

## The International Planetary Sunshade System - An Umbrella Project Combining Sustainable Energy Supply with Mitigation of Global Warming

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### Abstract

Climate change is the greatest threat of the 21<sup>st</sup> century, and despite all our efforts with renewable energy, current reports clearly indicate that our existing actions are not sufficient to prevent critical tipping points from being reached. In addition to various terrestrial geoengineering methods, there are currently efforts to investigate new ways of integrating space-based geoengineering into the short-term construction of a buffer solution - the International Planetary Sunshade (IPSS) system. The IPSS system offers new opportunities to link the challenges of a sustainable energy supply with the essential actions against climate change, whereby this poses new logistical and technological challenges that can only be mastered through the collaboration of space agencies, private companies, and the support of the society. Therefore, the integration into international roadmaps is essential to exploit synergies, shorten development timeframes and promote international cooperation against climate change. To achieve this goal, an evolutionary concept using lunar resources has been designed to achieve stepwise Earth independence and sustainable utilization of essential space resources.

Currently, there is a clear drive towards lunar exploration with many technologies in development aiming for self-sustainable lunar operations. In this context, the challenges of sustainable energy supply for lunar bases can be linked by integrating the planned technology developments in the context of space-based solar power, whereby this can significantly reduce the cost of constructing a sunshade constellation and the deployment time.

Based on a sunshade design study for an evolutionary sunshade concept, starting from a purely terrestrial sunshade design and the corresponding technologies, enabling a stepwise approach to a sustainable sunshade design based on lunar resources incorporating current international technology trends, a deployment plan for the implementation of the sunshade constellation within the century was developed. The parameterized modular sunshade concept is intended to enable time- and cost-variable adaptation of technologies to enable continuous optimization of the sunshade design by incorporating current knowledge and also to enable evaluation of opportunities for advanced applications, such as a solar power satellite for terrestrial and lunar applications. Based on the evolutionary design, a roadmap has been created for an initial demo mission with the essential technologies, enabling modular embedding of technology demonstrators based on scalable sunshade architectures. The primary goal of this demo mission is to demonstrate the shading effect of a sunshade constellation, the sustainable power supply via solar power satellites combined with wireless power transmission, and the scalability of the system architecture. The designed demo mission shall provide the foundation for a mega constellation setup that can enable cooperative exploration of further planets and beyond by exploiting the synergy potentials.

**Keywords:** climate change, space-based climate mitigation, space-based solar power, in-space manufacturing

### Acronyms/Abbreviations

ACS	Attitude Control System
ACS3	Advanced Composite Solar Sail System
CASSIOPeiA	Constant Aperture, Solid-State, Integrated, Orbital Phased Array
CCS	Carbon Capture and Storage
CDR	Carbon Dioxide Removal
ESTRACK	European Space Tracking network
IPCC	Intergovernmental Panel on Climate Change
IPSS	International Planetary Sunshade
ISMA	In-Space Manufacturing and Assembly
MBSE	Model-Based System Engineering
RCD	Reflective Control Device
SBSP	Space-based Solar Power

SEL1	Sun-Earth Lagrange Point 1
SPS	Solar Power Satellite
SRM	Solar Radiation Management
TRAC	Triangular Rollable and Collapsible
PARESC	PARAmetrized Evolutionary Sunshade Concept (for IPSS)

## 1. Introduction

### 1.1 Climate Change

Energy drives policies. The severe dependence on fossil fuels, such as oil and natural gas, has been revealed by the current global energy crisis caused by national and international events such as the ongoing global pandemic, severe droughts, and war. Consequently, gas has even been labeled as a green technology in the European Union to manage energy shock [1]. Additionally, despite the Paris Agreement's efforts to prevent irreversible climatic tipping points by limiting global warming to 2 K above pre-industrial levels [2], recent reports indicate that this goal will already be unachievable [3].

Recent climate trend estimates based on the evolution of greenhouse gas concentrations reveal that if existing technology and climate protection trends are discontinued, an increase in the global mean surface temperature of the Earth's atmosphere of more than 4 K is probable [4]. Although the temperature has only increased by around 1 K so far [5], the increasing warming of Earth's atmosphere has already profoundly affected extreme weather events, which have increased substantially in the past [6]. Based on these facts, many models predict an increase in droughts of up to 130 % with significantly higher intensities [7], with inaction costing the global economy US\$178 trillion by 2070 [8]. As we are aware that the time is running out, we must increase global efforts to mitigate climate change and accelerate the transition to net-zero energy to prevent irreversible climate tipping points.

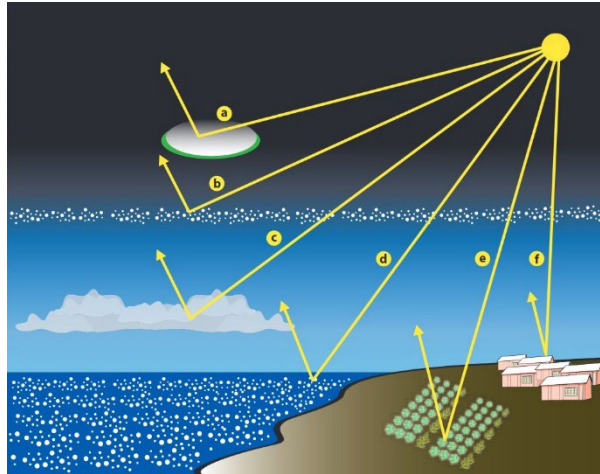
The already evident climatic consequences are progressively driving a societal reflection, albeit not only the transition to renewable energies but also an active decrease of carbon concentrations in the atmosphere will be required to restore the pre-industrial climate. The already evident climatic consequences are progressively driving a societal reflection, albeit not only the transition to renewable energies but also an active decrease of carbon concentrations in the atmosphere will be required to restore the pre-industrial climate. Therefore carbon dioxide removal (CDR) methods must be implemented in addition to the transition toward a zero-emission economy to achieve negative net global emissions. Reforestation, biomass energy production with CO<sub>2</sub> sequestration, land- and ocean-based weathering, ocean fertilization, and direct air capture [9] are only a few examples of potential CDR activities. Especially, carbon capture and storage (CCS) technologies are currently being discussed for near-term implementation in Europe as a result of the climate goals defined [10; 11]. However, the CDR actions required to achieve a substantial effect compared to the continuous emissions over time necessitate a large amount of land use, which directly opposes the existing intense land use [12]. Consequently, in addition to CDR, Solar Radiation Management (SRM) strategies are being researched. In combination, these two approaches may reduce and limit the impacts of climate change and buy time to evolve toward a net-zero civilization.

### 1.2 Solar Radiation Management in Space

Climate change drives Earth's energy balance. SRM is a geoengineering discipline that aims to modify the Earth's radiation balance by redirecting incoming solar radiation [13]. The purpose of changing the energy balance of the atmosphere is to reduce the surface temperature on Earth to create a time buffer for CDR actions as well as the energy transition. Examples of SRM concepts (Figure 1) are enhancing surface albedo [14–18], brightening marine clouds [19; 20], and—perhaps most famously—injecting aerosols into the stratosphere [20; 21]. Space-based approaches have gained more attention in recent years, as advances in space exploration and space-based solar power (SBSP) [22–24] present prospects to realize efficient and sustainable space-based SRM concepts, as will be described in further detail in this work.

The key benefit of space-based solar radiation management is the avoidance of modifying the atmosphere or land or sea surfaces. As a result, the only interference with the sensitive ecosystem is the decrease of incoming radiation [25]. Such radiation reduction requires a planetary sunshade, which covers the entire Earth like an umbrella. The sunshade allows relatively simple modeling and high predictability and controllability of the impacts on the Earth's climate by modifying only a single parameter, the solar constant. The potential and requirements for such a sunshade must be thoroughly investigated to evaluate its integration into climate mitigation strategies. The optimal orbital position for a sunshade is at Sun-Earth Lagrange Point 1 (SEL1) [26]. Positioning the sunshade at this semi-stationary location offers a favorable balance between system mass, shading area, and fuel-efficient operation. As Earth is in the antumbra of the sunshade, the shading impact on Earth is favorably nearly uniform, and further improvements of the shading pattern are achievable by individually controlled sunshades [27]. Numerous studies [27–29] have addressed

space-based geoengineering at SEL1 from a technological and climatic perspective, where the dimensions of sunshades based on various manufacturing and launch approaches are considered.



**Figure 1: Concepts for SRM [9].**

Current studies are focusing on an overall system analysis of the sunshade constellation using space resources for manufacturing to reduce the impact on the Earth's atmosphere from a large number of rocket launches [30; 31]. By aligning the required development activities with current trends, the proposed concept enables reducing the techno-economic effort of a sunshade system, turning it into a potential catalyst for multiple breakthrough space operations in the framework of a visionary umbrella project – The International Planetary Sunshade (IPSS).

### 1.3 Space-based Solar Power

Sunshades enable the drive towards sustainable energy. Sunshades not only enable the limitation of global warming but also offer a promising opportunity for a sustainable, promising space-based energy supply. Carbon-based energy sources are limited, and the impact of atmospheric pollution requires complementary strategies. Space-based solar power (SBSP) satellites offer a supportive technology to terrestrial solar power parks to meet the global energy demand. SBSP satellites combine the collection of solar energy by promising space-qualified solar cells, the conversion of solar energy to microwaves or by lasers, and wireless power transmission technologies to deliver electromagnetic energy to rectifying antennas at potential destinations. SBSP satellites have been investigated in numerous studies [22–24] due to their high potential to provide gigawatt levels of renewable energy to any location 24 hours a day.

The first concept of a solar power satellites (SPS) existed already in 1978. The SPS, presented by National Aeronautics and Space Administration (NASA) should be operated in a geosynchronous orbit at an altitude of 35,000 km with an inclination of 0°. This system was supposed to be able to produce 5 GW of energy and transmit it at a frequency of 5.41 GHz to a receiving infrastructure on Earth [32]. A further development of this concept is SPS-Alpha, which was presented in 2011 and should be more feasible compared to the original SPS concept [33]. Just five years later, the Constant Aperture, Solid-State, Integrated, Orbital Phased Array (CASSIOPeiA) concept was presented. The structure as well as the arrangement of the gallium arsenide solar cells of CASSIOPeiA was designed to avoid any cosine losses during energy generation [34]. Accordingly, the solar cells always face directly towards the sun and therefore improves the system efficiency compared to SPS-Alpha. Just like SPS [32] and SPS-Alpha [33], CASSIOPeiA is supposed to operate in a geosynchronous orbit [34; 35]. Transmitter antennas are needed to enable power transmission to Earth. In 2015, the Japan Aerospace Exploration Agency (JAXA) conducted a terrestrial experiment for power transmission that could receive 340 W of energy over 55 m. The transmitting power was 1.8 kW, which indicates a transmission efficiency of 18 %. JAXA's system has an area-specific mass of 31.25 kg/m<sup>2</sup>. Recent research at the California Institute of Technology (Caltech) has shown that the area-specific mass of a transmitting system could be reduced to 1.5 kg/m<sup>2</sup> [36]. A demonstration mission of these power transmission units, launched earlier this year, could provide important insights for the use of wireless power transmission applications in space.

The studies show that SBSP satellites will provide an opportunity to meet international climate goals in the coming decades due to energy uncertainty as well as climate challenges, as well as provide global competition for sustainable energy for production and transportation infrastructures as well as space capabilities [37]. SBSP offers numerous

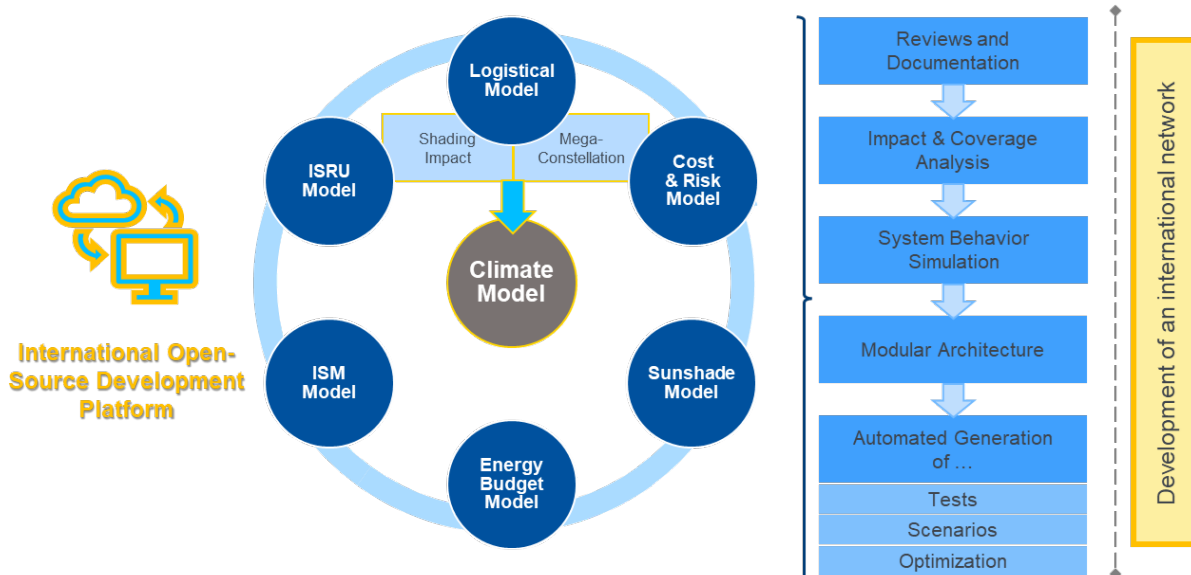
advantages for a wide range of applications. The growing population with an increase to 9.9 billion by 2050 [38] will have an increasing demand on energy production and distribution infrastructure. As a result, energy demands for all societal infrastructures will increase, with global energy demand already projected to rise from 25 trillion kilowatt-hours in 2020 to 45 trillion kilowatt-hours in 2050 [39]. Thus, SBSP could provide an essential complement to future global supply. Additionally, SBSP could provide an option for sustainable energy supply to larger industrial parks. Industrial applications can be directly supplied with renewable energy by placing rectifying antennas directly in industrial parks, replacing fossil fuel energy supply systems. Furthermore, future transportation applications could benefit from a direct space-based energy supply. Besides electric personal vehicles commercial shipping vehicles and vessels but also transportation vehicles like buses, trains as well as planes [40] are in focus, which could be supplied especially in remote areas without centralized energy distribution systems. Therefore, the deployment of a reliable, sustainable and affordable energy infrastructure is a fundamental building block for the global society.

#### 1.4 Motivation

Based on the roadmap developed in [30], the overarching objective is to establish a modular collaborative modeling platform for a digital IPSS model to assess by international cooperation the technological, logistical, and climatic framework conditions and to derive potential sunshade concepts (Chapter 2). For this purpose, an evolutionary parametric sunshade model has been developed [31]. In this paper, the initially derived concepts for technology demonstrators are presented to enable stepwise integration and testing of promising technologies based on a modular, scalable structure. A special focus has been placed on integrating SBSP technologies to include the dual use-case as solar power satellites. In this context, initial key figures for SBSP of the derived Sunshade demonstrators are presented in comparison to international SPS programs to identify the potential of the concepts.

## 2. IPSS Digital Model

The current research is concentrated on the analysis of possibilities to implement logistically and technologically modeled sunshade constellations to evaluate the impacts on the local and global Earth climate. Therefore, a digital model of the sunshade constellation is being developed in a model-based system engineering (MBSE) approach, which will be linked to climate forecast models (Figure 2). It is essential to consider the technological needs for sunshade manufacturing, resource extraction, and material logistics integrating sustainable launch systems. Furthermore, the system analysis will concentrate on parameter-based modeling of various sunshade designs to capture more advanced sunshade designs, such as a photovoltaic sunshade for use as a space-based power supply for terrestrial and lunar applications.



**Figure 2: IPSS International Open-Source Development Platform.**

The current approach includes an intensive exchange with international partners and an integration of current space-based solar power technologies [22–24] to conceptualize the IPSS system as a viable space-based energy source. Potential synergies with the development of solar power satellites for terrestrial applications, as well as critical

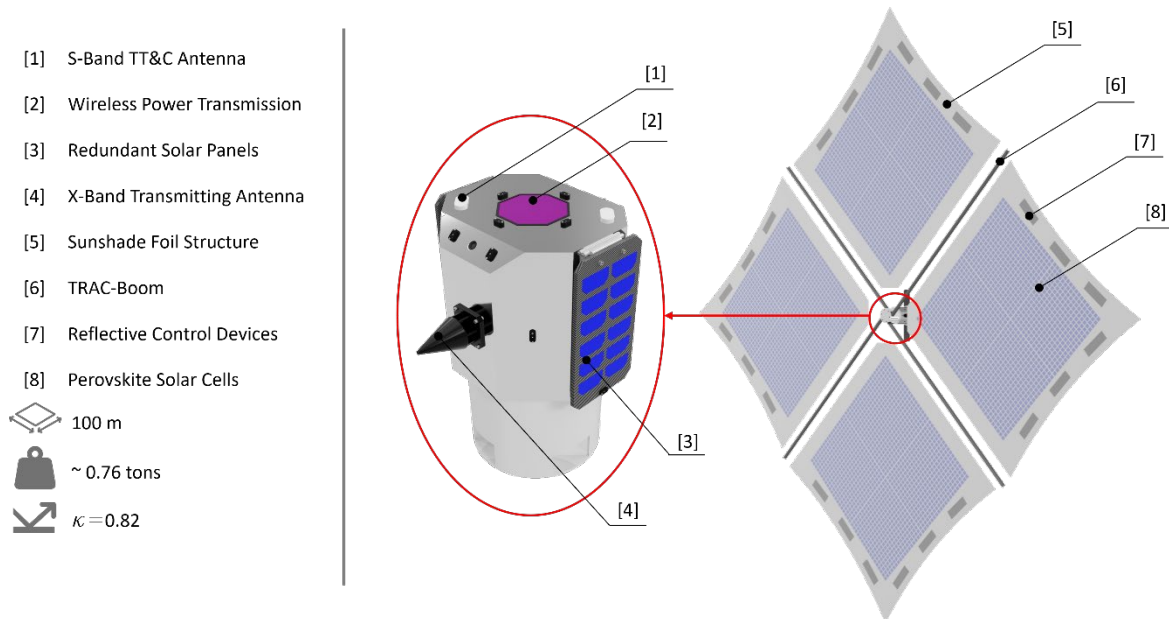
technology testing, will be incorporated. On the one hand, this approach enables the investigation of the features of robotic manufacturing of large structures utilizing moon reference material to aim at sustainable ideas for solar power satellites using space resources and, on the other hand, to research critical in-space manufacturing factors as well as material needs in initial testbeds in Earth orbit to derive the capacity of producing the sunshade constellation. The entire model should be adaptable and expandable to allow uncomplicated integration of future research and technology breakthroughs in the optimization process.

The main objective of the overall system analysis is to establish a flexible, digital model which will provide the framework for extensive parameter studies and serve as the central knowledge hub for integrating recent data gained from technological advancements and detailed subsystem analyses. A successful implementation as an open-source development platform allows for incorporation with future projects such as Destination Earth [41] or Digital Twin Earth [42] to complete the assessment of the total impact on Earth. In addition, the modeling platform design should meet European platform standards [43] to enable continuous advancement through affiliation with larger project projects (such as Horizon Europe, Cooperants [44]). In addition, the platform is intended to enable more detailed studies in collaboration with climate scientists to provide reliable study results for the upcoming Intergovernmental Panel on Climate Change (IPCC) assessment report which should establish the baseline to present space-based sunshades as a complementary option to Earth-based SRM methods on a broader scientific and policy level. In line with the technology roadmaps of international space agencies, the digital model is intended to offer early indications and a scientific baseline to enable step-by-step and short-term decisions on developments for the suitable in-space manufacturing infrastructure and, ultimately, on the final implementation of the sunshade system.

### 3. Modular System Architecture

In order to explore essential key technologies and logistical challenges for an IPSS concept, a PARAMetrized Evolutionary Sunshade Concept (PARESC) was developed. Based on an evolutionary approach and a modular system architecture [45], initial technology demonstrators were designed to enable the embedding of promising technologies such as SPS technologies to include the dual use-case in the demonstration missions.

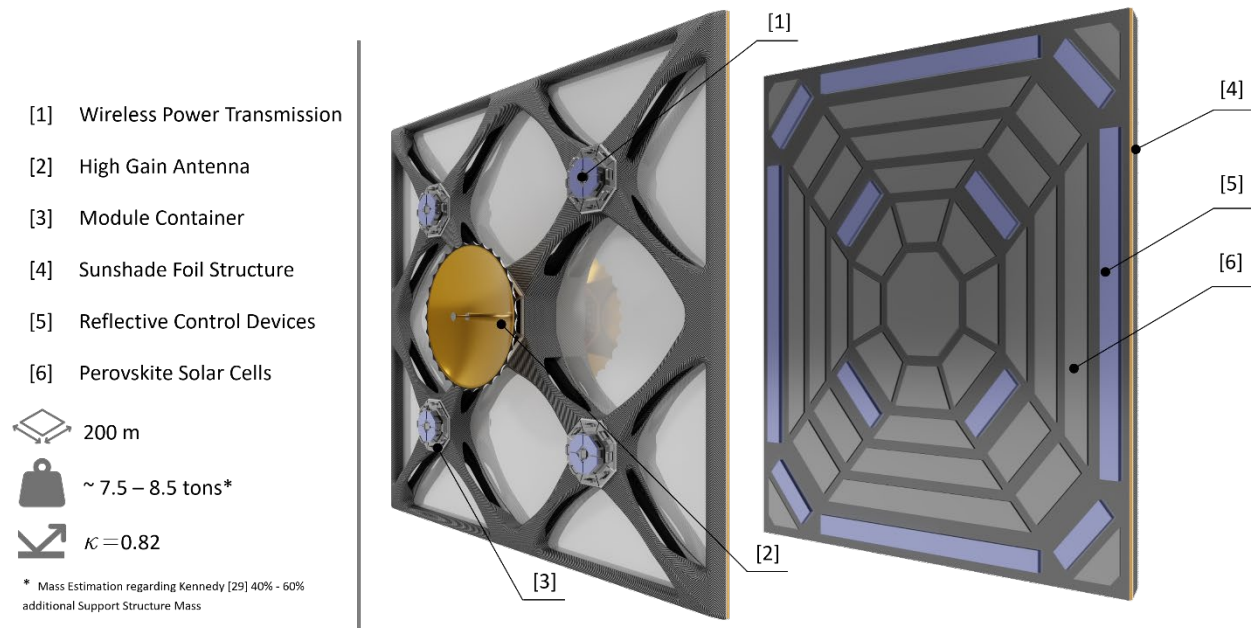
The IPSS demonstrator concept, which is scheduled for the year 2027, will be launched from Earth and will have an edge length of 100 m. Figure 3 shows a potential setup for such a demo mission inspired by the concepts of the Solar Cruiser [46; 47] and the Advanced Composite Solar Sail System (ACS3) [48; 49]. Since this sunshade demonstrator will be launched from Earth, it is necessary to provide deployment mechanisms for the foil structure. The triangular rollable and collapsible (TRAC) boom mechanism [50], which will also be used for the Solar Cruiser mission [46], is being considered for this purpose. The foil structure intended for this concept will consist of four layers. These should be built up as follows starting from the side facing away from the sun towards the sun facing side: 3  $\mu\text{m}$  aluminum, 50  $\mu\text{m}$  Kapton, 1  $\mu\text{m}$  aluminum, and 1  $\mu\text{m}$  silicon. The Kapton layer is responsible for the stability of the foil structure. The respective aluminum coatings are intended to improve the reflectivity of the foil and, at the same



**Figure 3: 2027 Earth Demonstrator Concept.**

time, offer the possibility of using solar sailing as propulsion technology. A similar composition of the foil structure has already been used for the James Webb Space Telescope [51]. The silicon coating should enable the implementation of perovskite solar cells and reflective control devices (RCD). In addition, radiation protection should be increased as well. The perovskite solar cells are the primary energy source of the sunshade [52]. The RCDs [46; 53], which are attached to the edges of the foil segments, should provide attitude control in combination with reaction wheels and magnetorquers. Using a foil deployment mechanism, two solar panels with the same cell type are to be installed in the electronics bay in addition to the perovskite solar cells on the foil to operate the sunshade with the redundant panels in the unlikely event of foil deployment failure. This allows at least the wireless power transmission to be tested. The wireless power transmission unit should correspond to the recently launched Caltech demo mission [54; 55]. The transmission frequency will be the industrial, scientific and medical band at 5.41 GHz, also used by other solar power satellites such as CASSIOPEiA [34] or SPS-Alpha [33]. The structure of the electronics bay should consist of a combination of 3D-printed aluminum and based on coreless filament winding manufactured carbon structures [56] to create the necessary stability for the launch and to be able to dissipate excess heat from the system via the aluminum structure. Omnidirectional X-band antennas will enable communication to the ground station for the downlink and S-band TT&C antennas for the uplink. The ground station network being considered is the European Space Tracking network (ESTRACK) of the European Space Agency (ESA) [57]. The orbit for this mission should be a sun-synchronous orbit with an altitude of ~1000 km and an inclination of ~120°.

The 2040 concept, shown in Figure 4, is an in-space manufactured sunshade that is designed to use up to 50 % lunar resources and has an edge length of 200 m providing a foil area of 40,000 m<sup>2</sup>. In-space manufacturing makes it possible to avoid deployment mechanisms and thus reduce system complexity and maximize reliability. The foil structure will be identical to the 2027 concept and will also include perovskite solar cells [52; 58] and RCDs [46; 53]. This sunshade will be set in a spin-stabilized state by implementing a ferrofluid-based ACS system [59] to provide the necessary rotation.. In combination with the RCDs, the attitude control of the sunshade will be realized. Unlike the 2027 sunshade demonstrator, the concept shown in Figure 4 consists of five bays. There are four decentralized bays equipped with wireless power transmission modules, which should be based on the technology developed by Caltech [54; 55], and a central bay containing the electronic components required to control the sunshade. Additionally, in the central bay the high-gain communications antenna is located, which is intended to provide a direct link to the ground station network [57] for sending telemetry data and receiving Earth commands. The in-space manufactured support structure can be constructed using robotic systems such as SpiderFab, currently under development [60]. The structure will be made from hybrid lunar basalt and terrestrial carbon fibers. The binder, which is needed to harden the fibers, will be provided from Earth. The basalt fibers can be produced using MoonFibre [61] and transported to the in-space manufacturing facility. The bay structures will be created from aluminum on the lunar surface using additive

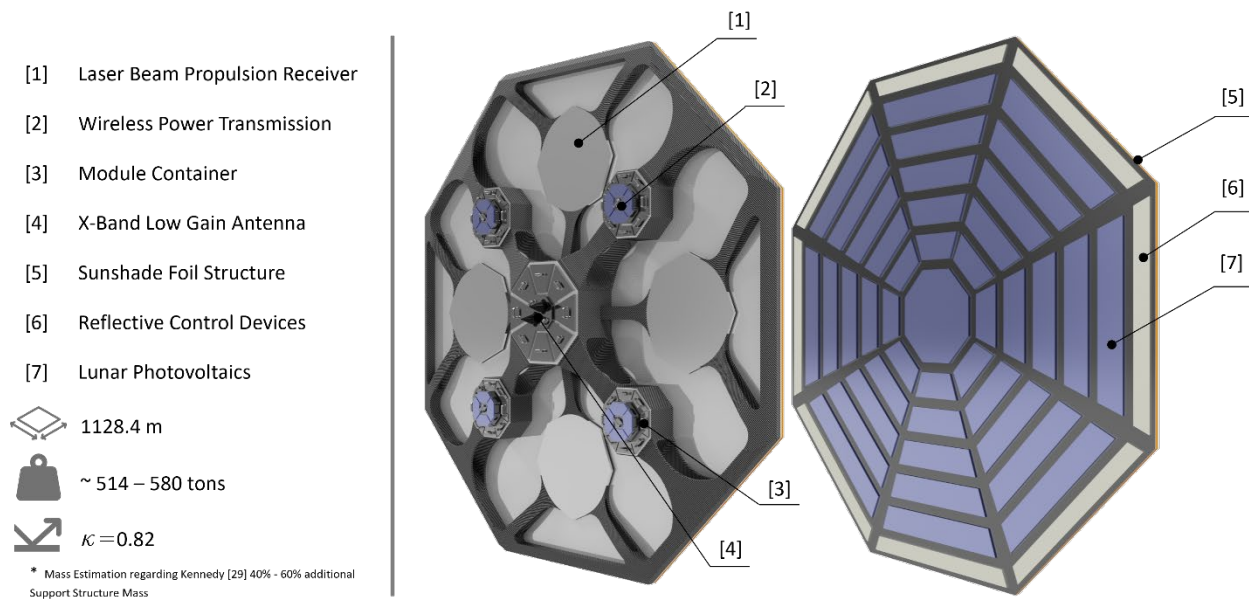


**Figure 4: 2040 Partially In-Space Manufactured Demonstrator with ~50 % Lunar Resources.**

manufacturing techniques [62]. The demonstration mission will be conducted in a halo orbit at SEL1 intended for the final sunshades to prove relevant functionalities and controllability in the operational environment.

Figure 5 shows the demonstrator concept planned for 2050. It has a diagonal of 1128.4 m resulting in a foil area of 1,054 km<sup>2</sup>. This concept consists of almost 90 % lunar resources and, like the 2040 demonstrator, will be manufactured in space. By changing the geometry of the sunshade from a square to an octagon in this development step, the effective shading area can be improved, and the support structure volume can be reduced by up to 14 % [63]. The support structure for this concept should be manufactured from lunar basalt fibers produced by the MoonFibre method [61], using the SpiderFab robot [60] and lunar binder [64]. The film structure is made of an aluminum foil with a thickness of 10 μm which is to be produced with lunar resources [65]. This foil shall be coated with a 3 μm silicon layer. In addition, lunar photovoltaics [66; 67] will be implemented to enable energy generation. As with the previous concepts, RCDs [46; 53] will be installed at the edges of the sunshade geometry for attitude control. In addition to the RCDs, laser beam propulsion receiver antennas are implemented on the side facing away from the sun [68]. With the help of a high-power laser located in the in-space manufacturing and assembly (ISMA) facility, orbit corrections and collision avoidance maneuvers can be realized.

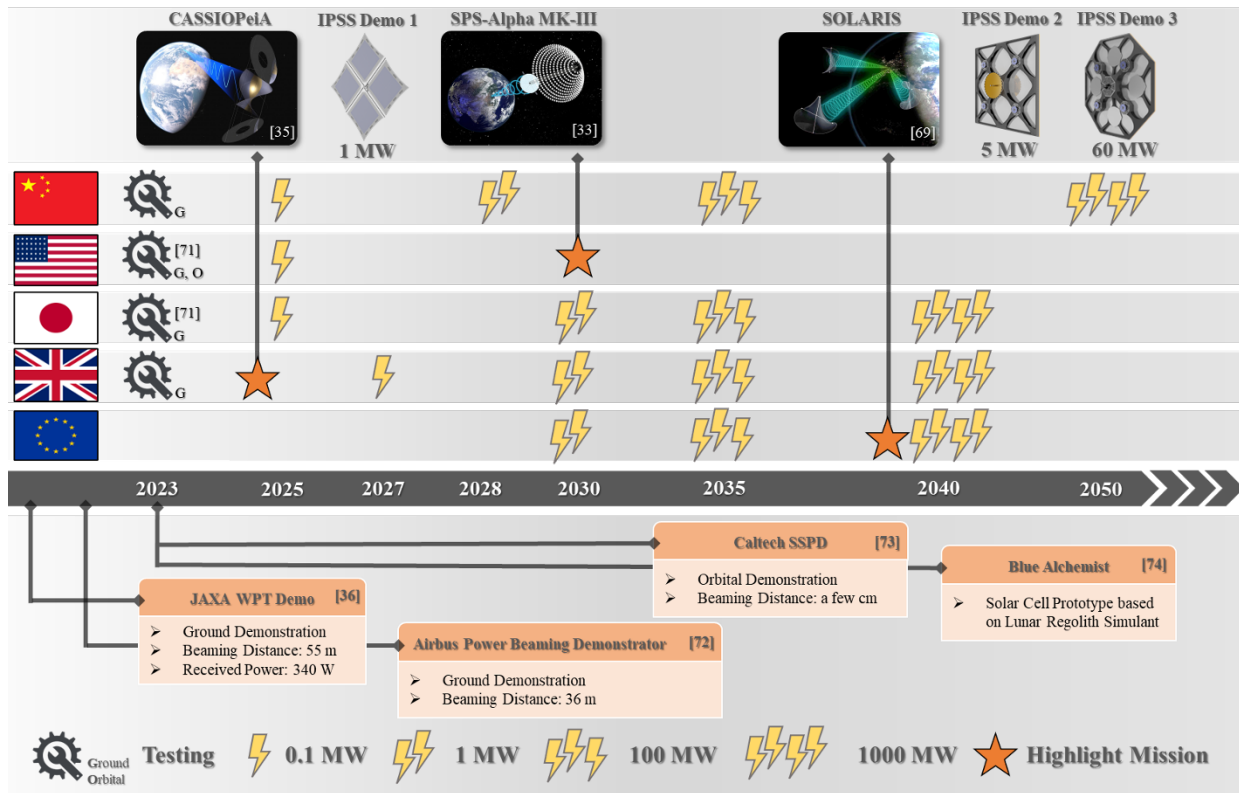
This concept has five modular bays, with four decentralized bays housing the wireless power transmission units [54; 55]. An X-band low-gain antenna module in the central bay realizes the communication in this evolutionary stage. Currently, a communication link between the sunshades and the ISMA facility is planned, whereby the ISMA facility will send relevant commands to the sunshades to organize the constellation. The ISMA facility forwards the telemetry data transmitted by the sunshade to the ground station network on Earth [57]. The demonstration mission will be conducted in a halo orbit at SEL1 intended for the final sunshades to prove relevant functionalities and controllability in the operational environment. With this demonstration mission, again performed in a relevant halo orbit at SEL1, the advanced functionalities for a scalable sunshade concept based on lunar materials should have been tested, thus demonstrating validated technological feasibility for sustainable in-space manufactured sunshades.



**Figure 5: 2050 Primarily In-Space Manufactured Demonstrator with ~90 % Lunar Resources.**

#### 4. SBSP Concept

The IPSS demonstrator missions shall enable synergies with SBSP roadmaps already in planning [33; 69; 70]. Figure 6 shows that the IPSS systems correspond well with the plans of various nations [71] to provide a sustainable energy infrastructure including SBSP as baseload technology [22]. Figure 6 also shows that global players are already conducting tests on the ground, such as JAXA's transmission demonstration [36] or Airbus' Power Beaming Demonstrator [72]. Orbital test missions have also been launched, such as Caltech's Space Solar Power Demonstrator earlier this year [54; 55; 73]. In addition to the use of terrestrial solar cells, current industrial efforts are ongoing, such as Blue Alchemist [74] to develop solar cells based on lunar regolith, which can be used not only for lunar



**Figure 6: Potential Synergies with National SBSP Goals and Technological Milestones.**

infrastructures but also for sustainable SBSP concepts based on space resources, as envisioned in the IPSS 2050 concept.

Table 1 compares the sunshade concepts presented in Chapter 3 with the solar power satellites concepts of SPS [32], SPS-Alpha [33] and CASSIOPeiA [35], which is currently under development. To achieve comparable values concerning the energy infrastructure, the calculation in Table 1 assumes that the variants of the IPSS demonstrator are in the same orbit as the other three solar power satellite concepts. Accordingly, a distance of 37,580 km is applied [35]. The size of a single sunshade in the respective development stages is relatively small compared to the other three concepts. However, the specific parameters such as mass-specific-energy (kW/kg) or the areal density (kg/m<sup>2</sup>) perform comparatively well. These values decrease drastically in the development stage of the IPSS 2050 concept. Since the IPSS 2050 concept relies increasingly on resources from the lunar surface, the solar cells are also produced with lunar materials, and the efficiencies of the lunar photovoltaics are lower by a factor of four than the efficiencies assumed for SPS, SPS-Alpha and CASSIOPeiA. Since for the first mass estimation of the IPSS concepts [63], a value of 60 % additional support structure mass according to Kennedy [29] was assumed, it can be expected that due to in-space manufacturing, the mass of the 2040+ concepts can be significantly reduced. The concepts to be compared (SPS, SPS-Alpha, CASSIOPeiA) shall all be launched from Earth and assembled in orbit. Consequently, the structures designed for these three concepts have to consider the loads during launch, and thus the geometries have to be developed much more stable as if they have been directly manufactured in space.

Concerning the receiver size parameter, the IPSS concepts would require significantly larger receiver infrastructures. However, it is essential to note that the calculation of the IPSS systems assumes only one sunshade at a time and not the expected constellation [30; 31]. The receiving infrastructure calculated could be used for the entire sunshade constellation, which would increase the overall system's effectiveness. In addition, it should be mentioned that the size of the receiving infrastructures, calculated using the correlations from [34], is inversely proportional to the diameter of the transmitting antenna. However, in the IPSS 2040+ systems, it was initially assumed that the wireless power transmission antenna should have an average area of 30 % concerning the actual sunshade area. This results from the fact that larger transmit antennas per sunshade would significantly increase mass due to additional support structures that would hold the antenna structures in place.

The demonstration as well as construction costs included in Table 1 are based on a scaling carried out using the estimations of the SPS system [32]. Based on this scaling, initial costs for the IPSS systems can be estimated.

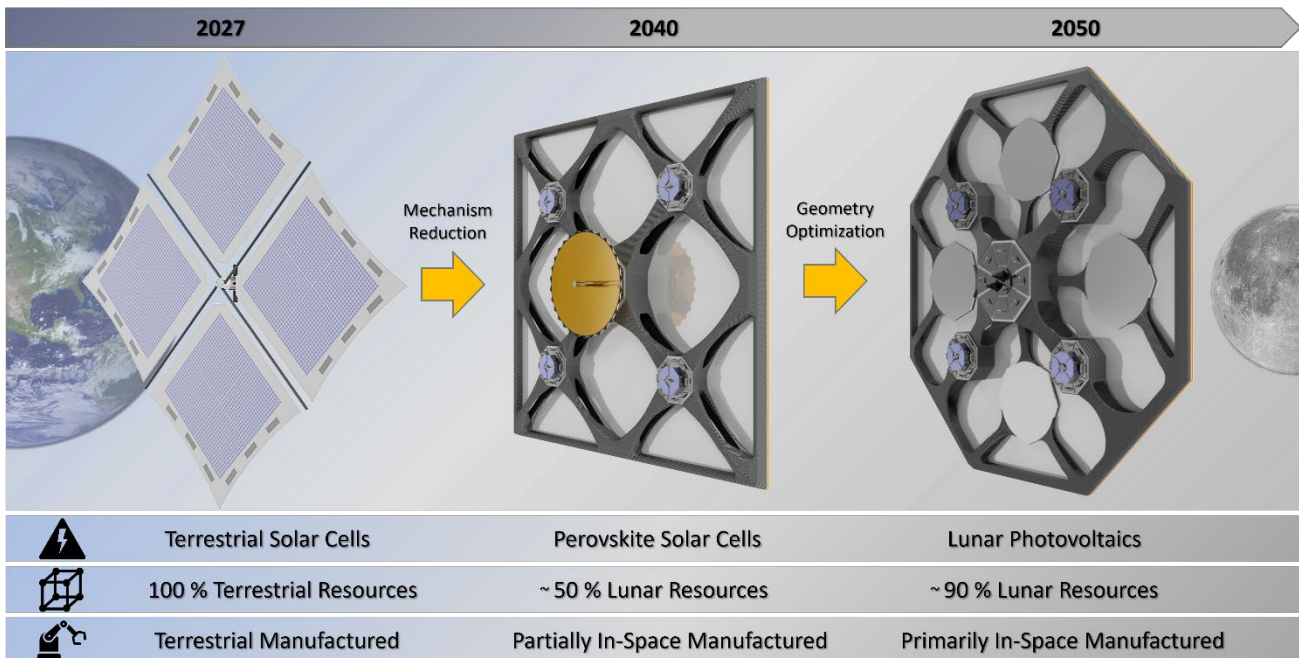
Even though the IPSS demonstrators have comparatively reduce efficiency than for example CASSIOPeiA, the IPSS 2040 concept can score in terms of approximated costs, whereby the mass-specific energy production is in a similar range.

**Table 1: Comparison of the IPSS demonstrators with SPS, SPS-Alpha and CASSIOPeiA.**

Solar Power Satellite System	SPS [32]	SPS Alpha [33]	CASSIOPeiA[35]	IPSS 2027	IPSS 2040	IPSS 2050
Photovoltaic Efficiency [%]	40.00	40.00	40.10	23.70	23.70	10.00
Satellite Size [km <sup>2</sup> ]	55.00	16.00	10.13**	0.01	0.04	1.05
Power/Satellite [MW]	5000.00	2400.00	1400.00	1.59	5.53	58.36
Mass/Satellite [t]	50000.00	16507.00	1623.00	0.76	7.50*	514.00*
Mass-Specific-Energy [kW/kg]	1.00	0.15	0.86	2.09	(8.50) <sup>o</sup> 0.74*	(580.00) <sup>o</sup> 0.11*
Receiver Size on Earth [km <sup>2</sup> ]	174.00	71.50	19.63	216739.87	1047.57	41.90
Demonstration Costs [million \$]	102000	29673***	18777***	19***	74***	1855***
Construction Costs [million \$]	11500	3345***	2117***	2***	8***	209***
Areal Density [kg/m <sup>2</sup> ]	0.91	1.03	0.16	0.08	0.19* (0.21) <sup>o</sup>	0.49* (0.55) <sup>o</sup>
Photovoltaic Area [km <sup>2</sup> ]	44.00**	2.20	8.10	0.01	0.03	0.76

- \* Mass Estimation regarding Kennedy [29] 40 % additional support structure mass
- o Mass Estimation regarding Kennedy [29] 60 % additional support structure mass
- \*\* Scaled Area regarding [75] 80 % fill ratio of photovoltaic
- \*\*\* Scaled Costs regarding SPS [32]

Figure 7 shows the evolutionary approach of the IPSS concepts. It can be seen that initially based on a purely terrestrial concept fully based on terrestrial resources, with the help of ISMA technologies concepts can be targeted, which can be produced from almost 90 % lunar resources. ISMA offers the possibility to reduce deployment mechanisms, allowing the structure to be designed for operational loads and thus reducing the structural mass. Furthermore, ISMA allows new manufacturing possibilities to design functionally integrated structures, enable structural extensions as well as perform geometric optimizations.



**Figure 7: Evolutionary Sunshade Design Approach.**

## 5. Conclusion & Outlook

SBSP satellites could be a complement for sustainable solutions against the climate and energy crisis. However, there are still numerous technological and logistical challenges to overcome to manufacture large structures in-space and to enable a sustainable integration of space resources. Building a digital IPSS model provides an opportunity to explore different scenarios to identify the technological development efforts for different concepts and, based on an intensive international collaboration, to envision a scheduled integration of an evolutionary sunshade design in combination with the terrestrial actions. In this context, the current SPS efforts could provide technological spin-ins to include the dual-use case of the sunshade.

In further work, the initial designs for the demonstrators should be further developed focusing on the requirements for ISMA, and corresponding overlaps with existing SPS programs should be identified to demonstrate the integration potential of the IPSS roadmap into international SPS roadmaps. Further, a life cycle sustainability assessment consisting of environmental life cycle assessment, social life cycle assessment, and life cycle costing should be performed for the presented concepts to provide well-founded reference values to consider the potential of the IPSS system as a scalable and sustainable space-based solar power concept for future space strategies.

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