited supply but also increased energy prices as supply gets shorter and extracting becomes more and more difficult and may not be economically reasonable [82].

2.5.2 Unpredictability Argument

The *unpredictability argument* translates into "we just don't know enough", which is very likely the case as geoengineering would interfere with a highly complex system. There is the urgent call for more research funding, and more nations and institutions getting involved, especially the ones from the global south, who will likely suffer most both from climate change and geoengineering.

Critics mention that the effects on environment, ecosystems, and societies are widely unknown and difficult to model. Unintended and irreversible consequences could be the outcome or the system does just not have the desired effect [11, 15].

While this is very likely to be true, there is a significant database of climate change and it's devastating future effects on us [36]. Either a world with geoengineering and a world without geoengineering will present potentially serious challenges, demonstrating the difficulty of the decision-making process. Especially the consequences of geoengineering needs to be studied further to be able to make informed decisions.

2.5.3 Slippery Slope Argument

The *slippery slope argument* states that humanity will never stop using and advancing on geoengineering to suit the global environment human needs, once implemented. This could already start with small outdoor experiments leading to large-scale deployment. Especially if several nations, institutions or companies do this at the same time, it poses the risk of conflict and even war [15].

Literature states that while experimental validation is required, the scale and duration of these experiments would likely need to be similar to deployment to obtain reliable data on climate (not weather) impacts [83]. This means that clarity about the global impacts of geoengineering deployment can only be achieved through an actual deployment decision [51].

Moreover, since proponents view geoengineering as a precursor to terraforming other planets to make humanity a multiplanetary species, the *slippery slope argument* takes on another dimension.

2.5.4 Technical Fix Argument

The *technical fix argument* criticises 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 may not solve some of the key problems related to climate change.

However, geoengineering is not intended to solve all climate change related issues, instead it is meant to contribute to climate change mitigation along with mitigation and adaptation efforts. Literature suggests that geoengineering-only would be ineffective or even make things worse, as with scaling up to compensate for mitigation comes a massive increase of side effects. Therefore, it is possible that no geoengineering method alone can mitigate anthropogenic climate change [14, 47].

2.5.5 Termination Shock

The *termination shock problem* states that geoengineering as a technical solution to the climate problem cannot be turned on and 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 [15, 84].

The UNEP suggests never implementing a system where it is not known how to reverse or turn down the effects once the task is done or how to compensate for the side effects since the unwise use of technology has brought us to the current situation [15].

2.5.6 Weather Control Instead of Climate Control

Literature suggests that global uniform decrease in RF does not have a global uniform cooling effect [14, 55, 85, 86, 87]. Reasons for that are, e.g., different climate seasons in the northern and southern hemisphere, the curvature of the earth but also the fact that changes in atmosphere, cloud or surface albedo, do not cause equivalent changes in planetary albedo [33]. This results in a situation where no geoengineering method should be applied in a uniform way. Even further, the effects of uniformly applied geoengineering could run counter to the intended goal [86].

Additionally, the geoengineering 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 is obvious that a deep understanding of weather control rather than "only" climate control is required for a successful implementation of SRM [85, 88]. Since the underlying principle of all SRM methods is the same, it also applies for sunshades in space [55].

Therefore, it is very likely that this technology will not only need to be very well understood, but also very precisely executed in time and region, resulting in controlled local changes on a regular basis [54, 55, 87]. *This would be a very powerful tool* that raises concerns about which set of design choices will allow for simultaneous control of all variables in all regions [85]. Based on human history, it can be seriously questioned whether humanity will be mature enough to use this technology for the benefit of all, if even possible.

Chapter 3

Evaluation of Relevant Literature

Since this work aims to evaluate space-based geoengineering approaches, a two-fold literature review has been conducted to (i) find, select, and, if necessary, define relevant evaluation criteria and (ii) examine a literature selection based on it's criteria coverage.

Hence, section 3.1 will cover applied methodology, section 3.2 will focus on (i) selection of evaluation criteria while in section 3.3 space-based geoengineering literature will be (ii) evaluated regarding the coverage of the given criteria set. To close this chapter, a conclusion will be given in section 3.4.

3.1 Methodology

(i) A comprehensive selection of geoengineering-related literature has been made. As geoengineering will likely influence all aspects of life, overarching human lifespan, it should be reflected in a given set of evaluation criteria. Therefore, the review has been widened from geoengineering-related literature to generic sustainability frameworks that could be adapted.

Literature selection was made based on scientific citations, variety of perspectives, online reads or views, media attention, publication date, and relevance to research objectives, while the latter is partly influenced by personal preference as research objectives have been chosen to allow for a certain degree of freedom. In any case, transparency about personal preference will be provided in sections 3.2 and 3.3.

Published works from years 1989–2023 were selected, which is, in terms of space-based geoengineering, an exhaustive coverage while general geoengineering literature has a history on a century scale [11]. In order to find sustainability-related frameworks that could be used to evaluate space-based geoengineering approaches, rather recent literature had to be studied, dating back to 2003.

To ensure statistical significance 70 publications comprising several thousand pages were examined. However, in section 3.2 only publications providing specific input that led to a selected criteria or framework will be presented to stay within scope of this thesis.

(ii) To *"reveal trends, relationships, (in)consistencies, and gaps in the literature in order to organize, evaluate, and synthesize what is known and what is unknown in a particular field"* [89], [90], a representing range of 20 space-based geoengineering-related publications divided in four groups was selected based on principles of (i). For every group at least three publications have been selected.

The selection then was analyzed by the chosen set of 18 geoengineering-related evaluation criteria and two generic frameworks, totaling 51 reviewed criteria per publication which results in 1020 data points. For each criterion-publication combination, the data point consists of a qualitative rating about how strong given criterion is covered. Based on this simple assessment scheme, see section 3.3, a quantitative evaluation was made.

All ratings can be found in figures 7, 8 and 9 in the appendix. To ensure data accessibility, results have been graphically analyzed, which is presented in section 3.3.

The systematic assessment allowed for a quantitative selection process, as was examined which space-based geoengineering approaches covering the widest range of criteria and how intense coverage of the criteria is. A selection of two space-based geoengineering concepts was made, which will serve as foundation for further description and evaluation in chapters 4 and 5.

3.2 Survey and Definition of Evaluation Criteria

In 2019, there were about 500 geoengineering-related journal papers written [22]. Literature on space-based geoengineering is even more limited, by an order of magnitude is estimated here, and no work has been found that focuses on evaluating different space-based approaches in a systematic assessment. Only Baum et al. presented an overview of 23 space-based geoengineering proposals, providing short concept descriptions – but the work focuses on expert perceptions on space-based geoengineering in general [49].

Additionally, Shyur and Keith presented an annotated bibliography of space-based geoengineering in 2019, briefly structuring 13 space-based geoengineering concepts after *"Type, Location, Mass (tonne), Area (*km^2*), Material, Notes and concerns"* [91]. Those brief overviews are typically found in introduction sections of space-based geoengineering literature, but these rather technical criteria do not provide a foundation for a comprehensive, systematic assessment.

A first view on space-based geoengineering literature reveals the lack of standardized frameworks to describe any geoengineering concept. Many authors use very different approaches when answering the same question, 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* and *effectivity* (see *efficacy* subsection in section 3.2.1). Since those criteria differ from each other [92, 93], difficulties and accuracy issues arise when trying to compare concepts, to give an example.

Authors also focus on very different topics, while covering similar topics with different depth. Hence, given information is rather split, which is why a wide evaluation criteria selection is needed – if the goal is to find the rare intersections that would enable a comparison. However, geoengineering evaluation criteria (GEC) that should ideally be addressed by all future proposals was derived in the course of an excessive study of which an overview is shown in table 3.1 and figure 3.3.

3.2.1 Geoengineering Evaluation Criteria

The majority of geoengineering literature consists of rather high-level assessments while mostly qualitative criteria are used to system or concept comparisons. Some comparison studies on geoengineering include space-based approaches. These publications give a good starting point for finding evaluation criteria.

One of them is the 2009 *Royal Society* report on geoengineering [13]. Shepherd et al. introduced four qualitative criteria, which are *effectiveness, affordability, timeliness,* and *safety.* In the report, each geoengineering method was evaluated by giving a rating from *very low* to *very high* and a short justification for each criterion, which can be seen for the example of space-based methods in figure 3.1.

Space-based methods		
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 (eg 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

Figure 3.1: Qualitative evaluation of space-based geoengineering in the geoengineering report of the *Royal Society* (Shepherd et al.) [13].

The *OHB System AG* (OHB) then utilized and enhanced the *Royal Societies* criteria for their *"Detailed SRM Study Report"* in 2020 [94]. A description and value was given to five different levels of each of the report's four criteria (except for *safety*). The *timeliness'* criterion definition is presented in figure 3.2 while the definitions for *effectiveness, affordability* and *safety* can be found in figures 2, 3 and 4 in the appendix.

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

Figure 3.2: OHB's detailed SRM study report timeliness trade-off criterion definition [94].

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.

The results of the report have been presented to the public, but the report itself was not. Therefore, the report's content is thankfully presented with the permission of OHB

Although those criteria allow for an initial analysis, which is important for decision making, there are strings to any high-level approach attached. E.g., *timeliness* highly depends on effort and prioritization, *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 an extremely complex issue.

Additionally, mentioned criteria depend on deployment scale and location, while the use of high-level qualitative criteria is rather given, as there is a lack of data. This illustrates the difficulty of determining criteria in the geoengineering domain.

Hereafter, a criteria selection will follow, in which for each a definition will be given. This will form the GEC set proposed in this work. A summary of selected criteria, together with their definitions, is given in table 3.1.

Social Acceptability and Public Perception

The *Royal Society* report suggests the criterion *public acceptability*, which will here referred to as *social acceptability*, as this is a commonly known criterion in social science. It can't 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"* [95].

To reach *social acceptability* of geoengineering, *public perception* is the underlying structure [96]. Public perception, in a technology context, can therefore influence policy and industry decisions towards implementation and can be described as *"all kinds of perceived benefits, barriers, or risks associated with a specific technology"* [96].

However, within geoengineering literature, *public perception* is rarely studied. Examples are Arning et al. [96] in 2019 and Corner et al., who published a *public perception* study of geoengineering in 2013 [97]. Furthermore, an expert perception study was done by Baum et al. in 2022 [49].

As an involved public is crucial for considering the implementation of geoengineering, it is important to make this research gap visible (see section 3.3.1). Hence, *public perception* and *social acceptability* were added to the criteria set.

Social Justice

Social justice is about 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"* [98]. As mentioned in chapter 2, climate change and geoengineering will influence regions and communities different and therefore *social justice* has to be of priority during all phases of the project to lower global inequalities.

Energy Justice

Energy justice is of two-fold importance. First, because of the transition to low carbon energy production [99, 100], contributing to mitigation adaptation efforts, and second, with respect to geoengineering, as, e.g., SRM results in unequal global solar radiation reduction and affects the solar energy sector.

Additionally, regions 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 nuclear power plants, but also wind- and solar energy farms.

Different *energy justice* frameworks have been introduced [101, 99], but in respect to the scope of 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"* [102], while *justice* in the energy context is discussed in [101].

Governance

Governance is of central concern and often mentioned among literature [49, 15, 13], yet no consensus has emerged. As mentioned in chapter 2, UN sees itself in a position to host an inclusive panel on *Governance* questions [15].

In addition, Keith et al. note the importance of *governance* as they predict the implementation of geoengineering likely to be 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 SG. It makes the case that good *governance* has the potential to positively impact the success of geoengineering [14].

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"* [13]. It must be applicable to *"small-scale outdoor experiments, technology development, financing ...[,] deployment"* [15], operations and phase-out.

Ethics

The *Ethics* criterion is often, to varying degrees, mentioned in literature [11, 13, 15, 61, 79, 94, 97]. 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 are explained in section 2.5.

Wording / Framing

In the social and communication science, *wording* and *framing* refers to *"the way we describe things and the analogies we use have an influence on how facts are perceived."* [103], as mentioned in an OHB-led interview. It is a very powerful, but in geoengineering context rarely studied tool, with Keith, Corner et al. and Nebling providing exceptions [11, 97, 103].

While sunshades are frequently described using rather technical terms, such as *"occulting disks"* [18, 55], there might be better wording to enhance *social acceptability* and *public perception*, which eventually leads to more research funding. Nebling stated 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"* [103].

This leads to the question, if *"geoengineering"* itself is an appropriate term, which is partly addressed by Keith [11]. To make this research section more visible, the *wording* and *framing* criterion is part of the GEC.

Deployment Time

The *deployment time* is a frequently mentioned and therefore important criterion, but it is mostly based on assumptions. In line with the work from Lenton and Vaughan [33, 43] and the UN [15], the *deployment time* is divided into two periods: The time required from (i) today to the start of deployment, i.e. including development time, and (ii) from there to full deployment.

Radiative Forcing Potential

Lenton and Vaughan investigated the *radiative forcing potential* of various geoengineering approaches, including sunshades, among 19 SRM and CDR methods. While they refer to *"climate cooling effectiveness"* [33], the IPCC defines *radiative forcing potential* as *"change in net irradiance at the tropopause, after allowing stratospheric temperatures to readjust to radiative equilibrium"* [32].

However, as mentioned in section 2.5, spatio-temporal SRM is needed to achieve global uniform cooling [14, 55]. Spatio-temporal control enables possible benefits such as global welfare maximization in respect to mitigation-adaptation scenarios, preservation of biodiversity, specifically preventing CTPs, pursuing SDGs, e.g., reduction of global inequalities [14], and the redistribution of malaria risk in developing countries would likely be feasible [104]. Besides mentioned positive aspects, misuse of this very powerful technology is possible and would have unprecedented negative consequences.

It is worth noting that a reduction of RF through SRM causes different spatial and spectral patterns than GHGs do. This means that SRM methods, even when scaled to offset net global RF contributions through GHGs, are not able to revers the effects of GHGs on climate [14].

Using *radiative forcing 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 [17, 19, 64, 65] and RSS [16] literature, while *radiative forcing potential* is a transparent criteria about a concept's ability and can be used for all geoengineering approaches. Hence, *radiative forcing potential* refers in this work to the ability to generate scaleable spatio-temporal RF to achieve a global uniform cooling effect.

Lifetime of Effect

The *lifetime of effect* for different geoengineering methods was assessed by Vaughan and Lenton in 2011 [43]. In former work they introduced the *effect decay rate*, which can be seen as a similar approach [33], But it adds the valuable information about the progression of the effect 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 or full deployment, taking into account heterogeneity of decay rates.

Efficacy

Efficacy generally means reaching the desired goal. It must not be confused with *efficiency*, which means accomplishing something with minimum resources and *effectiveness*, which is the ability of producing a desired result [93, 92].

In the context of geoengineering, Keith et al. defines that *"efficacy captures the limited ability of ... [SG] to reduce aggregate climate damages due to the heterogeneity of climate response to SG"* [14], while Lenton and Vaughan define it as *"ability to effect surface temperature changes"* [33] in respect to different geoengineering methods [33, 14, 55].

Efficacy is difficult to assess, therefore understudied, but most relevant for decision-making. This is why it has been chosen for the GEC set, while *effectiveness* is already covered by *radiative forcing potential* and *efficiency* is part of the *sustainability* criterion. As the given *efficacy* definition of Lenton and Vaughan is easier accessible, it has been adapted.

Side Effects

As discussed in chapter 2, geoengineering is likely to cause unintended *side effects*, and trade-offs must be made regarding non-geoengineering scenarios, the latter of which are likely to be more costly [14, 38]. In that context, Keith et al. included *side effects* within *impact* criterion that *"captures the human and environmental side-effects and costs associated with producing the SG's RF"* [14].

Keith et al. also assume that *side effects* increase with quadratic influence when SRM is used to fully offset anthropogenic climate change, resulting in the same damages as climate change would cause [14]. Therefore, the criterion is crucial.

The economic *side effects*, i.e. *costs* for geoengineering deployment and climate change, shall be given in GDP per year to allow for easier cost-benefit analysis and comparison. However, this work will not be *costs*-driven and *costs* will not be a separate criterion in the GEC set, but will be covered within the (economic) *side effect* criterion. The reasons for this decision will be given below.

While low-cost geoengineering options will likely increase the number of countries that would contribute to geoengineering efforts [14], it shall not be of highest priority as it would likely lead to resource allocation towards the most inexpensive methods – or those that claim to be. A deployment of the cheapest methods comes likely attached with the acceptance of increased side effects resulting in equally increased global inequalities, which current bias towards SAI shows [13, 15, 78].

Hence, a debate focused too much on costs could lead to the exclusion of more environmental friendly solutions such as sunshades [15, 105], the cost of which could likely be reduced to a more economically feasible level if research efforts were shared equally. Additionally, current cost estimates could have huge margin errors, which likely adds to an distorted evaluation of different methods. Instead, we should ask ourselves if a new way of assessment is appropriate here as the general pursuit of low costs and high profits brought us in today's situation.

Besides these considerations, it is assumed that costs will be no issue when decision makers and the people of developed countries realize what lies ahead. That is, because only an estimated annual spending 2% global GDP, is required to deploy geoengineering (SRM and CDR) for compensation for anthropogenic climate change, which equals the North Atlantic Treaty Organization (NATO) contribution target.

To summarize, the criterion *side effects* captures human, environmental, economic (including costs), and all other intended and unintended consequences associated with the generation of RF that differ from a uniform distribution of cooling effect [14].

Controllability

The need for an ability to control a given geoengineering method after deployment is often mentioned as key capability among literature [74, 55, 16, 43]. However, there is more to it than "just" steering RF.

The geoengineering approach must allow for transparent control, i.e. independent and open source monitoring, implementation of a transparent governance framework, accessibility for maintenance purposes, ability for continuous replenishment, low and assessable risk of failure with the aim to only allow the system to be used in a way that benefits society, which can be a technical and human challenge.

Reversibility

In their reports, both OHB [94] and the *Royal Society* [13] came to the conclusion that a more detailed assessment is needed[94], which led Shepherd et al. to propose a criteria set that future geoengineering proposals should address, aiming for increased comparability. Those criteria include *reversibility*, which can be understood as the ability to undo the effect and the understanding of how long it takes, together with the social, political, technical, and economic consequences of such action [13]. Especially in the geoengineering context, no system should be implemented that is not known how it can be reversed and how long it takes – therefore *reversibility* is among the GEC.

Technology Readiness Level

The *Technology Readiness Level* (TRL) methodology was introduced by NASA in 1970s and is used to assess the maturity of space technology [106]. However, due to the mostly conceptual nature of geoengineering literature, TRL methodology is rarely used. In the field of space-based geoengineering, TRL assessments can be found among the IPSS [17, 19, 64, 65] and RSS [16] literature, and in Borgue and Hein, 2023 [18].

In their work, Borgue and Hein additionally use the *Advancement Degree of Difficulty* (AD^2) methodology, which is used for risk assessment of technologies and addressing limitations of TRL, as TRL do not include the difficulty of reaching a higher level [107]. An overview of the nine TRL and AD^2 level is given in figures 5 and 6 in the appendix.

It is suggested that at least TRL will be adapted within geoengineering literature to enable comparison studies, but also for providing information about the current state of technology of each method, which allows for addressing research gaps and, e.g., informed decision making regarding resource allocation.

IPCC Mitigation Scenarios and Data

The IPCC assessment reports, such as the latest AR6, present the most comprehensive work on climate change and represents global scientific consensus. Therefore, it is most important that geoengineering literature refers to and integrates recent findings, especially given pathways. This would increase scientific value of each geoengineering concept and in general enhance credibility of the field, while allow for informed evaluation and decision making.

Integrated Assessment

As stated in chapter 2, geoengineering should, if ever, only be complementary implemented in a strong mitigation and adaption scenario. This leads to the need that geoengineering has to be assessed in the same, integrated way. Additionally, it is likely that several geoengineering methods will be implemented at the same time and this has to be reflected in assessments as well.

Wigley proposed a combined mitigation and geoengineering (SAI) strategy in 2006 to address increasing ocean acidity in an SAI-only scenario [12]. Keith et al. went further and published an *integrated assessment* model in 2021 that incorporates solar geoengineering (SG, equal to SRM), CDR, and mitigation into an assessment model to analyze trade-offs, but did not include adaptation [14].

It should be build upon these modeling efforts to enable informed decision making. Hence, the *integrated assessment* criterion refers to the integration of geoengineering, mitigation and adaptation and their different variants in regional- and global-scale assessment models.

Sustainability

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"* [108], which is in this work applied to Earth-based but also future space-based generations.

Even though dedicated sustainability framework will be introduced in section 3.2.2, the decision was made to include the *sustainability* criterion in the GEC set as it is intended to serve as a stand-alone framework.

Summary of Results

An overview and definitions of the selected GEC are presented in table 3.1 while figure 3.3 classifies the results in technical- and social responsibility criteria.

Table 3.1: A proposal of 18 GEC.

GEC	Title & Description
1.	**Radiative Forcing Potential:** Ability to generate scaleable spatio-temporal RF to achieve a global uniform cooling effect [14, 55].
2.	**Deployment Time:** It is divided into two periods: The time required from (i) today to the start of deployment, i.e. including development time, and (ii) from there to full deployment.
3.	**Lifetime of Effect:** Time until the effect no longer triggers measurable changes after partial or full deployment, taking into account heterogeneity of decay rates.
4.	**Efficacy:** *"Ability to effect surface temperature changes"* [33].
5.	**Side Effects:** Captures human, environmental, economic (including costs), and all other intended and unintended consequences associated with the generation of RF that differ from a uniform distribution of cooling effect [14].
6.	**Controllability:** Transparent control, must allow for independent and open source monitoring, implementation of a transparent governance framework, accessibility for maintenance purposes, ability for continuous replenishment, low and assessable risk of failure with the aim to only allow the system to be used in a way that benefits society, which can be a technical and human challenge.
7.	**Reversibility:** Ability to undo the effect and the understanding of how long it takes, together with the social, political, technical, and economic consequences of such action [13].
8.	**Technology Readiness Level:** Assessment of space technology maturity introduced by NASA in 1970s [106].
9.	**IPCC Mitigation Scenarios and Data:** Integration of latest IPCC findings, especially given pathways.
10.	**Integrated Assessment:** Integration of geoengineering, mitigation and adaptation and their different variants in regional- and global-scale assessment models.

Table 3.1: A proposal of 18 GEC. (Cont.)

GEC	Title & Description
11.	**Sustainability:** *“Meeting the needs of the present without compromising the ability of future generations to meet their own needs”* [108], applied both to Earth-based and future space-based generations.
12.	**Ethics:** Ethical concerns, such as moral hazard, technical fix argument, slippery slope argument, unpredictability argument, termination shock and concerns about enhanced weather control.
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”* [13]. It must be applicable to *”small-scale outdoor experiments, technology development, financing ...[,] deployment”* [15], operations and phase-out.
14.	**Wording / Framing:** *”The way we describe things and the analogies we use have an influence on how facts are perceived.”* [103].
15.	**Public Perception:** In a technology context, *”all kinds of perceived benefits, barriers, or risks associated with a specific technology”* [96].
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”* [102].
17.	**Social Acceptability:** *”The outcome of a collective judgment or collective opinion of a project, plan or policy”* [95].
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”* [98].

The figure shows selection of mostly strong criteria. The GEC set is well balanced between the technical and social responsibility domain, as 6 very strong technical criteria, 7 very strong social responsibility criteria and 4 criteria that are very strong in both fields have been selected.

Only the *wording* and *framing* criterion is in the lower third of both fields, while TRL and *social justice* criteria are only very strong in their respective field and very weak in the other. The chart clearly states that most criteria have a high intersection between the technical and social responsibility domain, which reflects the complex reality of geoengineering well.

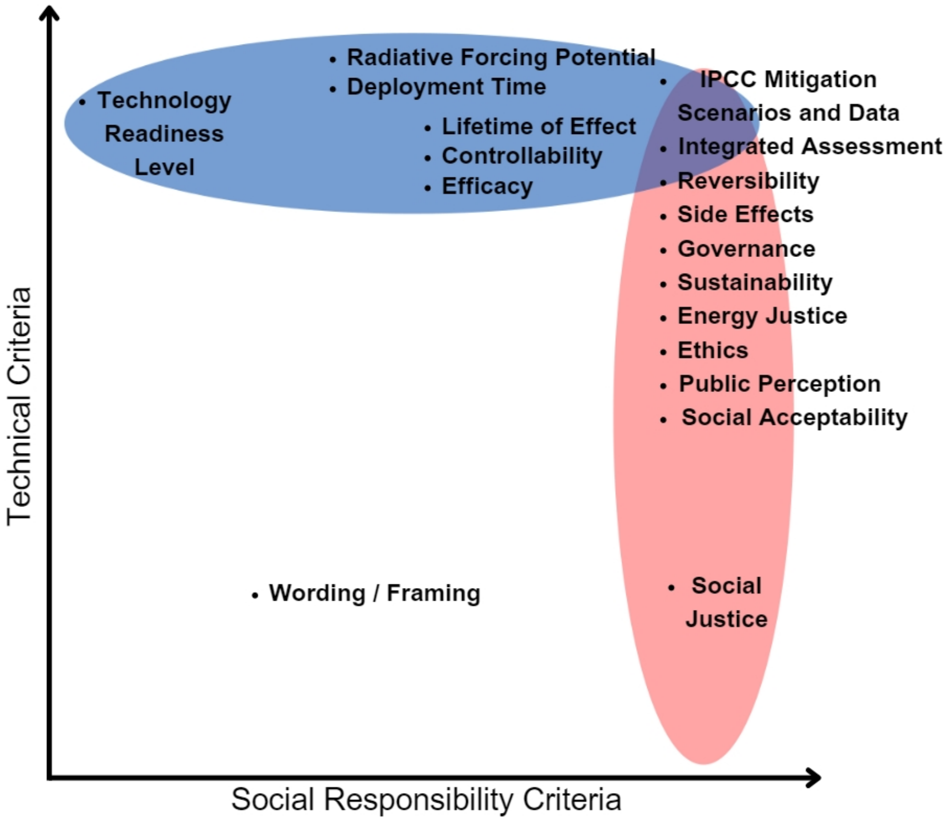

Figure 3.3: GEC classified in technical- and social responsibility criteria.

3.2.2 Sustainability Frameworks

Within experts it is discussed why space-based geoengineering is not considered as a feasible solution, despite it's potential [105]. There may be the high-cost argument, but as discussed it is rather theoretical as global scientific community estimate the cost of climate change to be much higher than implementing geoengineering, including space-based solutions, which therefore would be economically feasible [14, 18, 38, 109].

There may also be the argument that space-based geoengineering literature is very limited and a tremendous amount of research is necessary, which is probably why the latest UNEP report classifies space-based solutions not feasible, even though they cite three papers which came, in principle, to the opposite conclusion [16, 73, 79].

To overcome these obstacles, this work proposes to adapt to agendas of powerful institutions which would promote and potentially use the technology for the benefit of humanity, once they realize that space-based geoengineering contributes to their objectives, which eventually leads to an increase of research efforts.

Hence, it is important to understand "the language" of a given institution, which will be done by addressing their sustainability frameworks. The step after is to evaluate, if space-based geoengineering literature has answers to it, which will be done in section 3.3.2. The evaluation will likely reveal research gaps, which have to be addressed before results can be presented to given institutions.

For the assessment in this work, the UN Sustainability Goals SDGs [110], which are summarized in table 3.2, and the European Space Agencies (ESA) LCA Environmental Impact Indicators EII for space systems [111], which are presented and described in table 3.3, have been chosen as frameworks to evaluate space-based geoengineering approaches.

Table 3.2: The 17 UN SDGs [110].

SDG	Title & Description
1.	**No Poverty:** End poverty in all its forms everywhere.
2.	**Zero Hunger:** End hunger, achieve food security and improved nutrition and promote sustainable agriculture.
3.	**Good Health and Well-Being:** Ensure healthy lives and promote well-being for all at all ages.
4.	**Quality Education:** Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all.
5.	**Gender Equality:** Achieve gender equality and empower all women and girls.
6.	**Clean Water and Sanitation:** Ensure availability and sustainable management of water and sanitation for all.
7.	**Affordable and Clean Energy:** Ensure access to affordable, reliable, sustainable and modern energy for all.
8.	**Decent Work and Economic Growth:** Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all.
9.	**Industry, Innovation and Infrastructure:** Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation.

Table 3.2: The 17 UN SDGs [110]. (Cont.)

SDG	Title & Description
10.	**Reduced Inequalities:** Reduce inequality within and among countries.
11.	**Sustainable Cities and Communities:** Make cities and human settlements inclusive, safe, resilient and sustainable.
12.	**Responsible Consumption and Production:** Ensure sustainable consumption and production patterns.
13.	**Climate Action:** Take urgent action to combat climate change and its impacts.
14.	**Life Below Water:** Conserve and sustainably use the oceans, seas and marine resources for sustainable development.
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.
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.
17.	**Partnerships for the Goals:** Strengthen the means of implementation and revitalize the Global Partnership for Sustainable Development.

As geoengineering will likely influence all aspects of life including every human on Earth, addressing those comprehensive sustainability frameworks would eventually lead to increased public and scientific perception. The selection of the given frameworks have therefore partly been made based on personal preference, while also pursuing the thesis' objective to find sustainability-related criteria that can be applied to Earth- and space-based solutions.

Table 3.3: The 16 ESA Space System LCA EII, [111].

EII	Title	Unit	Description
1.	**Global Warming Potential**	kgCO_2-eq	Indicates the level of RF due to GHG emissions (100y).
2.	**Ozone Depletion Potential**	kgCFC-11-eq	Stratospheric ozone depletion due to the emission of ODS.
3.	**Human Toxicity Potential**	CTUh	Effect of emission of toxic substances on humans.

Table 3.3: The 16 ESA Space System LCA EII [111]. (Cont.)

EII	Title	Unit	Description
4.	**Fossil Resource Depletion Potential**	GJ Fossil	Decreasing availability of natural resources (including energy resources) such as iron ore, crude oil regarded as non-living.
5.	**Photochemical Ozone Formation Potential**	kgNMVOC	Tropospheric ozone formation due to action of solar light on primary pollutants, e.g., VOC.
6.	**Freshwater Eutrophication Potential**	kgP-eq	Impacts of macro-nutrients nitrogen and phosphorus leading, mainly, to oxygen depletion because of dead algae degradation. P is the limiting nutrient in aquatic ecosystems whereas N is the limiting nutrient in marine ecosystem.
7.	**Marine Eutrophication Potential**	kgN-eq	Equals 6.
8.	**Ionizing Radiation Potential**	kBq ^{235}U-eq	Effect on humans due to the emission of radioactive substances.
9.	**Freshwater Ecotoxicity Potential**	CTUe	Effect of emission of toxic substances on freshwater ecosystem (fauna and flora).
10.	**Marine aquatic Ecotoxicity Potential**	kg1,4-DB-eq	Effect of emission of toxic substances on marine ecosystem.
11.	**Air Acidification Potential**	kgSO_2-eq	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.

Table 3.3: The 16 ESA Space System LCA EII [111]. (Cont.)

EII	Title	Unit	Description
12.	**Primary Energy Consumption Potential**	MJ	Consumption of energetic resources (fossil, nuclear, biomass), expressed in MJ of primary energy.
13.	**Gross Water Consumption Potential**	m^3	Water withdrawals due to industrial processes in lakes, rivers, oceans, and groundwater.
14.	**Mass disposed in the Ocean**	kg	Total mass of stages disposed in the ocean.
15.	**AL_2O_3 Emissions in Air**	kg	Emissions in air of Aluminium oxide during launch event.
16.	**Mass left in Space**	kg	Total mass of space hardware remaining in orbit at the end of the mission.

3.3 Evaluation of Space-Based Geoengineering Literature

According to the literature selection principles introduced in section 3.1, 20 publications divided in four groups have been determined. While each work has already been introduced, the groups include concepts on space-based geoengineering that propose ISRU and ISMA, manufacturing on- and launch from Earth, no specific variant (general) and literature that discusses space-based geoengineering along with terrestrial approaches. An overview is presented in table 3.4.

With respect to Fix and Maheswaran, 2021, a paper and two thesis have been chosen because they complement each other and form the 2021 IPSS concept and are therefore considered to be one publication. This provides an example for limitations in comparability and influence of personal preference as several paper consist of sub-25 pages, while other publications, including the mentioned combination, are well over 100 pages.

As mentioned in section 2.4.1, the IPSS concept is being developed further resulting in a 2023 version, but key work has yet to be published to allow sufficient assessment. However, some of the newest findings have already been introduced in chapters 5, 6 and 7.

Table 3.4: Overview of selected space-based geoengineering literature for the criteria coverage evaluation. Literature selection principles have been introduced in section 3.1. In case of Fix, Maheswaran, 2021 – a selection of three publications was made, as they complement each other and form the IPSS.

Publication	**Title**	**Reference**
Space-Based (ISRU/ISMA)		
Early, 1989	*Space-Based Solar Shield to Offset Greenhouse Effect.*	[56]
McInnes, 2002	*Minimum Mass Solar Shield for Terrestrial Climate Control.*	[59]
Ellery, 2016	*Low-Cost Space-Based Geoengineering: An Assessment Based on Self-Replicating Manufacturing of In-Situ Resources on the Moon.*	[88]
Fix, Maheswaran, 2021	*Feasibility Study of a Sunshade in the Vicinity of the Sun Earth L1 Lagrange Point*; *Analysis of Logistical Construction Aspects of a Sunshade Concept in the Vicinity of the Sun Earth L1 Lagrange Point*; *Roadmap for an International Planetary Sunshade (IPSS).*	[17, 19, 64]
Bromley et al., 2023	*Dust as a Solar Shield.*	[74]
Space-Based (Earth-Launch)		
Angel, 2006	*Feasibility of Cooling the Earth with a Cloud of Small Spacecraft near the Inner Lagrange Point* (L1).	[60]
Fuglesang, Herreros, 2021	*Realistic Sunshade System at L1 for Global Temperature Control.*	[16]
Borgue, Hein, 2023	*Transparent Occulters: A Nearly Zero-Radiation Pressure Sunshade to Support Climate Change Mitigation.*	[18]

Table 3.4: Overview of selected space-based geoengineering literature for the criteria coverage evaluation. Literature selection principles have been introduced in section 3.1. (Cont.)

Publication	Title	Reference
Space-Based (General)		
Kennedy et al., 2013	*Dyson Dots: Changing the Solar Constant to a Variable with Photovoltaic Lightsails.*	[61]
Sánchez, McInnes, 2015	*Optimal Sunshade Configurations for Space-Based Geoengineering near the Sun-Earth L1 Point.*	[55]
Baum et al., 2022	*Between the Sun and Us: Expert Perceptions on the Innovation, Policy, and Deep Uncertainties of Space-Based Solar Geoengineering.*	[49]
Space-Based & Terrestrial		
Keith, 2000	*Geoengineering the Climate: History and Prospect.*	[11]
Lenton, Vaughan, 2009	*The Radiative Forcing Potential of Different Climate Geoengineering Options.*	[33]
Shepherd et al., 2009	*Geoengineering the Climate: Science, Governance and Uncertainty.*	[13]
Vaughan, Lenton, 2011	*A Review of Climate Geoengineering Proposals.*	[43]
Corner et al., 2013	*Messing with Nature? Exploring Public Perceptions of Geoengineering in the UK.*	[97]
OHB System AG, 2020	*Solar Radiation Management: Detailed SRM Study Report.*	[94]
Keith et al., 2021	*Optimal Climate Policy in 3D: Mitigation, Carbon Removal, and Solar Geoengineering.*	[14]
UNEP, 2023	*One Atmosphere: An Independent Expert Review on Solar Radiation Modification Research and Deployment.*	[15]
PSF, 2023	*State of Space-Based Solar Radiation Management.*	[78]

The literature was evaluated by using a simple evaluation approach to quantify criteria coverage, which is to examine the coverage intensity of each criterion. As can be seen in figures 7, 8 and 9 in the appendix, each criterion and publication set was rated either *no coverage (-)*, *low to medium coverage (+)*, *and detailed coverage (++)*, which leads to the corresponding intensity values *(0)*, *(1)* and *(2)*. An overview is presented in table 3.5.

Table 3.5: Definition of a simple assessment to quantify criterion coverage of selected space-based geoengineering literature. The sum of several criterion coverage intensities leads to *"cumulative intensity"*.

Coverage	Symbol	Intensity Value [-]	Description
None	-	0	No statement can be linked to a given criterion.
Low to medium	+	1	One to ten statements can be linked to a given criterion.
Detailed	++	2	More than ten statements can be linked to a given criterion.

It is important to repeat that the evaluation assesses whether the publications contain information on criteria, which is a useful tool to *"reveal trends, relationships, (in)consistencies, and gaps in the literature in order to organize, evaluate, and synthesize what is known and what is unknown in a particular field"* [89], [90]. Thus, it is not an evaluation of impact, which would lead to a high personal influence on the results.

To assess total criteria coverage of a given publication (see table 3.4) or criterion coverage among all publications (see tables 3.5, 3.6, and 3.7) *cumulative intensity* is introduced. Hence, *cumulative intensity* is the the sum of a group of criterion coverage intensities.

As selected literature differ in research objectives and much in scope it was found that normalizing results in respect to a "winning" publication would lead to an increased inequality in assessment and research gaps would no longer be reflected by the data. Also, providing a ranking between authors does not contribute to the evaluation's objectives.

In case of figure 3.4, a normalization of UN SDG and ESA space system LCA EIIs criteria sets against GEC could be useful, if the evaluation focuses on variations in *cumulative intensity* between those groups – but here, the focus is on total values and comparison within the groups, where normalization has no impact.

Normalizing results in respect to maximum achievable *cumulative intensity* was considered too, but still the publications do not aim to provide a wide assessment and due to the nature of results and assessment, no qualitative, partly not even quantitative changes could be observed through normalization.

Instead, normalization led to either decreased visual accessibility of data which is contrary to the figures objectives, or, when rounded to the nearest integer, inaccuracy. In summary, it led to the decision to present the data in its original state.

Figure 3.4 shows the *cumulative intensity* of GEC in blue, UN SDGs in orange, and ESA space system LCA EIIs in grey, comprising data of figures 7, 8 and 9, which can be found in the appendix. It can be derived that the GEC are mostly addressed, while UN SDGs are followed by ESA space system LCA EIIs.

While the maximum *cumulative intensity* would be 102, resulting from an intensity value of 2 for each publication-criterion set, the figure visualizes that Shepherd et al. reaches the highest overall *cumulated intensity* of 54, followed by Vaughan and Lenton with 50, which is about 50% of the possible maximum. Both belong to the group of space-based and terrestrial literature, where Lenton and Vaughan received a low total *cumulative intensity* of 14 due to it's specialization on RF *potential*, even tough it is a highly relevant paper (based on citations).

Within ISRU and ISMA related publications Fix and Maheswaran, representing the IPSS concept, achieve a high *cumulative intensity* of 32, doubling the value of the second strongest publication Bromley et al., while Early and McInnes provide the lowest results of the study, which can be referred to the early publication date and the low page count of three and five.

Fuglesang and Herreros presented the strongest publication on each of the three criteria sets within the Earth-launch group resulting in a *cumulative intensity* of 33, while Borgue and Hein scored 18 and Angel 12.

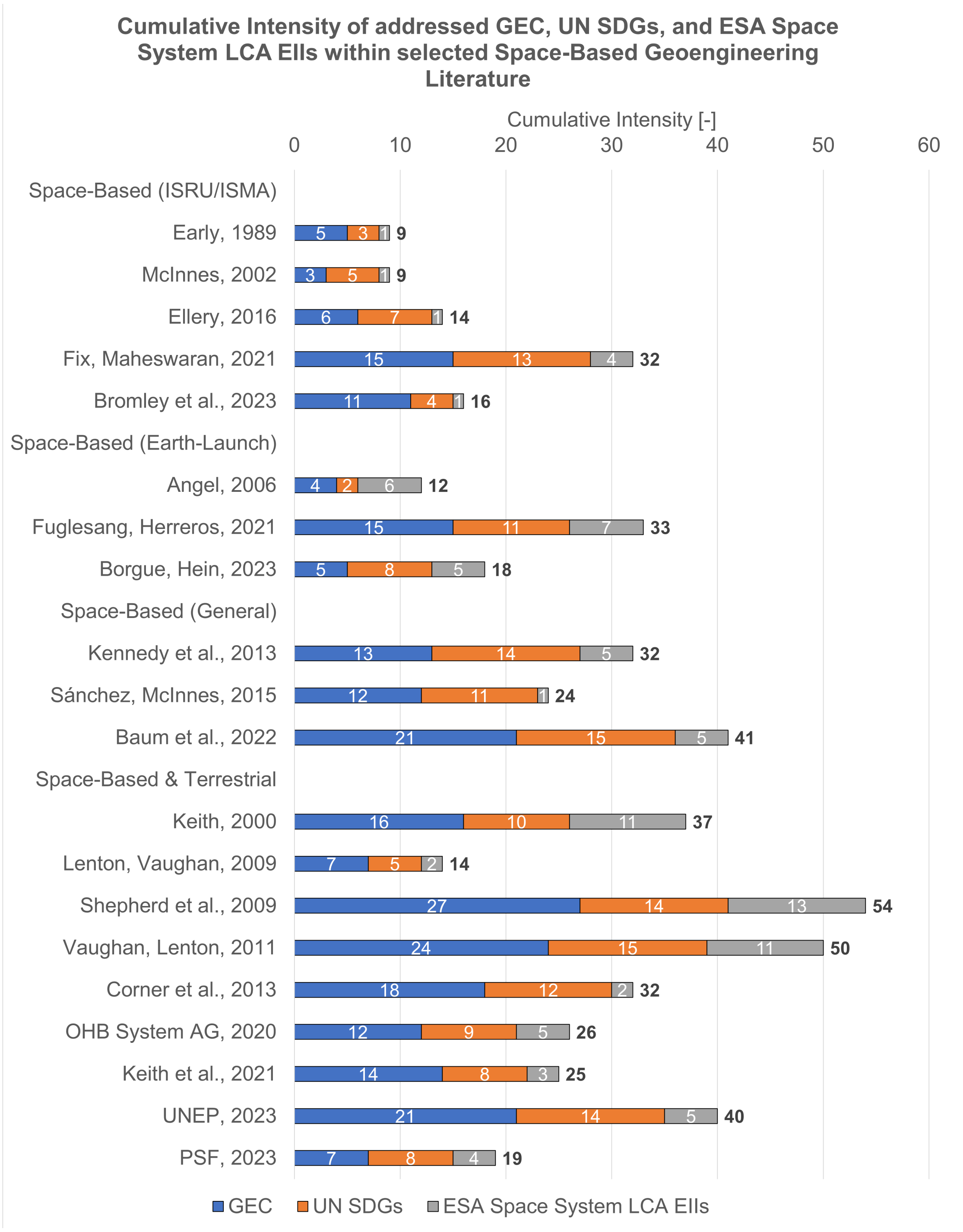

Figure 3.4: Coverage of GEC, UN SDGs, and ESA space system LCA EIIs within selected space-based geoengineering literature. Cumulative intensity indicates the extent to which a particular set of criteria is covered (max. value: 102). Raw data is shown in figures 7, 8 and 9 in the appendix.

Among the general space-based geoengineering literature selection Baum et al. reached the highest value of 41. It could be seen as surprising, given that it is a perception study, but a closer look reveals the interviewed experts address relevant topics, while answering to appropriate questions. Hence, the publication scores high on both technical and social responsibility criteria coverage, while the authors additionally provide a brief but wide introduction in different space-based geoengineering concepts, which additionally adds to the *cumulated intensity*.

Within the group, Kennedy et al. and Sánchez and McInnes follow with *cumulative intensities* of 32 and 24, while Sánchez and McInnes rather cover GEC, UN SDGs instead of ESA space system LCA EIIs. It is again an example for a highly relevant publication that focuses on creation of spatio-temporal RF, which in turn leads to an average *cumulative intensity*.

On average, there is no clear trend that newer publications lead to a higher *cumulative intensity*, which is surprising as both UN SDGs and ESA space system LCA EIIs were introduced in 2016 and a delayed increase was expected. Moreover, the UNEP report does not have the highest *cumulative intensity* of UN SDGs, instead Baum et al. and Vaughan and Lenton do, with Shepherd et al., Kennedy et al., and Fix and Maheswaran having comparable results. This leads to the next sections 3.3.1 and 3.3.2, where the criteria coverage of each set is examined more into detail.

3.3.1 Geoengineering Evaluation Criteria

Figure 3.5 visualizes the *cumulative intensity* of GEC, comprising data of figure 7 from the appendix. While a max. value of 40 can be reached, resulting from an intensity value of 2 for each of the 20 publications, the average *cumulative intensity* is 14, representing 35% of total maximum.

As the figure shows a strong focus on *side effects* and *controllability* with *cumulative intensities* of 28 and 27, it is surprising that RF *potential* has only an average value of 16, while it is the most important technical criterion. Second to that, *reversibility* and TRL receive a medium and low rating as well, which quantifies the lack of engineering solutions within space-based geoengineering literature.

Furthermore, *IPCC mitigation scenarios and data* coverage receives a medium value of 16, which corresponds to a low rating of *integrated assessment* of 12, stating

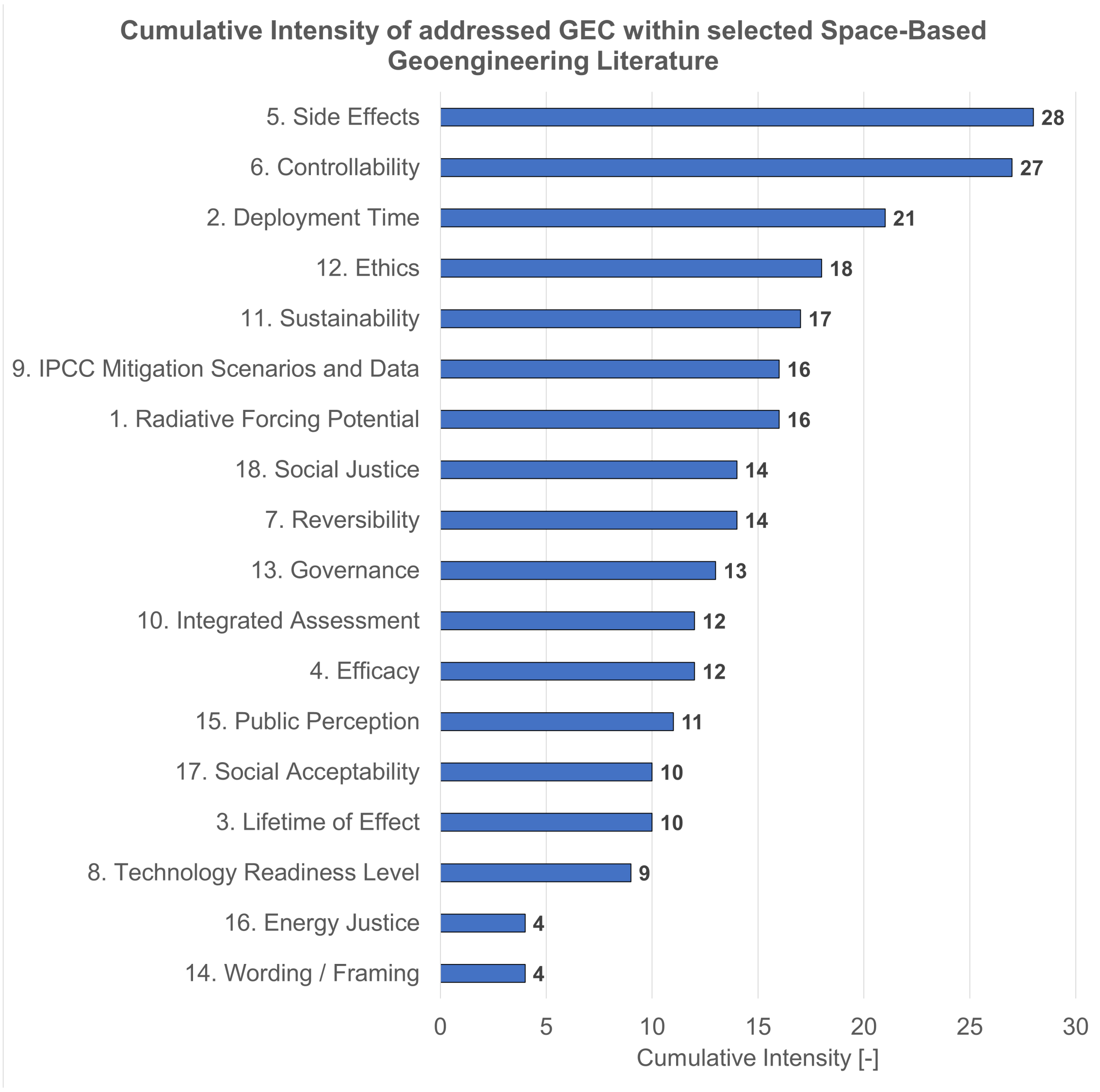

Figure 3.5: Coverage of GEC within selected space-based geoengineering literature. Cumulative intensity indicates the extent to which a particular criterion is covered (max. value: 40). Raw data is shown in figure 7 in the appendix.

important research gaps. *Wording* and *framing* and *energy justice* are the least covered criteria, which aligns with the assessment given in section 3.2.1 and especially the latter has to be addressed, as explained in the same section.

To summarize, there are more research gaps among technical and social responsibility criteria than sufficient coverage of a certain criterion. This is rather alarming, as the criteria are meant to be the most important, selected among hundreds.

3.3.2 Sustainability Frameworks

Figure 3.6 shows the *cumulative intensity* of UN SDGs, comprising data of figure 8, which can be found in the appendix. Again, a max. value of 40 can be reached, while average *cumulative intensity* is 11, representing 27.5% of total maximum. The SDG *Industry, Innovation and Infrastructure* gets the highest rating of 25, which is due to the high mentions of required industry, either located in space, on Earth, or both, in combination with the tremendous amount of research and engineering that is needed to implement a space-based geoengineering approach.

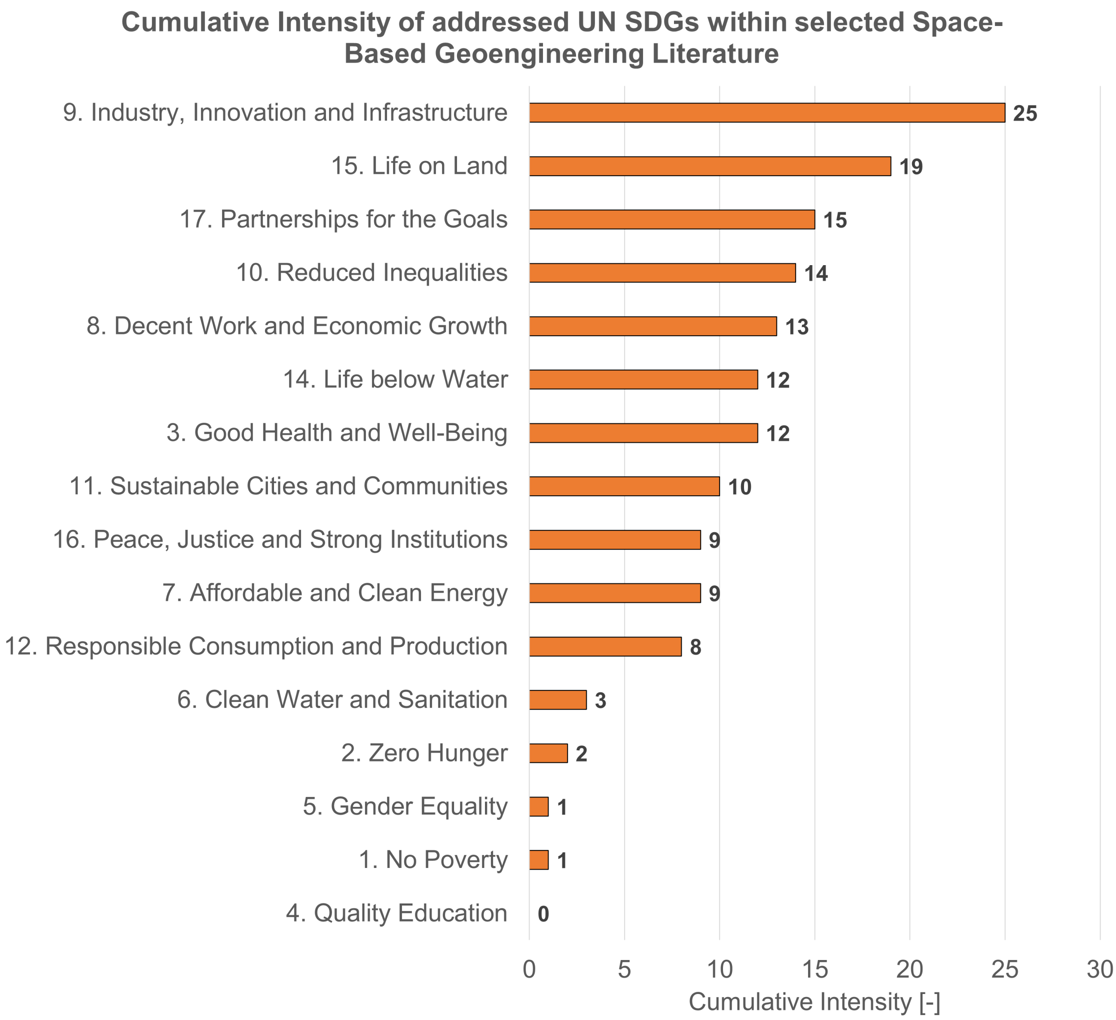

Figure 3.6: Coverage of UN SDGs within selected space-based geoengineering literature. Cumulative intensity indicates the extent to which a particular criterion is covered (max. value: 40). Raw data is shown in figure 8 in the appendix.

Therefore, the SDG *Industry, Innovation and Infrastructure* can be understood as the one that reflects technical research gaps. Second most addressed SDG is *Life on Land* with a value of 19, which is to be expected as life on Earth, in all its forms, will be heavily influenced.

To realise space-based geoengineering methods such as sunshades, a global effort is needed due to the scale of the task. This is only partly reflected by literature, as *Partnerships for the Goals* receives a rating of 15, followed by *Reduced Inequalities* that has an intersection with previous SDG, as all nations have to be included in the decision making process.

In comparison, the SDGs *Good Health and Well-Being*, *Sustainable Cities and Communites* and *Responsible Consumption and Production* achieve low ratings, which translates into research gaps on how a sustainable geoengineering world would work. Adding to it, *Clean Water and Sanitation*, *Zero Hunger* and *No Poverty* are almost uncovered. That is concerning as the global south, which is likely to be influenced very strong by climate change and geoengineering, seems to be excluded from considerations. While global inequalities are expected to rise if not a good *governance* structure will be implemented, as mentioned in chapter 2 and section 3.2.1, these research gaps have to be addressed. In that context, space-based geoengineering's influence on global food production and therefore distribution, has to be examined.

The evaluation on UN SDGs shows that space-based geoengineering literature needs to address the wider picture of consequences, while it seems that the SDGs are a sufficient tool to specify gaps which could be turned into a research agenda.

Figure 3.7 shows the *cumulative intensity* of ESA space system LCA EIIs, comprising data of figure 9, which can be found in the appendix. A max. value of 40 can be reached here as well, while the average *cumulative intensity* is 6, representing 15% of the total maximum. This shows, that ESA's EII are the least intensive covered criteria with the highest *cumulative intensity* of only 14 for *Human Toxicity Potential*.

It is important to note that while ESA provides specific assessment units (see table 3.3), intensity values have been given in respect to their descriptions, even if units are not mentioned. This was necessary to be able to include statements that clearly contribute to the criteria, but did not mention specific units.

Moreover, it was anticipated that the criterion *Mass left in Space* would be among the highest scores, but in respect to the maximum possible result the coverage is very low. This is rather surprising as an unprecedented amount of mass would be launched to space and it is of high interest how much would remain, e.g., in Earth orbits and if the disposed mass could be retrieved after the sunshades end of life.

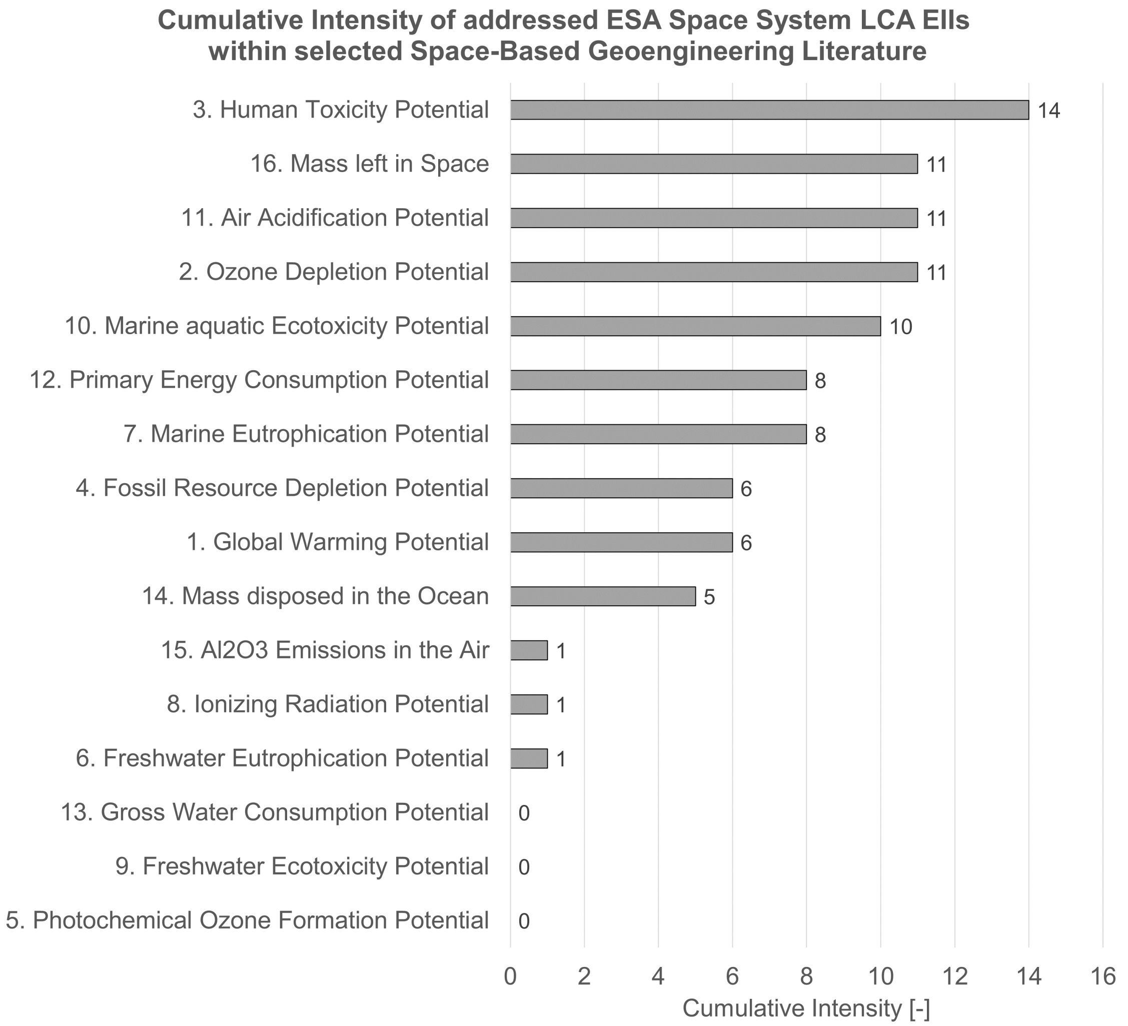

Figure 3.7: Coverage of ESA space system LCA EIIs within selected space-based geoengineering literature. Cumulative intensity indicates the extent to which a particular criterion is covered (max. value: 40). Raw data is shown in figure 9 in the appendix.

The EII focus significantly on marine and freshwater ecosystems, which is rarely addressed by space-based geoengineering literature and subsequently leads to very low ratings in these fields. In contrast to that, the criteria were implemented by

ESA for reasons, even though they seem to be unrelated. Especially in the context of a system that needs a new global industry to achieve climate and weather control, these criteria are of particular importance.

Due to the high number of required rocket launches and the required manufacturing industry for, e.g., launch- and space transportation vehicles, fuel production, and sunshades, no matter the approach, related research gaps of *Global Warming Potential*, *Fossil Fuel Resource Depletion Potential*, *Ozone Depletion Potential*, *Air Acidification Potential*, *AL_2O_3 Emissions in the Air* and *Photochemical Ozone Formation Potential* have to be researched, as they receive very low ratings.

Among those criteria, *Global Warming Potential* seems to efficiently quantify contributions to climate change, which sunshades aim to compensate, and should therefore be prioritized in research (see chapter 5).

To summarize, ESA space system LCA EIIs are important and well defined criteria that can be applied to space-based geoengineering approaches. However, the overall coverage is weak and needs to be increased if the goal is to enhance credibility and knowledge to allow for informed decision making.

3.4 Conclusion

The examination of terrestrial and space-based geoengineering literature led to a comprehensive set of 18 GEC whose goal is to reflect the overarching nature of geoengineering. Furthermore, the study of geoengineering unrelated literature led to the selection of two sustainability frameworks, namely UN SDGs and ESA space system LCA EII which allows for an evaluation through the lens of well known institutions.

The applied methodology enabled an assessment of criteria coverage among a selection of space-based geoengineering literature through the introduction of *cumulative intensity*.

However, the current state of literature reveals wide research gaps in all relevant fields. A clear trend in criteria coverage over time could not be observed, which is surprising as both UN SDGs and ESA space system LCA EII were introduced in 2016 and a delayed increase was anticipated. While ESA criteria are certainly not relevant to US-based publications, most authors were coincidentally Europe-based and the criteria, such as *Mass left in Space* are not in particular tied to the European space industry.

It was found that the GEC comprise a balanced set of technical and social responsibility criteria, which could be interpreted as an appropriate fit, while the two sustainability frameworks could be well integrated into the assessment, even though the high number of 51 criteria can be seen as a drawback. Hence, the GEC are intended to serve as a stand-alone evaluation framework.

However, mistakes during literature assessment and influence of personal preference could not be excluded from considerations which could have led towards a bias or misinterpretation of criteria, while it is neither aimed that GEC are appropriately defined or in any sense "complete".

The evaluation revealed that Shepherd et al., i.e. the 2009 Royal Society Report on geoengineering [13] and Vaughan and Lenton's 2011 review on geoengineering proposals [43] achieved the highest criteria coverage intensity. On the other hand, analysis on SDG coverage brought to light that very important SDGs such as *Zero Hunger* and *No Poverty* are almost uncovered, leading to the impression that global south is excluded from considerations. The high amount of research gaps, including the lack of engineering solutions and IPCC data integration could be seen as the major reason why space-based geoengineering approaches do not get traction in the debate.

Hence, to be considered as a serious complement to mitigation and adaptation, it is suggested to address stated research gaps. Ultimately, this would lead to greater acceptance by the public, the scientific community, and policymakers, while increasing the chances of bringing ESA to the debate, as it is likely that European efforts would include, if not led by the powerful institution, which also applies for the UN on a global level.

According to the thesis' objectives, a selection of space-based geoengineering alternatives, notably Earth-launch and in-space manufactured sunshades, should be derived for further evaluation. Hence, the two publications with the best ranking will be chosen. The leading publications in the respective ISRU/ISMA and Earth-launch groups are the ones proposing the IPSS [17, 19, 64] and RSS [16] concepts and will be taken for a further assessment in chapters 4 and 5.

Chapter 4

Concept Parameter

For each of the two concepts, which have been introduced in section 2.4.1 and determined for further evaluation in chapter 3, literature will be examined for proposed technical parameter. The results will be given in sections 4.1 and 4.2, while the parameter will be introduced in this section first.

In that context, the first parameter is the average solar constant $S_0 = 1371\ \frac{\mathrm{W}}{\mathrm{m}^2}$ at one astronomical unit (AU), while the distance equals $AU = 1.49598 \times 10^8$ km – the average sun to Earth distance. Various sources state slightly different amounts of S_0, and so does the RSS and IPSS literature.. Here, the given value was chosen in respect to IPSS literature [17], while the reason will become clear later in this chapter.

As S_0 is a two dimensional constant, it has to be adjusted to the three dimensional, spherical nature of Earth, which has a four times higher surface than it's two dimensional projection. This leads to $S = 342.75\ [\frac{\mathrm{W}}{\mathrm{m}^2}]$, which is the annual global mean flux of solar radiation at the top of the atmosphere (TOA) [17, 33].

Another important parameter is the planetary albedo $\alpha_p = 0.313$, which is the average proportion of reflected sunlight [33]. Hence, due to α_p, solar radiation flux that contributes to thermal balance is 235.47 $[\frac{\mathrm{W}}{\mathrm{m}^2}]$. The first set of defined parameter now allows for the introduction of the change in solar radiation

$$\Delta S = \frac{RF}{1 - \alpha_p}\,. \tag{4.1}$$

The equation defines, that a desired RF on Earth can only be achieved when the sunshade compensates for the reflected solar radiation due to α_p. This leads to the definition of relative solar radiation reduction

$$f = \frac{\Delta S}{S}\,. \tag{4.2}$$

As the objective of sunlight attenuation is a change in GMT, ΔT, a correlation between a change in RF and Earth's adaption to it has to be introduced.

$$\Delta RF = \lambda \cdot \Delta T\,. \tag{4.3}$$

λ refers to Earth's climate sensitivity, which quantifies how much Earth cools or warms for a given change in RF, after a certain adjustment period. A comprehensive assessment [112] in 2020 led to

$$\lambda = \frac{RF}{\Delta T} = 1.23\,\frac{W}{m^2K}\,. \tag{4.4}$$

Sunshades optical properties are crucial to the endeavours success and therefore focused on in concept proposals. The RSS literature refers to a sail efficiency factor Q, while the IPSS literature utilizes the optical surface property factor κ.

Effectively both summarize optical reflectance and re-emission properties of a surface, while a high value shows a high reflectance which equally results in a high exposure to solar radiation pressure SRP.

Further parameter to define sunshades are average areal density ρ_{Sh}, distance to Earth r_{Sh}, surface area A_{Sh} and mass M_{Sh}. As described in 2.4.1, the IPSS utilizes SBSP in on of their variants, therefore generated power by solar cells P_G will be stated in the table 4.2, if applicable.

4.1 Realistic Sunshade System

Table 4.1 provides an overview of the previously introduced parameter in respect to the RSS. The concept proposes two variants of lightweight solar sails, manufactured on Earth and launched by SpaceX Starship Super Heavy. While no RF values are given, the authors use an approach to calculate ΔT, that is different from the one used in IPSS literature.

As the latter approach is used in this work as well, it is applied to the RSS concept, as can be seen in table 4.3. The proposal addresses various subsystems so that the stated M_{Sh} refers to the total system weight.

Table 4.1: Overview of RSS parameters [16].

Parameter	**Optimal Sunshade**	**Conservative Sunshade**	**Unit**
Relative Solar Radiation Reduction f	1.00[a]		$[-]$
Radiative Forcing RF	-		$[\frac{\mathrm{W}}{\mathrm{m}^2}]$
Change in Solar Radiation ΔS	-		$[\frac{\mathrm{W}}{\mathrm{m}^2}]$
Change in GMT ΔT	1.00[a]		[K]
Sail Efficiency Factor Q[b]	0.20	0.50	$[-]$
Average Areal Sunshade Density ρ_{Sh}	8.80	21.90	$[\frac{\mathrm{g}}{\mathrm{m}^2}]$
Distance Sunshade to Earth r_{Sh}	2.36×10^6		[km]
Sunshade Surface Area A_{Sh}	3.79×10^6		[km^2
Sunshade Mass M_{Sh}	33.40×10^6	83.50×10^6	[tonne]
Generated Power by Solar Cells P_G	-		[W]

[a] Authors chose $f = 1\%$ and assumed $\Delta S = 1$ K based on studies by other authors [16].
[b] Equal to Optical Surface Property Factor κ, which is used within IPSS literature [17].

4.2 International Planetary Sunshade

Table 4.2 provides a parameter overview of the IPSS. The concept envisages two

Table 4.2: Overview of IPSS parameters [17].

Parameter	**Aluminium Sunshade**	**Photovoltaic Sunshade**	**Unit**
Relative Solar Radiation Reduction f	0.52[a]		$[-]$
Radiative Forcing RF	1.23		$[\frac{\mathrm{W}}{\mathrm{m}^2}]$
Change in Solar Radiation ΔS	1.79		$[\frac{\mathrm{W}}{\mathrm{m}^2}]$
Change in GMT ΔT	1.00[a]		[K]
Optical Surface Property Factor κ[b]	0.84	0.82	$[-]$
Average Areal Sunshade Density ρ_{Sh}	43.20	334.00	$[\frac{\mathrm{g}}{\mathrm{m}^2}]$
Distance Sunshade to Earth r_{Sh}	2.20×10^6	1.56×10^6	[km]
Sunshade Surface Area A_{Sh}	1.71×10^6	0.86×10^6	[km^2
Sunshade Mass M_{Sh}	73.74×10^6	286.00×10^6	[tonne]
Generated Power by Solar Cells P_G	-	73.00×10^{12}	[W]

[a] Authors chose $\Delta S = 1$ K and derived $f = 0.52\%$ based on Earth's climate sensitivity [17, 112].
[b] Equal to Sail Efficiency Factor Q, which is used within RSS literature [16].

variants, while the aluminium sunshade is the lighter option and the photovoltaic sunshade the heavier one, as it includes a SBSP solution and therefore would not only reduce the GMT but also make power generation on Earth redundant, as today's power demand is about 17 TW [17]. Thus, it would have a tremendous effect on mitigation efforts.

As already discussed, the concept aims for ISRU and ISMA. It seeks to achieve goals such as reducing the high number of required rocket launches and therefore environmental impact, together with an increased feasibility, since it is questionable whether a project of this magnitude can be accomplished from Earth alone.

4.3 Concepts in Shared Socio-Economic Pathway Context

As mentioned in chapter 3, it is important to merge latest IPCC data with geo-engineering's abilities to allow for an an integrated assessment, which then enables informed decision making. Hence, RSS and IPSS are presented in a comparison with SSPs of AR6, which have been introduced in section 4.3.

ΔT is calculated using equation 4.3, while utilizing climate sensitivity provides good results until SSP 2-4.5, while derived values for SSP 3-7.0 and SSP 5-8.5 are around 1 K above their higher limits (see table 2.2). However, it translates into an appropriate tool to evaluate sunshade concepts among IPCC data. It is notable that the concepts would only be able to compensate RF of strong mitigation scenarios.

Table 4.3: The RSS and IPSS in a context with the likely scenario of doubling atmospheric CO_2 by 2100 and the five SSPs introduced in section 2.1.3 (same time scale).

Param.	**IPSS**	**SSP 1-1.9**	**RSS**	**SSP 1-2.6**	**2 × CO_2[a]**	**SSP 2-4.5**	**SSP 3-7.0**	**SSP 5-8.5**
f [−]	0.52	0.81	1.00	1.10	1.70	1.91	2.97	3.61
RF [$\frac{W}{m^2}$]	1.23	1.90	2.35	2.60	4.00	4.50	7.00	8.50
ΔS [$\frac{W}{m^2}$]	1.79	2.77	3.43	3.78	5.82	6.55	10.19	12.37
ΔT [K]	1.00	1.54	1.91[b]	2.11	3.25	3.66	5.69	6.91

[a] IPCC states $RF = 3.9 \pm 0.5$ [$\frac{W}{m^2}$] resulting from a doubling of atmospheric CO_2 compared to 1750 (pre-industrial) levels [6]. Caldeira et al. suggest $RF = 4.0$ [$\frac{W}{m^2}$] resulting in $f = 1.7\%$ [46].
[b] Adjusted based on Earth's climate sensitivity [112].

Chapter 5

Concept Evaluation

Firstly, this chapter will focus on GWP of rocket launches, part of ESA space system LCA EIIs, which has been determined as an important research gap in chapter 3. Secondly, a trade-off between both concepts will be presented in section 5.3, utilizing an ISRU bootstrapping factor B_{ISRU} to determine if and when, launch cycle emissions wise, ISRU- and ISMA-based concepts can been seen as a more economically friendly alternative.

5.1 Concept Alignment

As stated in chapter 4, both concepts differ in scale. To be able to compare the concepts, their parameter needs to be adjusted to an equal level, while an overview of the of adjusted parameters is presented in table 5.1.

To achieve alignment, the parameter f, RF, ΔS, ΔT of both concepts brought to the same level through scaling the IPSS, which was done in consultation with the author to ensure that the adjusted concept is consistent with the original idea.

It is notable that both IPSS variants are around four to seven times heavier than respective RSS sunshades. This is due to manufacturing difficulties and material availability and reveals a major drawback of ISRU that is likely to persist for the foreseeable future.

Since mass derived from space resources does not have to be launched from Earth, the drawback may be compensated by an appropriate B_{ISRU}, which determines how much mass can be delivered to SEL_1 per mass that is brought to LEO from Earth.

Table 5.1: Adjusted parameters of RSS [16] and IPSS [17] to the same relative solar radiation reduction $f = 1\%$ to enable comparison.

	RSS – Earth-Launch[a]		**IPSS – ISRU/ISMA**[b]		
Param.	**Optimal Sunshade**	**Conservative Sunshade**	**Aluminium Sunshade**	**Photovoltaic Sunshade**	**Unit**
f	1.00				$[-]$
RF	2.35				$[\frac{W}{m^2}]$
ΔS	3.43				$[\frac{W}{m^2}]$
ΔT	1.91				[K]
Q,κ	0.20	0.50	0.84	0.82	$[-]$
ρ_{Sh}	8.80	21.90	43.20	334.00	$[\frac{g}{m^2}]$
r_{Sh}	2.36×10^6		2.20×10^6	1.56×10^6	[km]
A_{Sh}	3.79×10^6		3.28×10^6	1.65×10^6	[km^2]
M_{Sh}	33.40×10^6	83.50×10^6	141.80×10^6	550.00×10^6	[tonne]
P_G	-			140.00×10^{12}	[W]

[a] To achieve $f = 1\%$, ΔT was adjusted to 1.9 K, and accordingly RF and ΔS derived, based on Earth's climate sensitivity [112]. Recent publication shows the author adjusted to higher ΔT levels, as well [113].
[b] To achieve $f = 1\%$, sunshade parameters were linearly adjusted in consultation with the author.

5.2 Addressing GWP: Starship Super Heavy Launch Cycle Emissions

In some cases, the GWP evaluation already revealed that the proposed method is ineffective as the emissions resulting from deployment are likely to succeed the benefits [47, 33]. Hence, addressing those concerns is critical for a system that aims to mitigate or compensate for anthropogenic climate change. In that context it is important to mention, that assessing emissions related to launching mass into space is not a full LCA, as i.e. fuel production or manufacturing efforts are not included [16].

Assessing launch related emissions is not only applicable to a potential deployment as the overall number of launches greatly increases and their impacts have to be well understood and characterized [114].

Both, the IPSS and RSS concepts suggest the use of SpaceX Starship Super Heavy launch vehicle, as it is expected to be the most capable launcher short- and midterm. According to the concepts literature, a payload of 100 tonnes to LEO is assumed in this work [16, 19].

The launch emission assessment is based on recently released US Federal Aviation Administration (FAA) Programmatic Environmental Assessment (PEA) reports [115, 116, 117, 118, 119].

In the following sections launch cycle (launch, re-entry, and landing) related emission sources will be determined, which will then be quantified in terms of CO_2-eq to be able to state launch cycle emission related to each payload tonne.

5.2.1 Starship Super Heavy Combustion Process Emissions

Within RSS literature, Starship Super Heavy emissions are estimated to result in 2475 tonnes CO_2-eq per launch. However, the findings based on the FAA reports in table 5.2.4 show they are at least 50% higher.

In that context, it is important to note that in addition to the combustion related emissions during launch and landing, each Raptor 2 engine must be tested in a static fire test, which is assumed here to be a conservative estimate with a duration of 15 s each. Based on the reports, 3,799.2 tonnes of CO_2-eq are released as a result of Raptor 2's combustion process per launch cycle.

Table 5.2: CO_2-eq of Starship Super Heavy's combustion process – derived from 2022–2023 FAA reports [115, 116, 117, 118, 119].

Emission Source	**Combustion Process CO_2-eq [tonne]** [a]
Starship Super Heavy Launch	3,330.0
Starship Landing	27.3
Super Heavy Landing	114.6
Starship Static Test Fires (15 s) [b]	57.3
Super Heavy Static Test Fires (15 s) [b]	270.0
Launch Cycle [c]	**3,799.2**

[a] Based on GWP_{100}.
[b] Conservative, specified range from 5 s to 15 s.
[c] Engine Testing, Launch, and Landing of one Starship Super Heavy.

5.2.2 Starship Super Heavy Methane Venting Emissions

There are three types of emission sources in respect to Starship Super Heavy CH_4 venting. (i) Pre-cooling of Raptor 2 engines to reduce the thermal load during start-up, as the mechanical load is already very high and non-cooling would lead to engine failure (see figure 5.1). (ii) Venting of tanks during and after refueling in preparation for start-up, as liquid methane boils rapidly if not cooled and must escape to prevent tank explosion. (iii) After landing, venting of header tanks (the reports state low double-digit tonnes per launch).

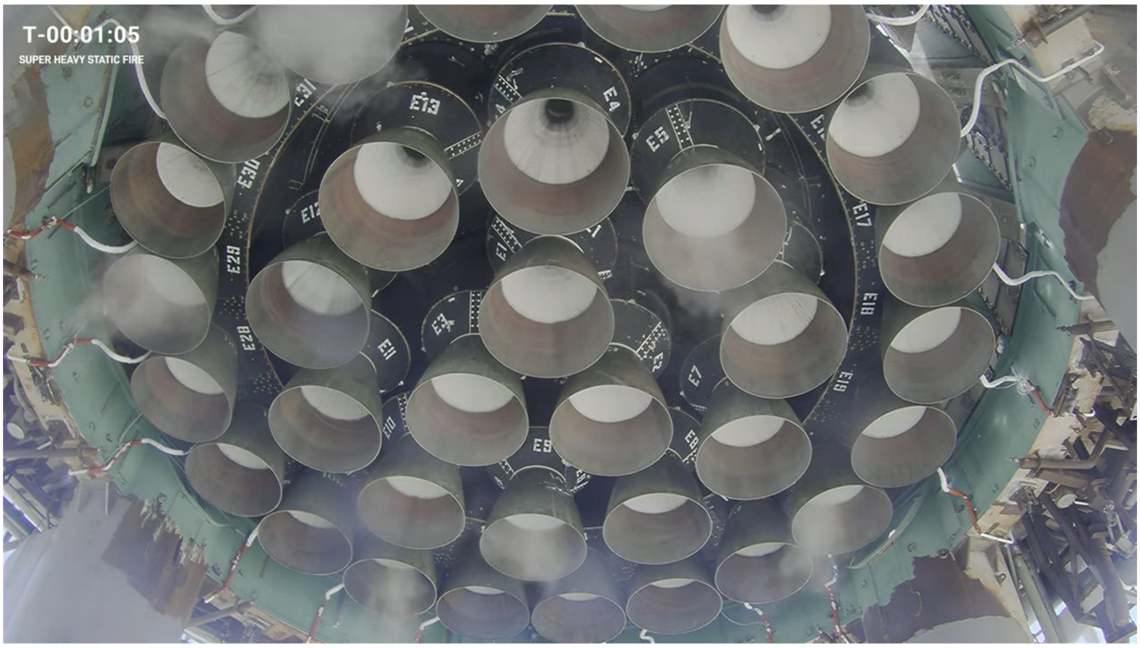

Figure 5.1: Pre-cooling Raptor 2 engines of the Super Heavy Booster in preparation of a static fire test [120].

For a selection of CH_4 venting related activities a sum of 23,000 tonnes CO_2-eq is given in the PEA [116]. Based on i.e. mentioned activities and involved Raptor 2 engines, results of table 5.3 have been derived.

The total of 4,135.1 tonnes CO_2-eq shows that methane venting is indeed a bigger emission source than combustion during launch. However, it is likely that (ii) will be solved by restoring CH_4 after landing, but as of today it is not considered due to safety reasons.

Table 5.3: CO_2-eq of CH_4 venting during Starship Super Heavy operations – derived from 2022–2023 FAA reports [115, 116, 117, 118, 119].

Emission Source	**CH_4 Venting CO_2-eq [tonne]**[a]
Starship Super Heavy Launch	3,901.7
Starship Landing	32.0
Super Heavy Landing	134.3
Starship Static Test Fires (15 s)[b]	67.1
Super Heavy Static Test Fires (15 s)[b]	316.4
Launch Cycle[c]	**4,135.1**

[a] FAA report data refers to CH_4 GWP_{100} of 28.0. However, given data was adjusted to latest IPCC findings, which assume a CH_4 GWP_{100} of 29.8 [30].
[b] Conservative, specified range from 5 s to 15 s.
[c] Engine Testing, Launch, and Landing of one Starship Super Heavy.

5.2.3 Starship NOx Re-Entry Emissions

In atmospheric science Nitrogen Oxides (NO_x) refers to Nitric Oxide (Nitrogen Oxide or Nitrogen Monoxide) (NO) and Nitrogen Dioxide (NO_2) as NO reacts with atmospheric ozone to NO_2. Hence, these gases must not be confused with major GHG Nitrous Oxide (N_2O).

Reusing rockets brings obvious economical advantages, but encourages discussions on environmental effects of spacecraft re-entry [121, 122, 123, 124]. Based on the Zeldovich mechanism [125], NASA studied thermal NO_x generation on Space Shuttle's re-entry [126, 127], while it is assumed that $17.5 \pm 5.3\%$ of the spacecraft's mass is released as thermal NO_x to the atmosphere. This, while NO_x is likely to be produced around the spacecraft's shock layer, due to the intense heat up of ambient air, not considering ablation effects [126, 127].

In a shunshade context, re-entry NO_x generation is mentioned in [18, 79] and no coverage was found among RSS and IPSS literature.

While the NO_x generation during re-entry likely depends on parameters such as spacecraft's flight trajectory, velocity, aerodynamic profile of the body, and it's mass, an estimated 20% NO_x re-entry mass fraction is assumed in this work, with reference to [128, 127].

Table 5.4: Estimated CO_2-eq of generated thermal NO_x during a single Starship re-entry.

Parameter	**Value**	**Unit**
Starship Dry Mass	120.0	[tonne]
Starship Payload	100.0	[tonne]
NO_x Re-Entry Mass Fraction	0.2	[%]
Generated NO_x per Re-Entry	24.0	[tonne]
NO_x GWP_{100}	114.0[a]	[CO_2-eq]
CO_2-eq per Re-Entry	**2,736.0**	**[tonne]**

[a] Best estimate derived from [129]. Study background: Tropospheric/low-stratospheric aviation emissions, low confidence-level.

The results presented in table 5.4 only covers Starship, as Super Heavy Booster is assumed to have a lower impact, indicating an interesting research gap. Additionally, weight loss during re-entry is neglected, as well as altitude and location of emission input, while the latter has an eminent influence on the GWP of NO_x, ranging from negative values (net cooling) to comparable high values such as 456 [30, 130, 131, 129, 132].

However, modeling requires intense resources, and is beyond this thesis' scope, which is, in respect to re-entry emissions, to show that there is a potential environmental hazard caused by hundreds of thousands or even millions of rocket re-entries, that has to be studied further.

5.2.4 Emissions per Launch Cycle

To summarize the results of sections 5.2.1, 5.2.2, and 5.2.3, table 5.5 provides cumulative emissions of one Starship Super Heavy launch cycle and respective CO_2-eq per payload tonne. It is notable that the results are significantly higher than stated in [16], even when excluding thermal NO_x generation during re-entry.

The determined CO_2-eq will be used in the next section to provide a rough estimate of total launch related emissions for the two concepts, ultimately leading to GMT increase projections.

Table 5.5: Summary of Starship Super Heavy CO_2-eq per launch cycle and launched payload tonne.

Emission Source	CO_2-eq per Payload Tonne [tonne]	CO_2-eq per Launch Cycle [tonne]
Combustion Process	38.0	3,799.2
CH_4 Venting	41.4	4,135.1
Re-Entry NO_x	27.4	2,736.0
Total	**106.7**	**10,670.3**

5.3 Concepts Trade-Off

As mentioned in 5.1, B_{ISRU} determines how much mass can be delivered to SEL_1 per mass that is brought to LEO from Earth. For this trade-off, a conservative and an optimal case has been derived from recent IPSS findings [67, 133], which are 4.1 and 0.7, respectively. The underlying model results are presented 10 in the appendix. Furthermore, the terrestrial M_{Sh} proportions are taken from [67, 68]. Here again, a conservative 55% and a high-ISRU case is used.

In case of the ISRU and ISMA concepts, additional mass for the space infrastructure M_{Infra} that needs to be launched from Earth, such as critical materials and manufacturing intense parts for lunar and SEL_1 manufacturing sites, lunar launch sites, space tugs, and fuel have to be added. These estimates have been derived from [133] and are presented in 5.6. After determining previous parameter, the total Earth-launch mass together with the total M_{Sh} and M_{Infra} portion of all involved was calculated for each variant.

The data shows that the optimal RSS still requires the least launches with 334,000, while only the aluminium sunshade in the optimal ISRU case is able to reach this level. Next higher number is required by conservative RSS with 835,000 Starship Super Heavy launches. Hence, left IPSS vartiants require 1,339,908 to 9,532,589 launches.

A baseline scenario is introduced, which suggests a 20 year deployment phase utilizing 20 launch cites in equatorial vicinity. To determine locations will be an important part of governance. This breaks the total launch numbers down to increase accessibility of the given data. The range from 2.3 to even 5.7 launches per day per launch site seems feasible, given united global efforts and a deployment start within 10 to 15 years. It is worth noting that on launch site may have several launch pads.

This leads to the total launch emissions per variant that integrates data from section 5.2, ranging from 3.6×10^9 to 101.7×10^9 tonnes CO_2-eq according to Starship Super Heavy Launch Cycles. Ultimately, given increase in GMT is presented in table 5.6.

The values have been determined based on relation between increase in global net CO_2 and RF, which is an estimated 1.7517×10^{-3} $\frac{\mathrm{W}}{\mathrm{m^2\,Gtonne}}$ [134]. The parameter was determined by IPPC, with the corresponding author explaining more into detail how the parameter is determined [135], while there are other approaches to determine this ratio [33, 136].

However, derived ΔT ranges from 0.0077 K for the optimal RSS sunshade to 0.2192 K for the photovoltaic IPSS concept in the conservative B_{ISRU} case. To sum up the trade-off, data has been normalized. This visualizes that generally, ISRU concepts hardly compete with an advanced Earth-manufactured sunshade, with only the aluminium sunshade in the optimal IPSS case reach it's level.

Table 5.6: Trade-off results of space-based geoengineering approaches (Earth-Launch (RSS) and ISRU/ISMA (IPSS) concept) in respect to climate impact of Starship Super Heavy launch cycle emissions utilizing two different B_{ISRU}.

Parameter	RSS - Earth-Launch		IPSS - ISRU/ISMA				Unit
	Optimal Sunshade	Conservative Sunshade	Aluminium Sunshade		Photovoltaic Sunshade		
M_{Sh}	33.4×10^6	83.5×10^6	141.8×10^6		550×10^6		[tonne]
Terrestrial M_{Sh} Portion	100	100	55	11	55	11	[%]
Terrestrial M_{Sh}	33.4×10^6	83.5×10^6	78.0×10^6	15.6×10^6	302.5×10^6	60.5×10^6	[tonne]
Additional Earth-Launch M_{Infra}	-		167.8×10^6	18.9×10^6	650.8×10^6	73.5×10^6	[tonne]
Total Earth-Launch Mass	33.4×10^6	83.5×10^6	245.8×10^6	34.5×10^6	953.3×10^6	134.0×10^6	[tonne]
Terrestrial M_{Sh} & M_{Infra} Portion	-		59	20	59	20	[%]
B_{ISRU}	-		0.7	4.1	0.7	4.1	[tonne]
Starship Super Heavy Launch Cycles – Baseline Scenario[a]							
Total	334,000	835,000	2,457,692	345,463	9,532,589	1,339,908	[–]
Daily Global Launch Cycles	46	114	337	47	1,306	184	[–]
Daily Launches per Launch Site	2.3	5.7	16.8	2.4	65.3	9.2	[–]
Starship Super Heavy Launch Cycle CO_2-eq – Baseline Scenario[a]							
Total	3.6×10^9	8.9×10^9	26.2×10^9	3.7×10^9	101.7×10^9	14.3×10^9	[tonne]
Yearly Global CO_2-eq	0.2×10^9	0.4×10^9	1.3×10^9	0.2×10^9	5.1×10^9	0.7×10^9	[tonne]
Resulting Global Mean RF and ΔT							
RF of total Launch Cycles	0.0062	0.0156	0.0459	0.0065	0.1782	0.0250	$[\frac{W}{m^2}]$
ΔT of total Launch Cycles	0.0077	0.0192	0.0565	0.0079	0.2192	0.0308	[K]
Normalized Trade-Off	**1.0**	**2.5**	**7.4**	**1.0**	**28.5**	**4.0**	[–]

[a] 20 years deployment phase, 20 launch sites in equatorial vicinity.

Chapter 6

Conclusion

As shown in chapter 5, the influence of high amounts of rocket launches is not negligible. The level of global yearly aviation emissions, which are estimated to be 800×10^6 tonnes CO_2-eq [137], would be reached, or even surpassed. However, as stated in section 5.4, emissions influence on climate highly depends on altitude and location of the input, which is not reflected in this work, while providing an interesting research gap.

The assessment leads to the conclusion, that a more detailed assessment is necessary, since it is neither a full sunshade manufacturing industry- or fuel production LCA nor the influence of several other sources that would potentially contribute to climate change, such as water vapour generation during launch or ablation during re-entry, is considered.

ISRU and ISMA do not provide an easy fix to the high amount of rocket launches, as the resulting structures are likely to be more heavy, which in turn requires a higher amount of supplementing materials launched from Earth. Resulting from that, heavier structures have to be brought to SEL_1 from the lunar surface, while the required fuel mass is estimated to reach the order of magnitude of M_{Sh} [133]. Hence, lunar fuel generation on a gigantic scale is critical to the success of an ISRU and ISMA based sunshade concept. To overcome this issue, the IPSS concept suggests the implementation of lunar magnetic coilguns [19, 64].

Hence, due to the added complexity of space logisitics and ISRU and ISMA at scale, while a reduction in the number of rocket launches and therefore potential impact on climate is not assured, an advanced Earth-manufactured concept such as the RSS seems more feasible and rational short- and midterm.

However, the presented evaluation does not account for the potential environmental benefits of the photovoltaic sunshade. A positive effect is also expected by the use of green CH_4. Additionally, only a full Earth based LCA of both Earth-manufactured and ISRU/ISMA based sunshades will allow a comprehensive assessment of which variant has the lowest net impact on climate, which they aim to preserve.

Chapter 7

Outlook

Chapter 6 leads to the question how the near-future sunshade development will look like. Recent publications reveal that both concepts are not only being further developed, but approaching a common ideal. While the RSS literature suggests a move towards using lunar resources, gradually over time, and adding SBSP to the sunshades capabilities [113], the IPSS concepts creators propose an evolutionary concept, transitioning from a fully Earth-build sunshade towards a high-ISRU bootstrapping factor concept, over time as well.

This approach allows for a rather soon deployment and aligns with a predicted general movement towards using space resources [65, 66, 67, 68]. Consequently, multiple iterations will be launched into space, evolving gradually over decades and incorporating the latest technological advancements.

SEL_1 appears far away, but it is located at only four times Earth-Moon distance, while several missions proved that SEL_1 and SEL_2, which are equidistant, can be utilized for space missions, such as *Deep Space Climate Observatory* (SEL_1) and *Gaia*, *Webb*, *Euclid* (SEL_2). Moreover, a mission to demonstrate sunshade technology *CoolEarth* is scheduled for this decade [138].

As the window of opportunity to begin large scale deployment closes, filling research gaps, which can be done by addressing proposed GEC, should be a top priority. At the same time, the UN should provide a forum for discussions on governance issues, as they proposed in [15].

Another promising project is *Destination Earth*. The 150 million Euro project, funded by European Union, aims to develop Earth's digital twin, while it is expected to provide first results by end of 2024 [139]. This is a major milestone, as it would allow to model desired and undesired effects of any geoengineering approach, allowing for careful risk-benefit analysis and informed decision making.

The challenge of deploying sunshades to address anthropogenic climate change as a supplementary measure alongside mitigation and adaptation efforts may appear monumental. However, considering the vast magnitude of the climate crisis, it becomes evident that solutions must match this scale. Therefore, we must maintain an open-minded approach to ensure the preservation of our beautiful planet and the continuation of all forms of life on it.

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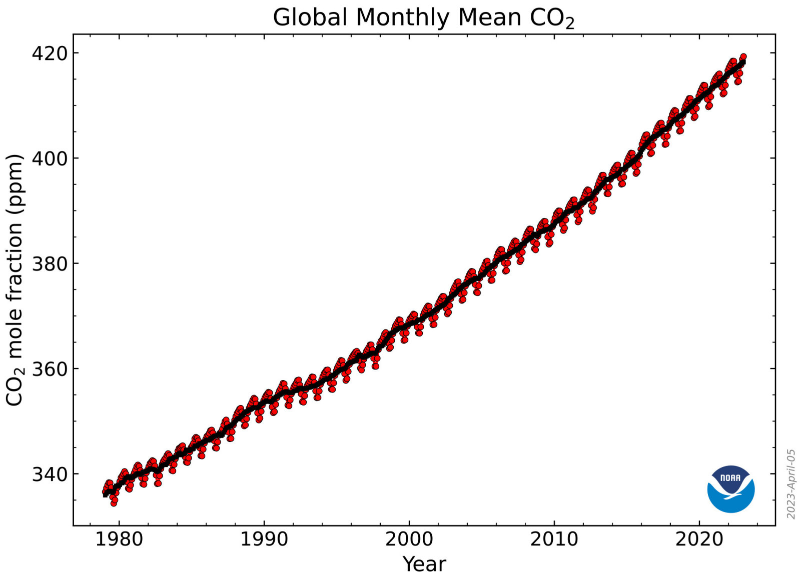
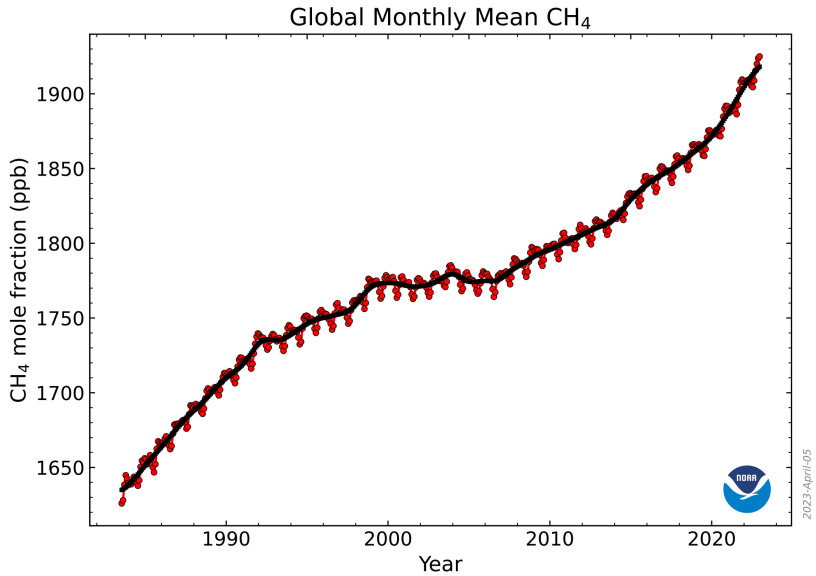
Appendix

A.

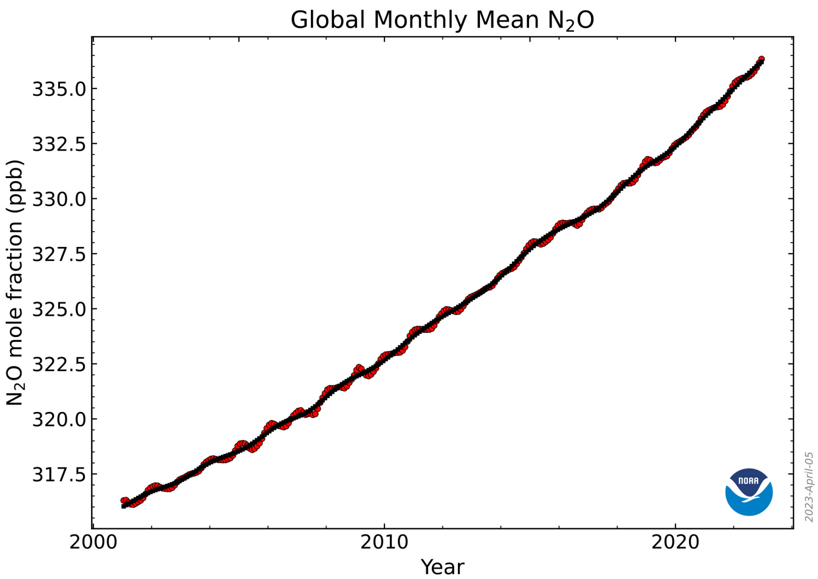


(a) Global monthly mean CO_2 trend.

Figure 1: Monthly mean abundance of the three greenhouse gases emitted by human activity until 2022 that are most significant contributors to climate change, globally averaged over marine surface sites, measured by NOAA [2]. (f.)



(b) Global monthly mean CH_4 trend.



(c) Global monthly mean N_2O trend.

Figure 1: Monthly mean abundance of the three greenhouse gases emitted by human activity until 2022 that are most significant contributors to climate change, globally averaged over marine surface sites, measured by NOAA [2]. (Cont.)

B.

Table 1: Summary of SSP narratives [35].

SSP	Title & Description
SSP1	Sustainability – Taking the Green Road (Low challenges to mitigation and adaptation): *The world shifts gradually, but pervasively, toward a more sustainable path, emphasizing more inclusive development that respects perceived environmental boundaries. Management of the global commons slowly improves, educational and health investments accelerate the demographic transition, and the emphasis on economic growth shifts toward a broader emphasis on human well-being. Driven by an increasing commitment to achieving development goals, inequality is reduced both across and within countries. Consumption is oriented toward low material growth and lower resource and energy intensity.*
SSP2	Middle of the Road (Medium challenges to mitigation and adaptation): *The world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns. Development and income growth proceeds unevenly, with some countries making relatively good progress while others fall short of expectations. Global and national institutions work toward but make slow progress in achieving sustainable development goals. Environmental systems experience degradation, although there are some improvements and overall the intensity of resource and energy use declines. Global population growth is moderate and levels off in the second half of the century. Income inequality persists or improves only slowly and challenges to reducing vulnerability to societal and environmental changes remain.*

Table 1: Summary of SSP narratives [35]. (Cont.)

SSP	**Title & Description**
SSP3	Regional Rivalry – A Rocky Road (High challenges to mitigation and adaptation): *A resurgent nationalism, concerns about competitiveness and security, and regional conflicts push countries to increasingly focus on domestic or, at most, regional issues. Policies shift over time to become increasingly oriented toward national and regional security issues. Countries focus on achieving energy and food security goals within their own regions at the expense of broader-based development. Investments in education and technological development decline. Economic development is slow, consumption is material-intensive, and inequalities persist or worsen over time. Population growth is low in industrialized and high in developing countries. A low international priority for addressing environmental concerns leads to strong environmental degradation in some regions.*
SSP4	Inequality – A Road Divided (Low challenges to mitigation, high challenges to adaptation): *Highly unequal investments in human capital, combined with increasing disparities in economic opportunity and political power, lead to increasing inequalities and stratification both across and within countries. Over time, a gap widens between an internationally-connected society that contributes to knowledge- and capital-intensive sectors of the global economy, and a fragmented collection of lower-income, poorly educated societies that work in a labor intensive, low-tech economy. Social cohesion degrades and conflict and unrest become increasingly common. Technology development is high in the high-tech economy and sectors. The globally connected energy sector diversifies, with investments in both carbon-intensive fuels like coal and unconventional oil, but also low-carbon energy sources. Environmental policies focus on local issues around middle and high income areas.*

Table 1: Summary of SSP narratives [35]. (Cont.)

SSP	**Title & Description**
SSP5	Fossil-fueled Development – Taking the Highway (High challenges to mitigation, low challenges to adaptation): *This world places increasing faith in competitive markets, innovation and participatory societies to produce rapid technological progress and development of human capital as the path to sustainable development. Global markets are increasingly integrated. There are also strong investments in health, education, and institutions to enhance human and social capital. At the same time, the push for economic and social development is coupled with the exploitation of abundant fossil fuel resources and the adoption of resource and energy intensive lifestyles around the world. All these factors lead to rapid growth of the global economy, while global population peaks and declines in the 21st century. Local environmental problems like air pollution are successfully managed. There is faith in the ability to effectively manage social and ecological systems, including by geo-engineering if necessary.*

C.

Effectiveness		
Criteria Value	**Description**	**Value**
1	Has a negligible impact on mitigating the effects of global warming.	<20% Reduction of the 2% solar radiation reduction/reduction in CO_2, compared to a doubling of CO_2 in the atmosphere, compared to pre-industrial values.
2	Can only provide a small contribution to mitigating the effects of global warming, due to fundamental limitations.	20<>40% Reduction of the 2% solar radiation reduction/reduction in CO_2, compared to a doubling of CO_2 in the atmosphere, compared to pre-industrial values.
3	Can provide a contribution to mitigating the effects of global warming, due to fundamental limitations.	40<>60% Reduction of the 2% solar radiation reduction/reduction in CO_2, compared to a doubling of CO_2 in the atmosphere, compared to pre-industrial values.
4	Can significantly reduce the thermal effects of global warming.	60<>80% Reduction of the 2% solar radiation reduction/reduction in CO_2, compared to a doubling of CO_2 in the atmosphere, compared to pre-industrial values.
5	Has the potential to mitigate all thermal aspects of global warming.	80<>100% Reduction of the 2% solar radiation reduction/reduction in CO_2, compared to a doubling of CO_2 in the atmosphere, compared to pre-industrial values.

Figure 2: OHB's detailed SRM study report effectiveness trade-off criterion definition (adjusted) [94].

Affordability		
Criteria Value	Description	Value
1	Highest lifecycle cost for a 2% reduction (or maximum application of the concept), and a lifecycle of 20 years.	>$10 trillion
2	High lifecycle cost for a 2% reduction (or maximum application of the concept), and a lifecycle of 20 years.	$1 trillion <> $10 trillion
3	Medium lifecycle cost for a 2% reduction (or maximum application of the concept), and a lifecycle of 20 years.	$0,1 trillion <> $1 trillion
4	Low lifecycle cost for a 2% reduction (or maximum application of the concept), and a lifecycle of 20 years.	$0,01 trillion <> $0,1 trillion
5	Lowest encountered lifecycle cost for a 2% reduction (or maximum application of the concept), and a lifecycle of 20 years.	< $0,01 trillion

Figure 3: OHB's detailed SRM study report affordability trade-off criterion definition [94].

Safety	
Criteria Value	**Description**
1	The concept is difficult to control, in the most realistic case, will result in at least one of the following impacts: • Global loss of life • Permanent disability to people due to injury on a global scale • Global loss of property/financial loss • Severe global environmental damage • Global/large scale destruction of ecological systems
2	There is a measure of controllability and in the most realistic case, will result in at least one of the following impacts: • Permanent partial disability on a country wide scale • Injury to people requiring hospitalization on a local scale • Local loss of property/financial loss • Local environmental damage • Local destruction of ecological systems
3	The concept is relatively easy to control, in the most realistic case, will result in at least one of the following impacts: • Injury to individuals • Property/financial loss to a community • Local moderate environmental damage • Local moderate ecological damage
4	Due to the high controllability of this concept, in the most realistic case, will result in at least one of the following impacts: • Loss of property/financial loss to individuals • Local minor environmental damage • Local minor ecological damage
5	In the most realistic case, will have no noticeable negative impact on Earth or space.

Figure 4: OHB's detailed SRM study report safety trade-off criterion definition, ranging from no noticeable impact to at least one severe impact. [94].

D.

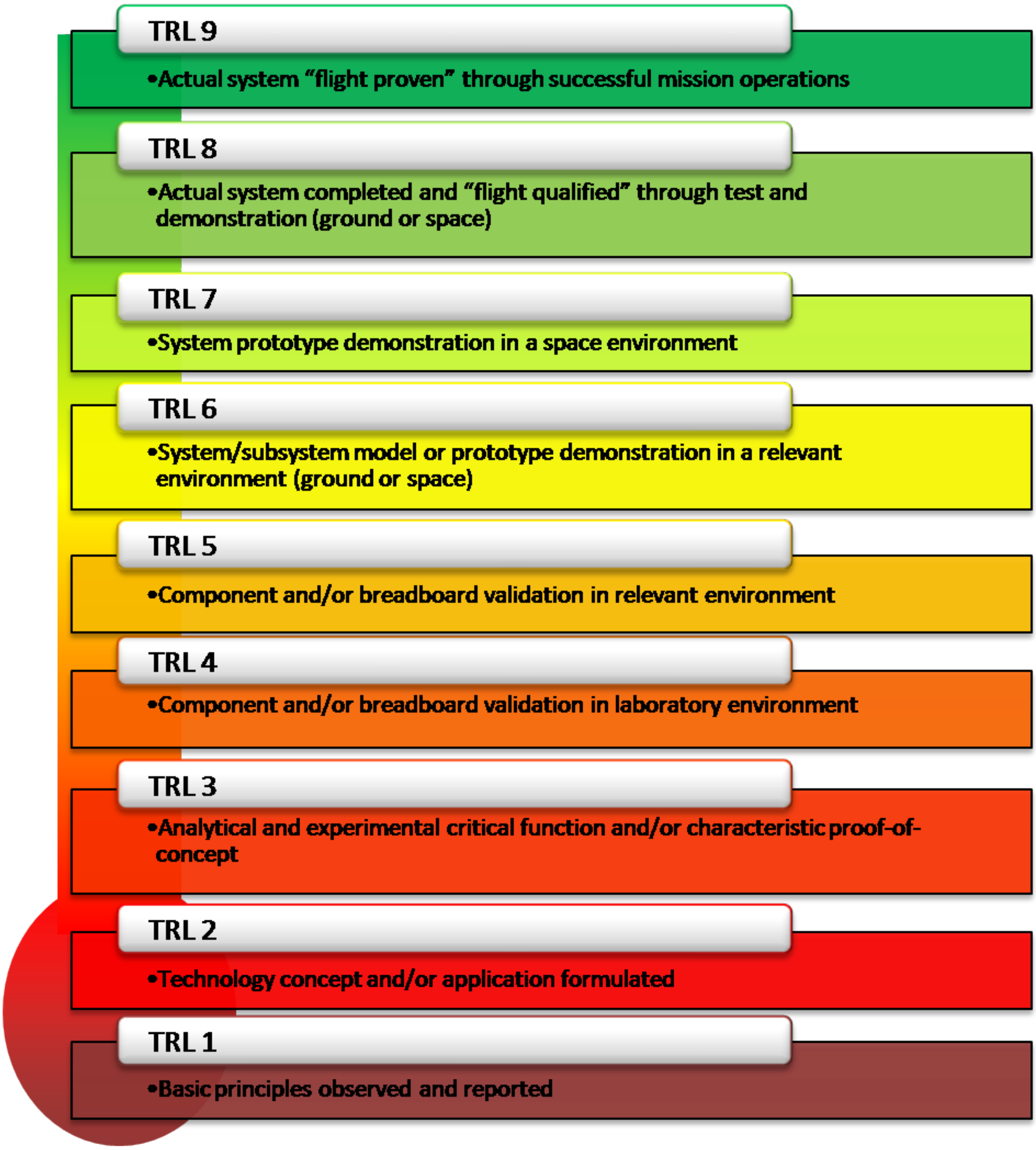


Figure 5: Definition of the nine TRL, introduced by NASA in 1974 [106].

AD2 Increasing Risk

Level		AD2	Risk
9	Chaos	Requires new development outside of any existing experience base. No viable approaches exist that can be pursued with any degree of confidence. Basic research in key areas needed before feasible approaches can be defined.	90+%
8	Unknown Unknowns	Requires new development where similarity to existing experience base can be defined only in the broadest sense. Multiple development routes must be pursued.	80%
7	Unknown Unknowns	Requires new development but similarity to existing experience is sufficient to warrant comparison in only a subset of critical areas. Multiple development routes must be pursued.	70%
6	Unknown Unknowns	Requires new development but similarity to existing experience is sufficient to warrant comparison on only a subset of critical areas. Dual development approaches should be pursued in order to achieve a moderate degree of confidence for success. (desired performance can be achieved in subsequent block upgrades with high degree of confidence.	50%
5	Known Unknowns	Requires new development but similarity to existing experience is sufficient to warrant comparison in all critical areas. Dual development approaches should be pursued to provide a high degree of confidence for success.	40%
4	Well Understood	Requires new development but similarity to existing experience is sufficient to warrant comparison across the board. A single development approach can be taken with a high degree of confidence for success.	30%
3	Well Understood	Requires new development well within the experience base. A single development approach is adequate.	20%
2	Well Understood	Exists but requires major modifications. A single development approach is adequate.	10%
1	Well Understood	Exists with no or only minor modifications being required. A single development approach is adequate.	0%

Figure 6: Definition of the nine AD^2, introduced by Bilbro in 2008 [107].

E.

Geoengineering Evaluation Criterion / *Publication*	1. Radiative Forcing Potential	2. Deployment Time	3. Lifetime of Effect	4. Efficacy	5. Side Effects	6. Controllability	7. Reversibility	8. Technology Readiness Level	9. IPCC Mitigation Scenarios and Data	10. Integrated Assessment	11. Sustainability	12. Ethics	13. Governance	14. Wording / Framing	15. Public Perception	16. Energy Justice	17. Social Acceptability	18. Social Justice
Space-Based (ISRU/ISMA)																		
Early, 1989	-	+	-	-	-	+	-	-	-	-	-	+	-	-	-	-	+	+
McInnes, 2002	-	-	-	-	+	+	-	-	-	-	+	-	-	-	-	-	-	-
Ellery, 2016	-	+	-	-	-	+	+	-	-	-	+	+	-	-	+	-	-	-
Fix, Maheswaran, 2021	+	+	+	-	+	+	+	++	++	+	+	+	+	-	-	+	-	-
Bromley et al., 2023	-	++	++	-	+	++	++	-	-	-	+	-	-	-	-	-	-	+
Space-Based (Earth-Launch)																		
Angel, 2006	-	+	-	-	+	+	+	-	-	-	-	-	-	-	-	-	-	-
Fuglesang, Herreros, 2021	-	++	+	+	++	++	+	++	+	-	+	-	+	-	-	-	-	+
Borgue, Hein, 2023	-	+	-	-	+	-	-	++	+	-	-	-	-	-	-	-	-	-
Space-Based (General)																		
Kennedy et al., 2013	+	-	-	-	++	+	+	+	+	-	+	+	-	-	+	+	+	+
Sánchez, McInnes, 2015	++	++	-	++	+	++	-	-	+	-	+	-	-	-	-	+	-	-
Baum et al., 2022	-	+	+	+	++	++	+	-	+	+	++	+	++	-	++	+	++	+
Terrestrial																		
Wigley, 2006	++	++	+	-	+	+	+	-	+	++	-	-	-	-	-	-	-	-
Harvey, 2008	-	++	+	-	++	++	-	-	-	-	-	-	-	-	-	-	-	-
MacMartin et al., 2016	+	+	-	+	+	+	-	-	-	+	+	+	+	-	+	-	+	-
Space-Based & Terrestrial																		
Keith, 2000	+	+	-	+	++	+	+	-	+	+	-	++	+	++	+	-	-	+
Lenton, Vaughan, 2009	++	-	-	+	+	++	-	-	+	-	-	-	-	-	-	-	-	-
Shepherd et al., 2009	++	++	+	+	++	++	++	+	++	+	+	++	++	-	++	-	++	++
Vaughan, Lenton, 2011	++	++	++	++	++	++	++	-	++	++	+	+	+	-	+	-	+	+
Corner et al., 2013	-	-	-	-	++	+	-	-	+	+	++	++	+	++	++	-	++	++
OHB System AG, 2020	+	+	-	-	++	+	+	-	-	-	++	++	+	-	-	-	-	+
Keith et al., 2021	++	++	+	++	++	++	-	-	-	++	-	+	-	-	-	-	-	-
UNEP, 2023	+	+	+	+	++	++	-	+	+	++	+	++	++	-	+	-	+	++
PSF, 2023	+	-	-	-	+	-	-	-	+	+	+	+	+	-	-	-	-	-

Figure 7: Evaluation criteria coverage of selected geoengineering literature from 1989–2023. Metric: ”++” – detailed coverage; ”+” – low to medium coverage; ”-” – no coverage.

UN Sustainability Goal / *Publication*	1. No Poverty	2. Zero Hunger	3. Good Health and Well-Being	4. Quality Education	5. Gender Equality	6. Clean Water and Sanitation	7. Affordable and Clean Energy	8. Decent Work and Economic Growth	9. Industry, Innovation and Infrastructure	10. Reduced Inequalities	11. Sustainable Cities and Communities	12. Responsible Consumption and Production	13. Climate Action	14. Life below Water	15. Life on Land	16. Peace, Justice and Strong Institutions	17. Partnerships for the Goals
Space-Based (ISRU/ISMA)																	
Early, 1989	-	-	-	-	-	-	-	-	+	-	-	-	+	-	+	-	-
McInnes, 2002	-	-	+	-	-	-	-	-	+	-	-	-	+	+	+	-	-
Ellery, 2016	-	-	-	-	-	-	+	+	++	-	-	+	++	-	-	-	-
Fix, Maheswaran, 2021	-	-	-	-	-	-	++	+	++	+	+	+	++	-	+	-	++
Bromley et al., 2023	-	-	-	-	-	-	-	-	+	+	-	-	+	-	+	-	-
Space-Based (Earth-Launch)																	
Angel, 2006	-	-	-	-	-	-	-	-	+	-	-	-	+	-	-	-	-
Fuglesang, Herreros, 2021	-	-	+	-	-	-	-	+	++	+	+	+	++	-	+	-	+
Borgue, Hein, 2023	-	-	+	-	-	-	-	+	++	-	-	-	++	-	+	-	+
Space-Based (General)																	
Kennedy et al., 2013	-	-	+	-	-	-	++	+	+	+	+	+	++	+	+	+	+
Sánchez, McInnes, 2015	-	-	-	-	-	-	+	+	+	++	+	-	++	+	++	-	-
Baum et al., 2022	-	+	-	-	-	-	+	+	++	+	+	+	++	+	+	+	++
Terrestrial																	
Wigley, 2006	-	-	-	-	-	+	-	+	+	-	-	-	++	+	+	-	-
Harvey, 2008	-	-	-	-	-	+	-	-	+	-	-	-	++	++	+	-	-
MacMartin et al., 2016	-	-	+	-	-	-	-	-	+	+	-	-	++	-	+	+	+
Space-Based & Terrestrial																	
Keith, 2000	-	-	+	-	-	-	+	-	+	-	-	-	++	++	++	+	-
Lenton, Vaughan, 2009	-	-	+	-	-	+	-	-	-	-	-	-	+	+	+	-	-
Shepherd et al., 2009	-	-	+	-	-	+	-	++	++	+	-	-	++	++	+	+	+
Vaughan, Lenton, 2011	-	-	+	-	-	+	+	+	+	+	+	-	++	++	++	+	+
Corner et al., 2013	-	+	+	-	+	-	-	+	-	+	++	++	++	-	-	+	-
OHB System AG, 2020	+	-	+	-	-	-	-	-	+	+	-	-	++	-	+	+	+
Keith et al., 2021	-	-	+	-	-	-	-	+	+	+	-	-	++	-	+	-	+
UNEP, 2023	-	-	+	-	-	-	-	-	+	++	++	-	++	+	+	++	++
PSF, 2023	-	-	-	-	-	-	-	+	++	-	-	+	++	-	-	-	++

Figure 8: SDG coverage of selected geoengineering literature from 1989–2023. Metric: "++" – detailed coverage; "+" – low to medium coverage; "-" – no coverage.

ESA Space System LCA Environmental Impact Indicator / Publication	1. Global Warming Potential	2. Ozone Depletion Potential	3. Human Toxicity Potential	4. Fossil Resource Depletion Potential	5. Photochemical Ozone Formation Potential	6. Freshwater Eutrophication Potential	7. Marine Eutrophication Potential	8. Ionizing Radiation Potential	9. Freshwater Ecotoxicity Potential	10. Marine aquatic Ecotoxicity Potential	11. Air Acidification Potential	12. Primary Energy Consumption Potential	13. Gross Water Consumption Potential	14. Mass disposed in the Ocean	15. Al2O3 Emissions in the Air	16. Mass left in Space
Space-Based (ISRU/ISMA)																
Early, 1989	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+
McInnes, 2002	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+
Ellery, 2016	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-
Fix, Maheswaran, 2021	-	+	-	+	-	-	-	-	-	-	-	+	-	-	-	+
Bromley et al., 2023	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-
Space-Based (Earth-Launch)																
Angel, 2006	+	-	+	+	-	-	-	-	-	-	-	++	-	-	-	+
Fuglesang, Herreros, 2021	++	-	+	+	-	-	-	-	-	-	+	-	-	-	-	++
Borgue, Hein, 2023	+	+	+	-	-	-	-	-	-	-	+	-	-	-	-	+
Space-Based (General)																
Kennedy et al., 2013	-	-	+	-	-	-	-	-	-	+	+	-	-	-	-	++
Sánchez, McInnes, 2015	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+
Baum et al., 2022	-	+	+	-	-	-	+	-	-	+	+	-	-	-	-	-
Terrestrial																
Wigley, 2006	-	+	-	+	-	-	-	-	-	+	+	-	-	-	-	-
Harvey, 2008	++	+	-	++	-	+	++	-	+	++	-	++	+	++	-	-
MacMartin et al., 2016	-	+	+	-	-	-	-	-	-	-	+	-	-	-	-	-
Space-Based & Terrestrial																
Keith, 2000	-	+	++	+	-	-	++	-	-	++	+	-	-	+	-	+
Lenton, Vaughan, 2009	-	-	-	-	-	-	+	-	-	-	-	-	-	+	-	-
Shepherd et al., 2009	-	++	+	+	-	+	++	-	-	++	+	++	-	+	-	-
Vaughan, Lenton, 2011	-	+	+	+	-	-	++	-	-	++	+	+	-	++	-	-
Corner et al., 2013	-	-	+	-	-	-	-	+	-	-	-	-	-	-	-	-
OHB System AG, 2020	+	-	++	-	-	-	-	-	-	-	+	-	-	-	+	-
Keith et al., 2021	+	+	-	-	-	-	-	-	-	-	+	-	-	-	-	-
UNEP, 2023	-	++	+	-	-	-	-	-	-	+	+	-	-	-	-	-
PSF, 2023	-	+	+	-	-	-	-	-	-	+	+	-	-	-	-	-

Figure 9: ESA LCA Environmental Impact Indicator coverage of selected geoengineering literature from 1989–2023. Metric: "++" – detailed coverage; "+" – low to medium coverage; "-" – no coverage.

F.

	Total Concept Efficiency
Concept 1 | No Lunar Utilization | Direct Flight To SEL1 | Chemical	0.224853778
Concept 1 | No Lunar Utilization | Direct Flight To SEL1 | Electric	0.55173163
Concept 2 | No Lunar Utilization | Stop At EML | Chemical	0.233218555
Concept 2 | No Lunar Utilization | Stop At EML | Electric	0.548281972
Concept 3 | Minor Lunar Utilization | Terrestrial Fuel Origin | Chemical	0.281804474
Concept 3 | Minor Lunar Utilization | Terrestrial Fuel Origin | Electric	0.655453254
Concept 4 | Minor Lunar Utilization | Hyrbid Fuel Origin | Chemical	0.408636999
Concept 4 | Minor Lunar Utilization | Hyrbid Fuel Origin | Electric	0.981126718
Concept 5 | Minor Lunar Utilization | Lunar Fuel Origin | Chemical	1.808015991
Concept 5 | Minor Lunar Utilization | Lunar Fuel Origin | Electric	1.533415447
Concept 6 | Major Lunar Utilization | Terrestrial Fuel Origin | Chemical	0.374566504
Concept 6 | Major Lunar Utilization | Terrestrial Fuel Origin | Electric	0.803072722
Concept 7 | Major Lunar Utilization | Hybrid Fuel Origin | Chemical	2.034876495
Concept 7 | Major Lunar Utilization | Hybrid Fuel Origin | Electric	4.104758663
Concept 8 | Major Lunar Utilization | Lunar Fuel Origin | Chemical	8.879591621
Concept 8 | Major Lunar Utilization | Lunar Fuel Origin | Electric	5.875085452

Figure 10: Total concept efficiency of space logistic concepts for the 2023 IPSS. The ratio determines how much mass can be delivered to SEL_1 per mass that is brought to LEO. The figure shows adjusted model data derived from [67, 133].

	IPSS - ISRU/ISMA				
	Aluminium Sunshade		Photovoltaic Sunshade		
ISRU Logistics Case [-]	Conservative	Optimal	Conservative	Optimal	
RSS - Earth-Launch - Optimal Sunshade					
Proportion of Terrestrial Material to Outperform Earth-Manufacturing [%] - Sunshade	7	11	2	3	Lower than these values to succeed.
Proportion of terrestrial material to outperform Earth-manufacturing [%] - Sunshade and Logistics	8	19	2	5	
Target ISRU-Bootstrapping-Factor [tonne]	11.5	4.3	47.4	19.5	Higher than these values to succeed.
RSS - Earth-Launch - Conservative Sunshade					
Proportion of terrestrial material to outperform Earth-manufacturing [%] - Sunshade	19	27	5	7	Lower than these values to succeed.
Proportion of terrestrial material to outperform Earth-manufacturing [%] - Sunshade and Logistics	20	47	5	12	
Target ISRU-Bootstrapping-Factor [tonne]	4.0	1.1	18.3	7.2	Higher than these values to succeed.

Figure 11: The table shows required B_{ISRU} of IPSS to outperform the RSS concept in terms of launch cycle emissions. Green indicates that required B_{ISRU} lies within the assumed feasibility range of 0.7 to 4.1, orange indicates a close miss and red indicates impracticability.