The Space Option Star - S⊕S

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2.5 Space-Based Solar Power, Powering Civilian Space Development
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ABSTRACT

The Space Option Star (S⊕S) is a Space Solar Power (SSP) demonstrator and orbital artwork which represents a logical early step for any energy from space development program. The S⊕S mission has a dual purpose: first, its technical mission represents an in-situ demonstration of energy from space technologies and, secondly, its communication mission is to raise public awareness about the potential of the Space Energy Option to address the Energy Dilemma and the Climate Emergency facing the world population. The space segment of the Space Option Star would perform an early demonstration of the basic technological elements of space solar power. Electricity generated by the S⊕S's solar arrays would flow to co-located microwave transmitters to beam power toward a companion spacecraft, which will then use this power to transmit video and other interactive communications from orbit to public locations around the world such as art and science museums and schools. The societal context for the development of the Space Option Star is the Energy Dilemma and Climate Emergency. In addition to S⊕S being an acronym for the Space Option Star project, we are using this project to send the message "save our spaceship" with "spaceship" being modern civilization. As all art is fundamentally political and, as the S⊕S project powerfully conveys a truthful and important message, it should impact the policy discourse related to energy use on Earth. As an orbital artwork, the Space Option Star will have a more flexible envelope for development than a pure engineering project and will directly involve the public in a variety of ways. In a recent (2020) European Space Agency (ESA) call for new space missions and concepts, the Space Option Star was selected from the 201 submissions and included in a 'Space Resources and Infrastructure' group for further development as a possible ESA mission.

PAPER

1 The Energy Dilemma

Among all of nature's diverse systems, energy is the principal driver of the increasing complexity of galaxies, stars, planets, and life-forms in the expanding universe. Energy flows engendered largely by the expanding cosmos seem to be as universal as anything yet found in nature. Indeed, unlocking Earth's vast energy reserves enabled our species to embark on an industrial revolution leading to a technological civilization that is on the threshold of expanding permanently into the near cosmos. Earth's energy reserves are finite and inadequate for this next stage of a cultural and societal evolution which would enable humanity to become a spacefaring species.

Earth's terrestrial energy reserves are finite and inadequate for this next stage of a cultural and societal evolution which would enable humanity to become a spacefaring species. Humanity is facing an imminent *Energy Dilemma* in that the limited proven reserves of fossil fuels could reach exhaustion levels at mid-century and none of the current terrestrial energy options – nuclear – wind - ground solar (PV) – can be sufficiently scaled to achieve the goal of divesting from fossil fuels by the year 2050 as is being called for by the United Nations, the European Union, and numerous organizations to address the *Climate*

Emergency. However, the largest market on Earth is for energy and, as such, supplying inexhaustible and clean energy from space would be not only affordable but also immensely profitable.

The BP Statistical Review of World Energy 2020, a commonly used as a source for global energy data lists World Primary Energy Consumption by fuel, i.e. oil, natural gas, coal, nuclear energy, hydroelectricity, and renewables by region and by country. [1] The BP report lists these in totals in exajoules (EJ) which, when converted to terawatt hours (TWh) results in the following figures: total world energy consumption was 162,194 terawatt hours (TWh), combined fossil fuels from coal, natural gas and oil = 492.34 EJ = 136,761 TWh (84.2%), nuclear energy 10,461 TWh (6.5%), hydroelectricity, 6,922 TWh (4.3%) and 8,050 TWh (5%) from renewables and other energy sources.

The review shows that total world energy consumption in 2019 was 583.90 EJ including: renewables: 28.98 EJ, hydroelectricity: 37.66 EJ, nuclear energy: 24.92 EJ, coal: 157.86 EJ, natural gas: 141.45 EJ and oil: 193.03 EJ.

Using nuclear power as an example, to replace current worldwide fossil fuel usage of 136,761 TWh with nuclear power (assuming a 90% availability) would require the deployment of up to 17,347 new 1-GW nuclear reactors. This means, for the next 30 years, 578 nuclear power plants would have to go online each year. For Europe, this would mean 2,173 new 1-GW nuclear reactors would be required to replace fossil fuels.

Using renewables to meet this goal, the installed power generating capacity for wind power needs to be some 3.5 times higher and for solar PV, 6-7 times higher than nuclear power. Installing this much capacity seems unlikely and, more importantly, both of these energy sources are intermittent and cannot be stored efficiently and are particularly sensitive to winter weather. Therefore, these two alternative energy sources are not adequate for meeting humanity's energy needs and climate goals

As to economic considerations, using the 2019 total world energy consumption of 162,194 TWh mentioned in the BP report, it is possible to estimate the world energy market by using an average price per kWh US $0.13 as calculated by GlobalPetrtolRices.com, the value of the world energy market is approximately $21 trillion US dollars ($ 21,085,220,000.000).[2] The energy markets around the world are in a state of flux due to the pursuit of decarbonization and the search for viable terrestrial alternatives. However, as this market is the largest in the world, finding the most viable sustainable alternative is the ultimate economic opportunity and it will influence all areas of human activity.

2 The Climate Emergency

Due to the many assessments and reports issued since 1990 by the United Nation's IPCC – Intergovernmental Panel on Climate Change – and the subsequent international commitment to address the climate issue achieved in the 2015 Paris Agreement on climate change which, as of February 2020 has now been signed by 189 countries. Thus, the world population has become increasingly alarmed that a period of global warming may have commenced which could lead to environmental catastrophe by the end of this century. Numerous scientific studies have shown that this warming is caused by rising levels of CO_2 in the atmosphere which is attributed to the continued dependence on the use of fossil fuels to satisfy most of humanity's energy needs. A worldwide program to address the impending climate disruption has been incorporated into the United Nation's Agenda 2030 including the Paris Agreement and the 17 Sustainable Development Goals as well as through a number of international conferences, sub-organizations and public-private partnerships. [3] Similar measures are being promoted, developed, and adopted by environmental and scientific organizations worldwide. [4]

As it is the Sun which warms the surface of Earth and drives the hydrologic cycle, it is the primary source of energy for the climate system which keeps Earth suitable for life. The sunspot cycle of the Sun also has much do with the changes in the climate and scientists report that the current long period of low sunspot activity may indicate that the Sun is entering a Solar Minimum which could lead to a severe cooling effect similar to the last Little Ice Age. [5] Solar activity which modulates the influx of galactic cosmic rays (high-speed particles that strike the Earth from space), has been shown to have a direct influence on cloud formation and has been correlated with warmer periods during high solar activity and cooling periods during low levels of solar activity. Severe global cooling would probably be much worse for humanity than the predicted rise in global temperatures as this would directly affect food production and require additional energy for heating and maintaining all aspects of society. In either case, addressing the climate emergency will require massive

amounts of clean energy production for a growing population to adapt and survive a severe warming or cooling situation.

3 The Space Energy Option

The idea of harnessing energy in space originated with the Russian and Soviet rocket scientist and astronautical pioneer Konstantin Eduardovich Tsiolkovsky in 1926. In 1941, science fiction writer Isaac Asimov published the short story “Reason”, in which a space station transmits energy collected from the sun to various planets using microwave beams. The technical concept of delivering clean solar energy from space in the form of a Solar Power Satellite (SPS) was introduced by Peter Glaser in 1968 which he patented in 1973. Since then, Space-Based Solar Power (SBSP) has been researched in various governmental and institutional studies which have validated the technical feasibility. Although the engineering challenges are significant, all the core technologies already exist and have been tested. As such, the *Space Energy Option* is the only near term technically feasible and scalable energy alternative currently available to humanity to divest from fossil fuels while meeting its future energy needs, climate obligations and for restoring the environment.

Addressing the *Energy Dilemma* will require massive amounts of clean energy production for restoring the environment and meeting the energy needs of a growing population. Addressing the *Climate Emergency* will require massive amounts of clean energy production to adapt and survive a severe warming or cooling situation. Having sufficient energy would also allow our species to solve the water crisis, create new transportation fuels, reduce poverty, stimulate progress in the developing countries, sustain the world economy and to end conflict over finite energy resources. Harvesting inexhaustible energy in space and equally distributing it to all people of all nations would enable the entire population of Earth to have a prosperous and hopeful future in contrast to current policies and measures being implemented to permanently downsize society in order that humanity may continue to live within the confines of a planet defined by the limits of its atmosphere. Indeed, humanity's future on Earth is irrevocably linked to its future in space.

4 The Space Option Star

The S⊕S has a dual purpose: first, its technical mission represents an early *in-situ* demonstration of SBSP which should help to justify its development cost; second, its communication mission is to alert and inform the world population about the *Energy Dilemma* and to call attention to the *Space Energy Option*.

In 2003, the European Space Agency (ESA) contracted the authors to re-examine the technology for large expandable structures in light of any new technological developments for the purpose of celebrating the 2016 Winter Olympics.[6] Our study included the examination in some technical detail of a large icosahedron to be built utilizing the chemically rigidized expandable structures (CRES) technology that had been under development in the United States and in Europe for over thirty years, although not yet used for a space structure of this dimension.[7] In 2008, the idea of incorporating space solar power elements and other interactive technologies was introduced.

The *Space Option Star* will utilize an inflatable laminated membrane technology incorporating a thin-film photovoltaic outer surface. Once in orbit, the reflective, faceted shape of the S⊕S will reflect sunlight as it rotates causing it to appear as a blinking star in the night sky for a period of approximately one month. In addition to the visibility aspects which will make *Space Option Star* a significant global communication event available to much of the world’s population, interactive components will enable communication with *Space Option Star* at public locations around the world such as art and science museums and schools. The technical mission of the S⊕S will be to collect sunlight, transform it into electrical energy and then transmit this energy via a concentrated beam to provide power for an auxiliary, unattached object in orbit which will then use this power to communicate with the Earth.

As such, the S⊕S will be an early *in-situ* demonstrator of Wireless Power Transmission (WPT). Last but not least, the S⊕S will be developed as commercial investment opportunity involving a consortium of companies, institutions and individuals with the goal that the obtained proprietary knowledge and experience can be applied by the shareholders to making the idea of harvesting energy from space for Earth a commercial reality. In this context the S⊕S will be an interdisciplinary, multi-dimensional art, science, technology and educational project designed to inform and excite the world population about the importance and urgency of implementing the Space Energy Option and the many advantages of using space technology to meet many

of the growing essential needs of the humanity as well being an example of the inherent commercial opportunities involved in space development.

4.1 Technical Mission

The space segment of the *Space Option Star* would perform an early demonstration of the basic technological elements of SBSP especially WPT. Electricity generated by the icosahedron's solar arrays would flow to co-located microwave transmitters to beam power toward a companion spacecraft, which will then use this power to transmit video and other interactive communications from orbit to public locations around the world such as art and science museums and schools (Fig. 1.).

The suggested configuration of the S⊕S project elements builds upon a variety of studies (of similar aim) and technological concepts. For instance, the “power satellite” requires a (relatively) large size to collect sufficient solar power and to support a representative high-gain transmitter, as will be the case for operational items. On the other hand, in order to reduce costs, simplified designs are preferred. Here, the icosahedron geometry approximates an omnidirectional object, with the Sun illuminating similar surface areas at any given time, thus removing the need for an (active) attitude control system. Similarly, array antennas can track the receiver's position electronically, eliminating dedicated steering mechanisms. Either the solar panel PV facets will be manufactured as a hybrid with the antennas integrated in the photovoltaic membrane, or the transmitters will be integrated into the icosahedron structure. These would be controlled and coordinated by an array of interconnected computer chips that would track and focus the WPT beam onto the auxiliary spacecraft.

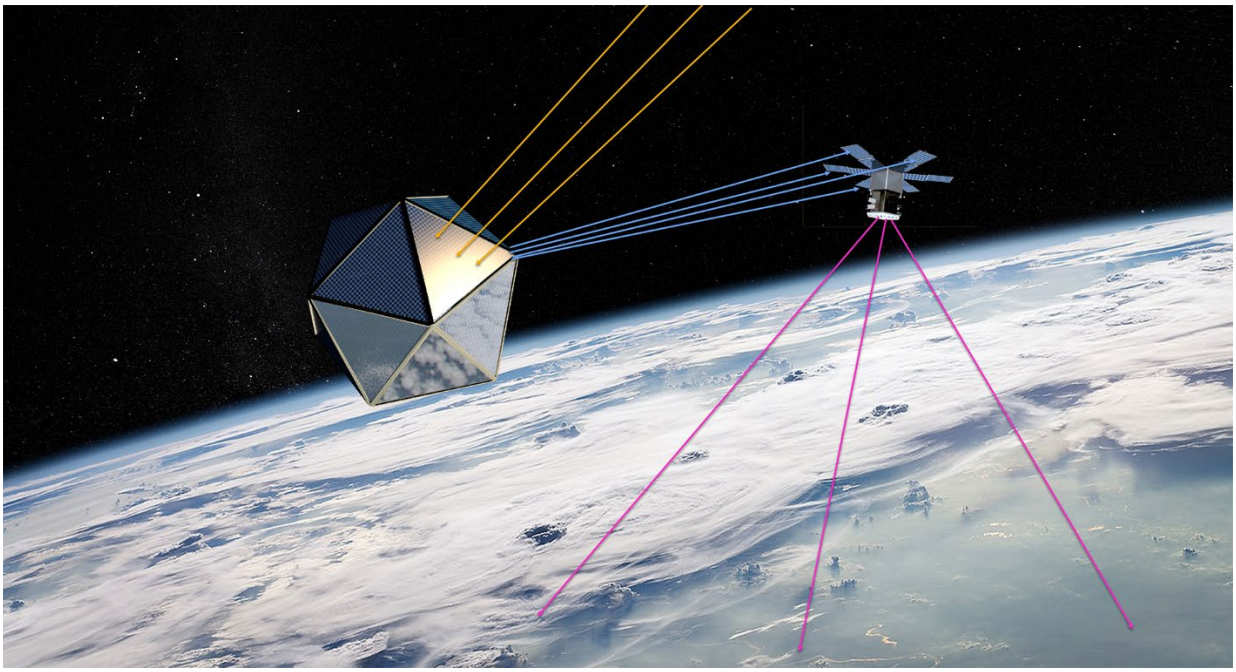

Figure 1. S⊕S in-situ WTP demonstration

The choice of this geometry is further supported by various factors, beginning with its classical simplicity: As one of the five Platonic solids, it is composed of 20 triangular facets, with 30 sides and 12 vertices. Vertices and sides are realized as nodes and tubular struts that form a skeleton supporting the membrane-like facets. As the satellite tumbles, the flat triangle's surfaces will reflect sunlight causing it to appear in the night sky as a blinking star. This way, the S⊕S would be visible to much of the world’s population during its limited orbital lifetime.

The above-mentioned ESA study conducted by the authors looked at the size, the mass, and the visibility of such an icosahedron with a 100 meter extension. It was determined that such a “star” would reach a magnitude of about -4.4 (which would correspond to Venus at its brightest), with orbits that allow a lifetime of approximately 30 days. Indeed, an 85-m sphere ought to reach -4.4 in magnitude at a slant range from a 760-km orbit; an equivalent icosahedron's lifetime estimate comes to some 24 days.

An icosahedron equivalent to an 85-m sphere ought to reach a magnitude of -4. at a slant range from a 760-km orbit, with an orbital lifetime estimated at some 24 days. As the object's orbit decays, it will become more brilliant, as suggested in Figure 2.

Orbital height	400 km	600 km	600km	760 km	760 km
Slant angle	0°	0°	45°	0°	45°
Reflected image size on the ground	1,005,000km2	2,262,000km2	4,524,000 km2	3,629,000km2	7,258,000km2
Estimated magnitude	-6.15	-5.27	-4.52	-4.76	-4
Approximated orbital lifetime	0.38 days	5.25 days	5.25 days	24.5 days	24.5 days

Figure 2. Orbital characteristics of the Space Option Star

4.2 Communication Mission

The *Energy Dilemma* and the *Climate Emergency* discussion above provides the societal context for the development of the *Space Option Star* (S⊕S) as an art intervention in orbit. SOS is commonly used as the international Morse code distress signal (· · · – – – · · ·). In popular usage, SOS became associated with such phrases as *"save our ship", "save our souls" and "send out succour"* but officially it does not stand for anything specific. In addition to *SOS* being an acronym for the *Space Option Star* project, we are using this project to send the message *"save our spaceship"* with "spaceship" being modern civilization. As all art is fundamentally political and, as the S⊕S project powerfully conveys a truthful and important message, it should impact the policy discourse related to energy. As an artwork, the *Space Option Star* will have a more flexible envelope for development than a pure engineering project and will directly involve the public in a variety of ways.

In the mid-1980's and early1990's the authors introduced and developed several large scale orbital sculpture concepts.[8] The publicity surrounding our projects and to that of Peter Beck's *Humanity Star* launched on January 21, 2018 [9] and to Trevor Paglen's *Orbital Reflector* launched on December 3, 2018 [10] exemplifies the novel and controversial aspects of deploying a visible orbital artwork, which indicates that even during the developmental stage, substantial public attention can be focused on the message of such a project.

As inexhaustible clean energy from space is a space solution that addresses the Energy Dilemma, the Climate Emergency, the Economic Crisis and Water Scarcity, the S⊕S will become a symbolic "Star of Hope", something that is both positive and superlative while making the public aware of how energy from space can help to "Save Our Spaceship".

A circle divided by a cross " ⊕ " is the Greek astronomical symbol of planet Earth and, as such, the symbolic logo connects space development with environmental consciousness.

Pre-Launch Communication Activities:

1. Kick Off = immediate press coverage
2. Episodic video campaign documentation
3. Interactive website with blog (https://spaceoptionstar.space/)
4. Social media campaign
5. Invite corporate sponsorship
6. Promote clean energy from space awareness
7. Public demonstration with a functioning model of the S⊕S (5-8 meters in dia.)
8. Partner with universities and museums
9. Public participation via crowdfunding, t-shirts, posters, etc.
10. Build tension & excitement before launch
11. Live coverage of launch

Post-Launch Communication Activities:

1. Live video from space: Combining the Overview Effect + S⊕S

2. Internet interactive action connected to the S⊕S
3. 'S⊕S - in the Sky" worldwide viewing schedule
4. "Wish upon a Star" inspirational campaign
5. Promote foot traffic to universities and museums
6. Learning campaign activated in schools
7. Space Energy Option open discussion in the media
8. Describe and promote space solutions to other terrestrial problems
9. Build confidence with space benefits for everyone
10. Successful de-orbiting of the S⊕S

4.3 Recent Project Developments

In 2020 the European Space Agency issued a call for new space missions and concepts." What's next? New space mission ideas and concepts". [11] The Space Option Star was selected from the 201 submissions and was included along with other energy from space proposals, in a 'Space Resources and, Infrastructure' group for further development as a possible future ESA mission (Fig. 3). ESA will eventually pick 3-5 ideas for implementation as missions.

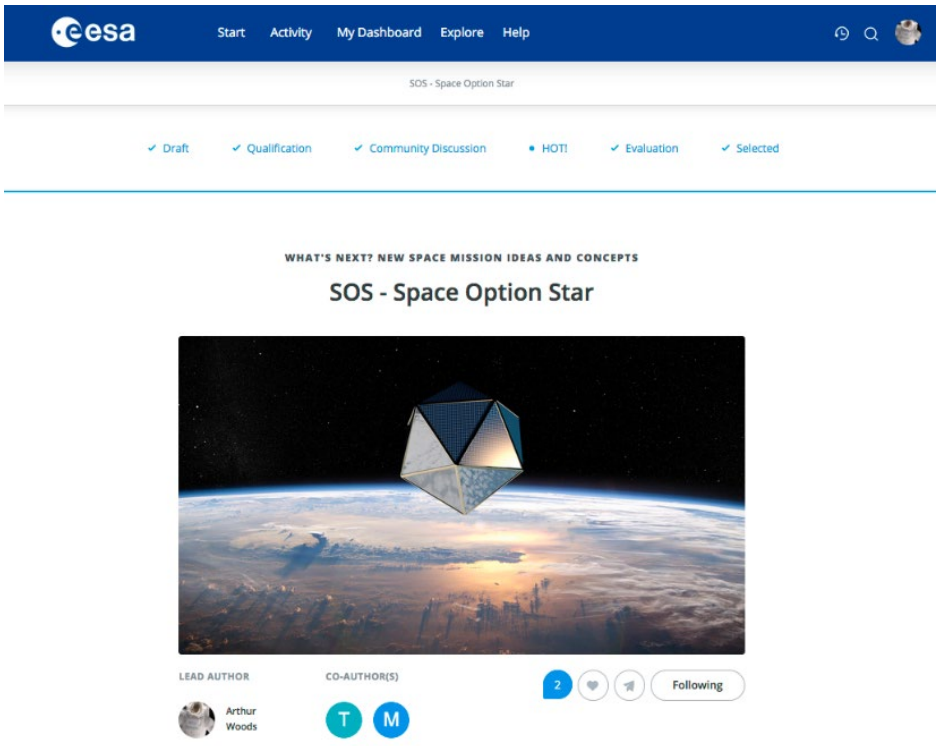

Figure 3. S⊕S Selected on the ESA OSIP (Open Space Innovative Platform) [12]
ideas.esa.int

"A Star is Born" a 5.37minute video illustrating the launch and deployment of the S⊕S, its communication mission and the societal context (Fig.4.).

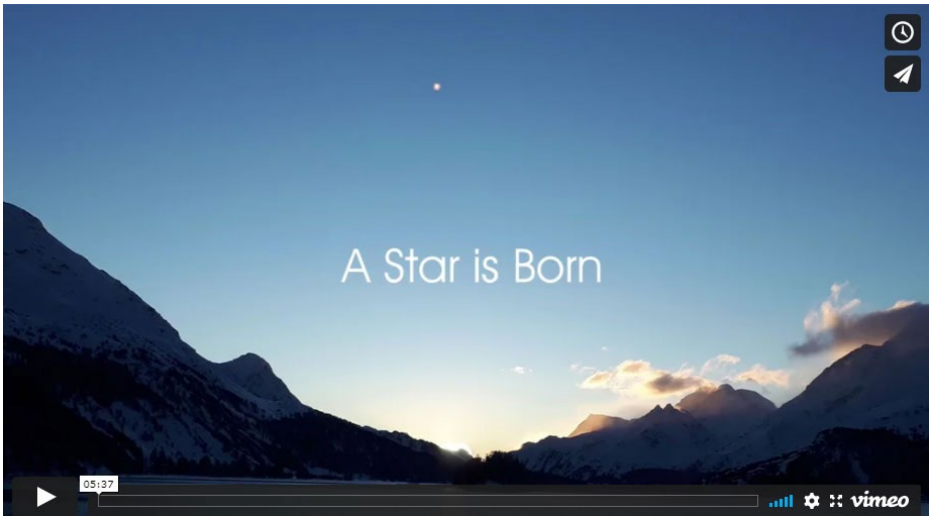

Figure 4. 'A Star is Born' S⊕S Video on Vimeo
https://vimeo.com/511524939

4.4 Mission Timeline and Costs

- Phase 0: Current. Space Option Star project definition, multi-media visualization, models and publications in various media.
- Phase 1: 1 year. Technical definition and feasibility assessment. Collaborations, cooperation and fundraising. Funding milestone: € 500,000
- Phase 2: 1-2 years. On-ground integrated demonstration of CRES (Chemically Rigidizable Expandable Structure) technologies as applied to the Space Option Star and development of a functional exhibition object (5 to 8 meters dia.). Marketing and financial assessment together with public-private partnership implementation. Funding milestone: € 1,000,000
- Phase 3: 2-3 years. Space deployment of small prototype Space Option Star as a technology certification mission. Funding milestone: : € 5,000,000
- Phase 4: 3-5 years. In-orbit realization of a full-size Space Option Star with auxiliary spacecraft. Funding milestone: : € 30-50,000,000

Estimated Mission Cost: € 50 million

5 Conclusions

Humanity is facing an imminent *Energy Dilemma* which, in addition to the *Climate Emergency,* deserves the focus of world attention. As energy is the key element, the solutions to solving both of these issues are interrelated and interconnected. Addressing the *Climate Emergency* will require massive amounts of clean energy production to adapt and survive a severe warming or cooling situation. Addressing the *Energy Dilemma* will require massive amounts of clean energy production for restoring the environment and meeting the energy needs of a growing population. Our calculations indicate that none of the alternative terrestrial energy options – nuclear, wind and ground solar (PV) – can be sufficiently scaled to achieve the goal of divesting from fossil fuels and achieve net-zero CO_2 levels by the year 2050 as is being called for by the United Nations, the European Union, many governments and numerous organizations. The *Space Energy Option* represents the only near term technically feasible alternative to addressing these two critical energy related issues. As a visible and interactive orbital art intervention, the *Space Option Star (*S⊕S*)* incorporates and demonstrates a disruptive energy technology which should impact public discussion concerning humanity's future energy options.

The S⊕S encompasses several important aspects:

- S⊕S will be an early in-situ demonstration of the basic SBSP technologies.
- S⊕S will stimulate the further development of expandable structures and/or additive manufacturing technologies for very large space structures that have been under development for a number a years but not deployed at this scale.
- S⊕S "Space-to-Earth" interactions will involve the public via schools and museums as well as the social media.
- S⊕S will be a visible "star" (100 meters in diameter) and, as the largest single object ever deployed in space, it will have a high public outreach potential alerting the world to the Space Energy Option for addressing the Energy Dilemma and Climate Emergency.
- S.O.S. is commonly used as the international Morse code distress signal (· · · – – – · · ·). In addition to S⊕S being an acronym for the Space Option Star project, we are using this project to send the world and its leaders the message: "Save Our Spaceship" .
- If S⊕S should be realized as the first step of a determined space solar power program signifying a solution to the above issues is under development, it will provide "hope" for a more positive future for humanity on Earth and beyond.

6 About the Authors

Arthur R. Woods is an independent researcher and astronautical artist with two art projects successfully flown on the Russian Mir space station: the Cosmic Dancer in 1993 and Ars Ad Astra in 1995 in the context of EuroMir95. He is a member of the International Academy of Astronautics and co-chair of the Moon Village Association Cultural Considerations Working Group.

Dr. Marco C. Bernasconi is an expert in lightweight structures, astronautical systems, and astronautics and society assessments. During his career he gained extensive experience in the development of ultralight structure technologies and application designs. He has repeatedly served as a consultant to the European Space Agency (ESA) for futures assessment (1995-97, 2001-2003), and contributed to a number of study groups within the International Academy of Astronautics (IAA), of which he's been a full member since 1995.

ACRONYMS

CRES	Chemically Rigidizable Expandable Structure	**TWh**	Terawatt-hours
ESA	European Space Agency	**OSIP**	Open Space Innovative Platform
EJ	Exajoule	**PV**	Photovoltaic
GW	Gigawatt	**SBSP**	Space-Based Solar Power
IPCC	Intergovernmental Panel on Climate Change	**S⊕S**	Space Option Star
km	Kilometer	**SPS**	Solar Power Satellite
kW	Kilowatt	**SSP**	Space Solar Power
kWh	Kilowatt-hours	**WPT**	Wireless Power Transmission

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