Executive Summary Report

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SBSP Pre-Phase A System Study

Executive Summary Report

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Change Records

ISSUE	DATE	§ CHANGE RECORDS	AUTHOR
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03	19/12/2023	Updated §2.3 and §2.9	SBSP Team
04	20/12/2023	Updated §2.1	SBSP Team

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1 Introduction

This Executive Summary Report concisely summarise the work performed through the 5 tasks of the “Pre-Phase A System Study of a Commercial-Scale Space-Based Solar Power (SBSP) System for Terrestrial Needs” study. The study explores the feasibility and preliminary analysis of a Space-Based Solar Power (SBSP) concept involving the collection of solar energy in space for wireless transmission to Earth.

2 Summary of the work performed

2.1 Reference Use-Case

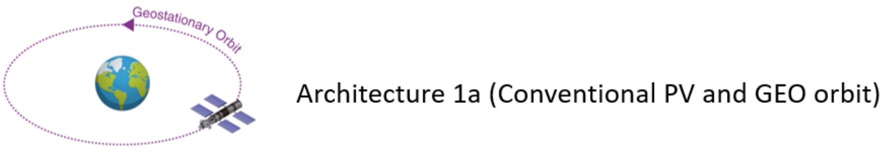
Between 17 and 20 April 2023, just after the study technical kick-off meeting, ESA has organized consultation meetings with the following relevant energy sector players: Schellhas Engineering, Microsoft, EDF, TransnetBW, EirGrid Group / ENTSO-E and Shell. These stakeholders were interviewed by our Consortium to establish a consistent set of stakeholder needs and expectations for a prospective future SBSP service.

Based on the stakeholders consultation meetings outcome, an On-Grid use-case with the the following characteristics has been selected by the Consortium:

Up to 1GW ± TBD % constant baseload power available 24/7 to be provided from one or several SPS to one GPS in Europe

2.2 Architecture Trade-offs & Selection

Following a critical review of SBSP existing concepts and related technologies, the following architecture is adopted for the SPS:



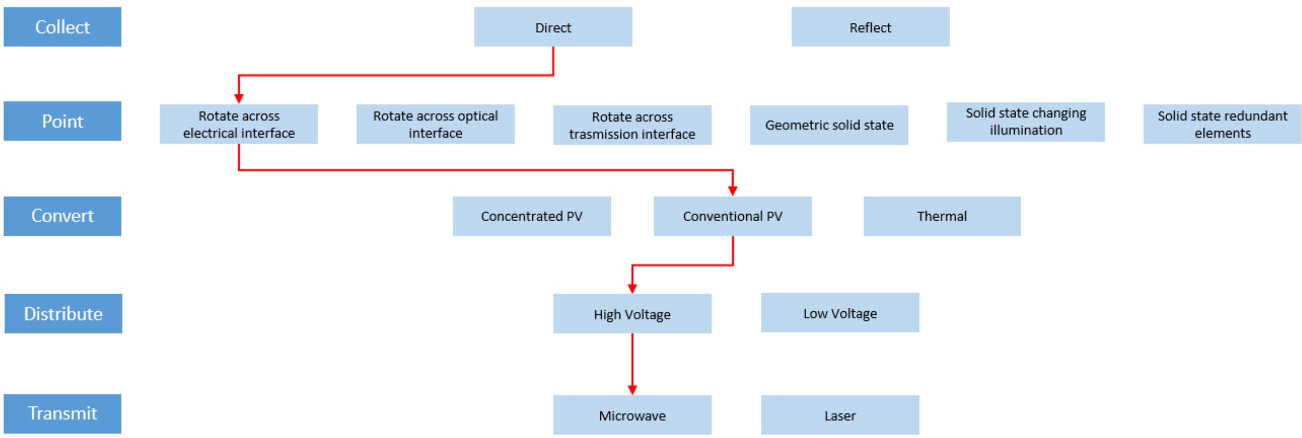


Figure 2-1 SPS Architecture 1a (Conventional PV and GEO orbit)

The trade-offs summary is presented in Table 2-1

	Performed Trade-off	Selected option
Space Segment	Orbit trade-off	Geostationary orbit
	Operating frequency trade-off	5.8GHz
	Cells technology selection	Perovskite cells
	DC to RF power conversion trade-off	SSPA
	Structures and materials for solar array modules trade-off	Flexible Roll-out Structures
	In-space transportation and infrastructure trade-off	Injection in LEO
Ground Segment	GPS location trade-off	On-shore
	GPS location (country) trade-off	Spain
	Energy storage system trade-off	Supercapacitors

Table 2-1 Trade-offs summary

2.3 Concept of Operations

The mission phases are summarized in Figure 2-2

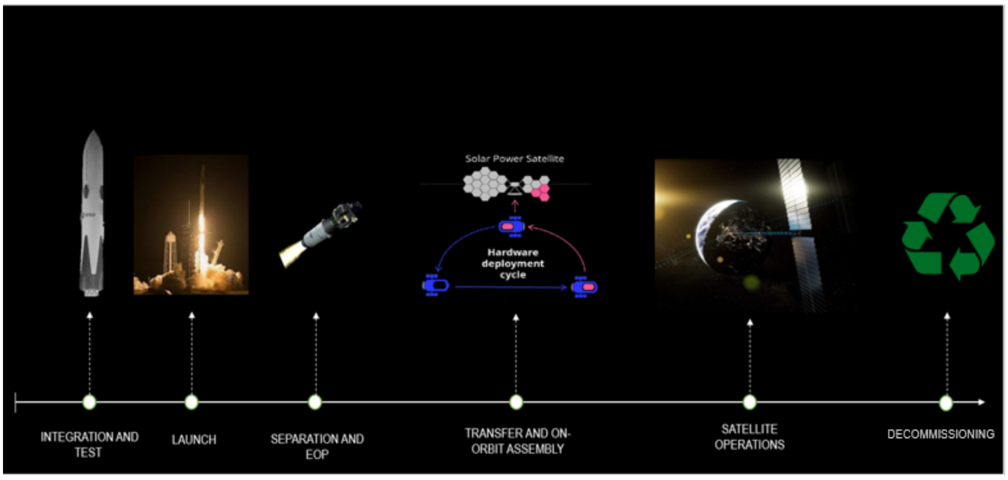


Figure 2-2 Mission phases overview

and the SPS launch, deployment and assembly strategy reported in Figure 2-3

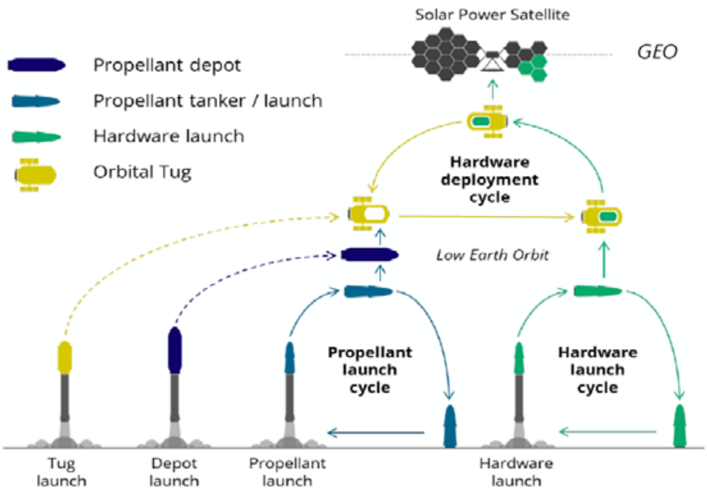


Figure 2-3 SPS launch, deployment and assembly

The concept foresees a modular in-orbit assembly for the antenna and the solar arrays, with several launches to LEO with cargos. Once in LEO, an orbital tug is used to move the hardware from LEO to GEO. A propellant depot is needed to refuel the tug during the mission.

Once in GEO, the hardware is assembled thanks to the contribution of robotic systems. The concept foresees the capability to operate the SPS in a <u>reduced power mode</u> before the complete assembly take place. This will grant solar power beaming from early stage of the mission allowing in orbit test and refinements.

For the decommissioning, as the graveyard orbit is not compliant with the Zero Debris policy, the SPS will be disassembled with the help of the robotic systems and then recycled. Two options are proposed:

- *Lunar recycling* (Figure 2-4): the robotic systems disassemble a small hardware part from the SPS and the orbital tug, after being refueled, transfers it to the Moon. This hardware decommissioning cycle is then repeated. The Orbital Tug is capable to perform GEO to Moon orbit and back trip as the Delta V required is similar to the LEO to GEO transfer;
- *In-situ recycling*: the SPS will be disassembled and then recycled in GEO via in-orbit manufacturing.

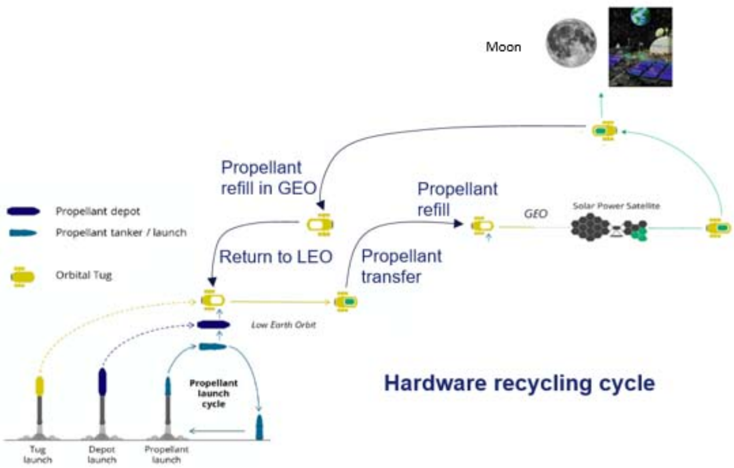


Figure 2-4 SPS Moon disassembly and decommissioning

2.4 System Size Optimization

A main mathematical model containing the efficiency chain parameters, is implemented in an SBSP digital framework. This integration aims to shed light on the potential impact of variations in key design parameters related to the three principal SBSP domains: Ground Power Station area, solar panels area and on-board antenna area.
The baseline solution adopted has the following values:

System areas	Area value [km^2]
Ground Power Station	34
Photovoltaic Assembly	6.2
On-board antenna	0.44

Table 2-2 Optimized area values for the selected architecture

2.5 System Overview

The Solar Power Satellite overview is provided in Figure 2-5.

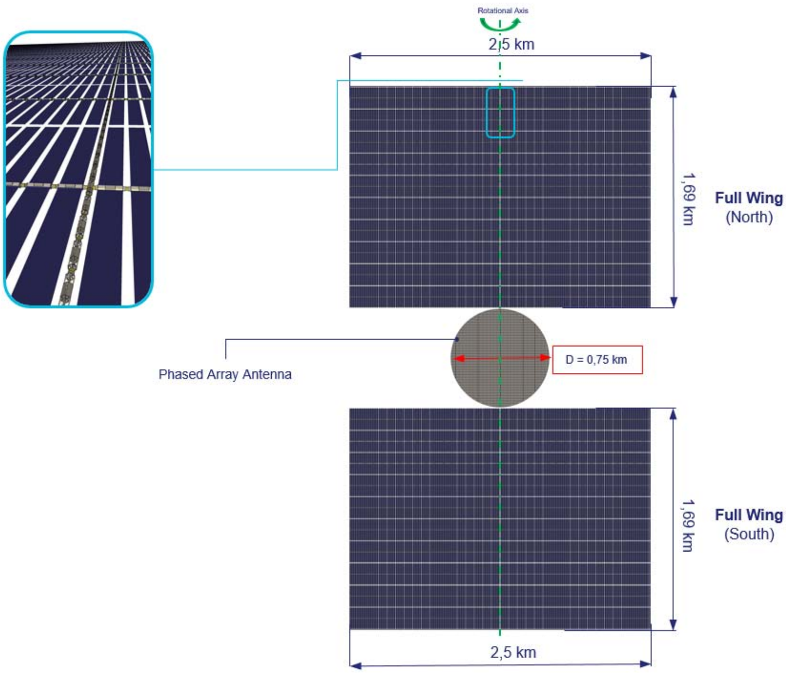


Figure 2-5 SPS overview

Due to the size of the solar arrays system, the body axes are considered fixed w.r.t. the two solar array full wings. In this reference frame, the antenna rotates along the x-axis to follow the Earth's relative movement.

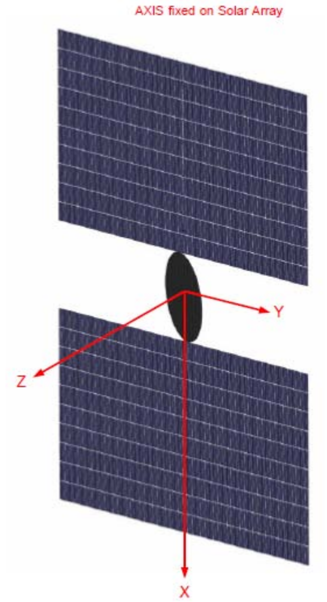


Figure 2-6 Satellite axis reference frame

In terms of attitude, the antenna shall be nadir pointing, while the solar array z-axis shall be parallel to the Sun vector as much as possible. This means that the antenna shall be nadir pointing for the whole duration of the mission, thus the body plane y-z is considered to be on the same plane of the equator. The rotation of the Phased antenna structure (0.75km diameter, 250tons mass) is one of the main technological challenges of this project. Although the speed is very limited (360°/24h, i.e. 15°/h), there is no space heritage for similar bulky solutions. The use of thrusters coupled with a free joint is excluded (for fuel consumption reasons) so motorized rotary joints are baselined.

A global stiffness requirement in terms of first structural frequency for the current Solar Power Satellite solution is established based also on AOCS considerations and the inertia evaluated. The disturbance acting on the S/C are estimated and a simplified and fully decoupled architecture is proposed.

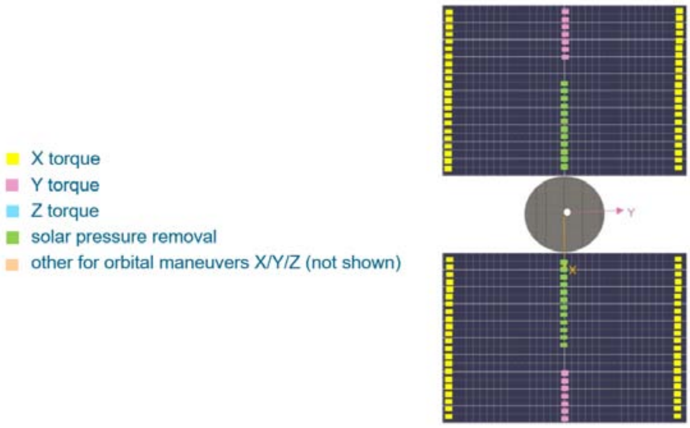


Figure 2-7 RCS accommodation

A preliminary design is also put forward for the electrical power subsystem, the phased array antenna and the thermal control subsystem.

Concerning the Ground Power Station, the dimensions depend on:

- Transmission frequency (the higher the frequency the lower will be the GPS area, if the antenna area is fixed)

- GPS latitude (the higher the latitude the longer will be the footprint of the power beam)
- On-board antenna area (the higher the antenna area the lower will be the GPS area, if the frequency is fixed)

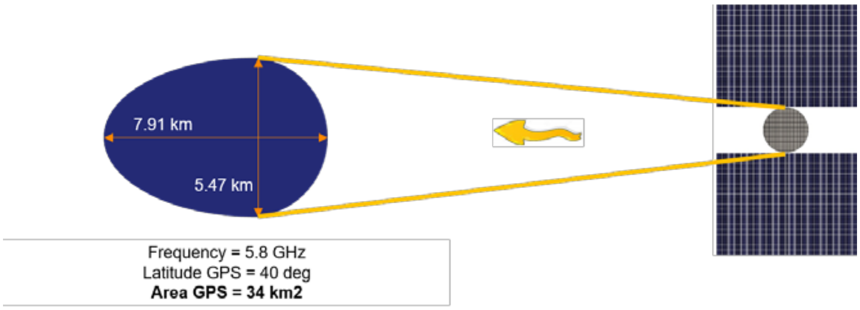


Figure 2-8 GPS footprint

The selected option, based on inclined mesh panels, and the retrodirective beam pointing concept is shown in Figure 2-9 and Figure 2-10.

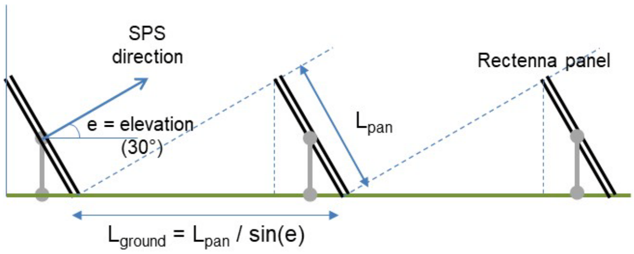


Figure 2-9 Inclined mesh panel

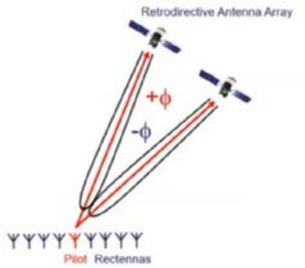


Figure 2-10 Retrodirective beam pointing concept (Credits: CWI)

The free area between the inclined mesh panels could be used for dual purpose, such as crop production.

2.6 In-Orbit Assembly Highlights

The in-orbit manufacturing is a crucial technology allowing to fully exploit the launcher's fairing. With robotic systems capable of join components in the operational orbit it would be possible to maximize the amount of transported mass without modifying the modules design. By stacking the module's components in a tight configuration, the fairing can be fully exploited.

It would be possible to link each modules with no need of docking mechanisms.

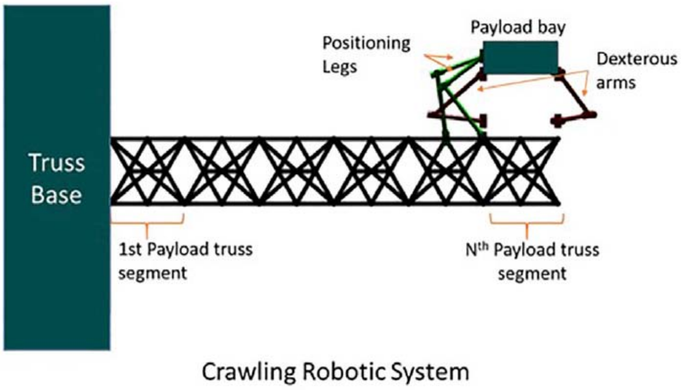


Figure 2-11 Robotic system example (Credits: U.S. Naval Research Laboratory)

In order to evaluate the amount of robotic systems required to perform the in-orbit assembly the following assumptions are taken:

- 4 robots to assembly 1 module in 4 hours
- 8 hours/day for robotic operations
- 100 modules arrive at the same time with the orbital tug and have to assembled in 11 days (before the next tug with other modules arrives)

With these assumptions, the required amount of robotic systems to build the SPS in 2 years is 24.

Space pallet meant to host assembly parts in space logistics, robotically actuated package fillers and fasteners and interfaces compatible with robots need to be studied.

2.7 System Budgets

The mass budget of the proposed architecture is summarized in Table 2-3.

Item	Mass [tons]
PVA	1870
Phased Array Antenna	250
Structure	3370
AOCS	100
EPS	1018
Mechanisms	30
TOTAL	**6640**

Table 2-3 Mass budget

The power link budget is reported in Table 2-4.

Efficiency	Value	System efficiency	Power [MW]
	Solar Power Generator (0.24)		8593
Photovoltaic cell efficiency	0.29	0.29	2492
Solar panel surface efficiency	0.86	0.25	2143
Illumination efficiency	0.99	0.247	2122
Power line efficiency	0.99	0.245	2100
Power conditioning efficiency	0.98	0.24	2058
	Wireless Power Transfer (0.64)		
Power distribution network	0.98	0.235	2017
Power conditioning efficiency	0.98	0.23	1976
RF power generator	0.83	0.19	1641
Antenna efficiency	0.98	0.187	1608
Atmospheric attenuation	0.98	0.18	1575
Beam collection efficiency	0.833	0.153	1312
	Ground Power Station (0.77)		
Rectenna panel surface efficiency	0.98	0.15	1285
Rectenna efficiency	0.833	0.125	1071
Power line efficiency	0.99	0.124	1060
Power conditioning efficiency	0.95	0.117	1007

Table 2-4 Power link budget

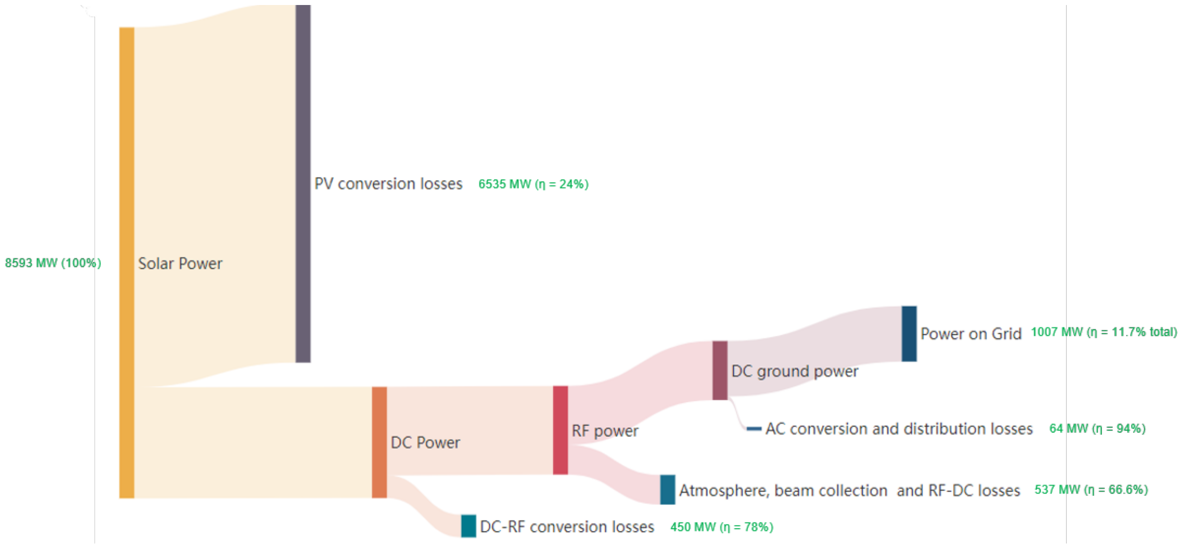


Figure 2-12 SBSP Sankey diagram

2.8 Preliminary Assessment Of CO_2 Production For SBSP Mission

Taking into account preliminary evaluations, it is possible to calculate a first estimate of the GHG parameter for CO_2 evaluated as the total amount of CO2 divided for the energy provided during the entire SPS lifetime.

CO_2 for SBSP deployment	**12 527 kt_{eCO2}**
GHG (CO_2)	56 g_e/kWh

Table 2-5 GHG emission estimation

The preliminary result obtained is compatible with other energy sources already available on the market. The SBSP CO2 production breakdown pie chart is provided in Figure 2-13.

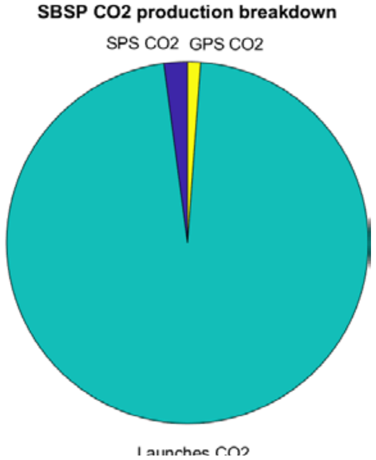


Figure 2-13 SBSP CO2 production breakdown

2.9 System Cost & Energy Estimation

All the cost evaluations reported in this chapter are based on assumptions taken from the relevant literature, including the cost-benefit analysis documents provided by ESA as input of the study (e.g. SOW RD1 and RD2). This cost assessment is not to be considered as a commitment on the part of Thales Alenia Space.

The SBSP mission costs are divided in four areas as shown below.

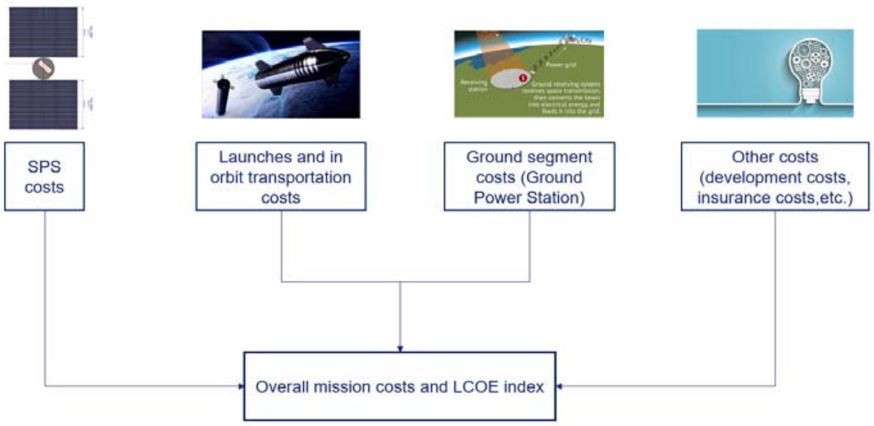


Figure 2-14 High level cost division

Considering the cost breakdown presented above and a plausible estimation for launch costs the total cost for a FOAK (First Of a Kind) SBSP system is evaluated. Also the CAPEX (capital expenditure) and the OPEX (operational expenditure) are estimated considering an appropriate cost grouping showed below with the correspondent values (see Table 2-6).

<table>
<tr><th>Parameter</th><th colspan="4">Composition and value</th></tr>
<tr><td rowspan="11">CAPEX</td><td rowspan="5">SPS costs</td><td>Truss module costs</td><td>0.01 B$</td><td rowspan="11">7.71 B$</td></tr>
<tr><td>Roll-out modules (with PVA) costs</td><td>0.18 B$</td></tr>
<tr><td>Node modules costs</td><td>0.002 B$</td></tr>
<tr><td>WPT system costs</td><td>0.50 B$</td></tr>
<tr><td>AOCS costs</td><td>1.43 B$</td></tr>
<tr><td rowspan="3">Launch and in-orbit trans-portation/assembly costs</td><td>Launch costs</td><td>3.31 B$</td></tr>
<tr><td>In-orbit transportation costs</td><td>1.65 B$</td></tr>
<tr><td>Robotic hardware costs for assembly</td><td>0.004 B$</td></tr>
<tr><td rowspan="3">GPS costs</td><td>Land occupation costs</td><td>0.06 B$</td></tr>
<tr><td>Rectenna mesh costs</td><td>0.17 B$</td></tr>
<tr><td>GPS power control costs</td><td>0.36 B$</td></tr>
<tr><td rowspan="3">OPEX</td><td colspan="2">Insurance costs</td><td>1.7 B$</td><td rowspan="3">3.66 B$</td></tr>
<tr><td colspan="2">OM costs</td><td>1.6 B$</td></tr>
<tr><td colspan="2">AOCS thrusters refueling costs</td><td>0.36 B$</td></tr>
<tr><td>TOTAL SBSP MISSION COST</td><td colspan="4">11.4 B$</td></tr>
</table>

Table 2-6 : Cost assessment results

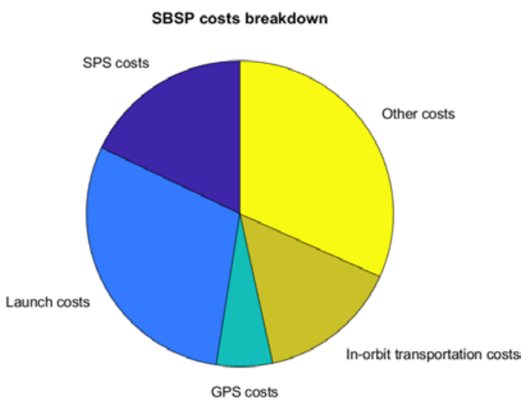


Figure 2-15 SBSP costs breakdown

According to the above considerations and given the assumptions taken for system costs the following Levelized Cost of Energy (LCOE) is obtained for a FOAK SBSP system:

Parameter	Value	
Expected energy generated over the system lifetime	Lifetime = 30 years 1 %/year degradation rate 1 GW 24h 365 days BOL	**223.4 TWh**
LCOE	**158 $/MWh (≈ 15.8 ₵/kWh)**	
LCOE for the 10th of a kind SBSP system	**143 $/MWh (≈ 14.3 ₵/kWh)**	

Table 2-7 Total energy delivered and LCOE results

The resulting LCOE is calculated using a 15% discount rate, a reasonable choice given the complexity and uncertainties associated with the SBSP project.

The learning curve approach is applied to assess a preliminary estimation of what could be the cost for an n-of-a-kind (NOAK) system with respect to a first-of-a-kind (FOAK). The slope of the curve applied for these calculations is 0.90, which is a credible assumption based on the experience gained from more than 10 SPS deployments. Consequently, for cases involving fewer than 10 systems, a slightly more conservative curve slope of 0.95 is adopted (see Table 2-8). For what concerns the cost per SBSP mission for the NOAK, the learning curve is applied only to the hardware costs (and not for example launch or orbit transportation costs).

Number of SPS	Cost per SPS [B$]	Cost per SBSP mission [B$]
1	2.06	11.4
5	1.81	11.0
10	1.43	10.5
30	1.25	10.3
50	1.15	10.1
86	1.05	10

Table 2-8 Results of learning curve approach for multiple SPS deployment

After having analyzed the entire energy cost breakdown, the main results are showed below:

Parameter	Formula	Value
SBSP Energy investment (e.i)	SPS e.i + GPS e.i + Electrical storage system e.i + Launches e.i + In-orbit transportation e.i	**7.30 TWh**
EPBT	SBSP Energy investment / Energy delivered per day	**300 days**
ERoEI	SBSP Energy returned / SBSP Energy investment	**31: 1**

Table 2-9 Final energy analyses results

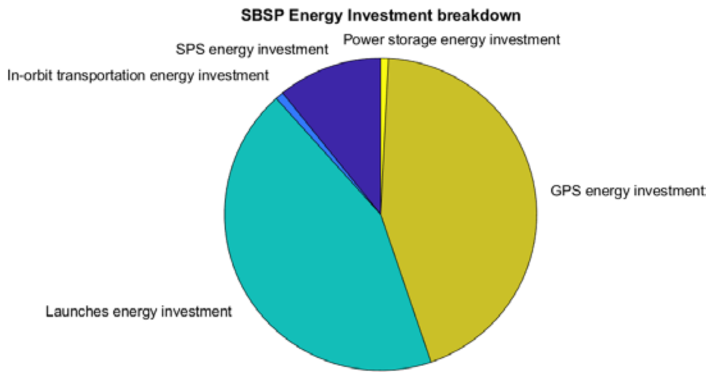


Figure 2-16 SBSP energy investment breakdown

2.10 SBSP Roadmap

The SBSP development roadmap towards a commercial scale SBSP system development, including major demonstrators along the way, proposed by our Consortium is shown in Figure 2-17.

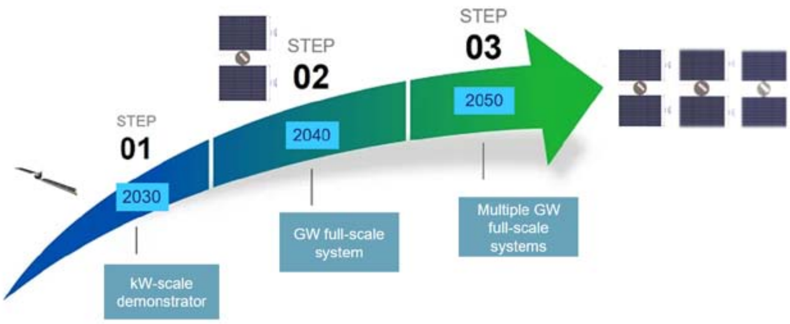


Figure 2-17: SBSP Roadmap

2.11 Preliminary Recommendations For The Demonstrator Mission

For our first SBSP demonstrator, some viable solutions have been identified considering a ground power generation capability of maximum 1 kW. The following configurations are proposed:

Area GPS [km2]	Power on ground [kW]	Power generated in orbit [kW]	Area solar array [m2]	Area on-board antenna [m2]	On-board antenna diameter [m]
10	1	200	560	500	25.2
5	0.5	200	560	500	25.2
1	0.5	480	1400	1000	35.7
1	0.01	72	230	100	11.3

Table 2-10 Four possible demonstrator configurations

These combinations are just examples and represent a subset of potential configurations for achieving this values of output power. The proposed solutions arise from an initial compromise involving the three primary SBSP domains: the GPS area, the PV area, and the on-board antenna area. In future studies, these values may be subject to adjustments and are presented here solely to illustrate the scale of the systems that must be considered for a demonstrator mission.

The demonstrator allows to test various aspects of SBSP technologies, in order to assess the feasibility of their use in the full-scale system. In particular it allows to test and validate:

- emerging cell technologies, such as Perovskite, in space environment
- the power conversion performances
- the effectiveness of wireless power transmission
- the reliability of the SPS components (such as roll-out deployment mechanisms)

All of these steps are considered crucial to allow the full-scale system to be constructed and operated.

Due to the nature of the system, many critical technologies will not be available in the timeframe of the first demonstrator satellite. One of these is probably going to be the In-Orbit assembly technologies although many studies are developing these capabilities, like Thales Alenia Space In-Orbit Servicing (IOS) demonstration mission. In order to be independent from other satellites, a one-launch mission is suggested for the first demonstrator mission. Using as reference the values from the 0.01 kW on ground proposed satellite in Table 3-1, it would be possible to use deployable solar panels and a foldable/inflatable phased array antenna to fit the satellite inside a single launcher fairing. The ISS ROSA demonstrates the capability to deploy large solar panels from a compact container, while many studies are tackling the concept of foldable phased array antennas, which may allow to insert a 100 m^2 antenna in a 5 m diameter fairing (like the Ariane 6 or Falcon 9 ones). Other promising papers regarding foldable phased array sheets, like Caltech’s one, may allow to reduce the volume required furthermore in the near future.

The satellite’s design shall prioritize the maximization of both solar array and antenna areas in order to reduce the required GPS area. Considerations on the beam collection efficiency will also help in reducing the GPS area, for example by collecting only the peak of the intensity profile, increasing the mean rectenna efficiency.

In line with the considerations reported in this section, a demonstrator mission will play a pivotal role in assessing the viability of a full-scale Space-Based Solar Power (SBSP) mission.

2.12 Conclusions

The space-based solar power (SBSP) solution proposed presents a promising perspective for addressing our growing energy needs.

- **Technical Feasibility**: the technical analysis reveals that the concept of harnessing solar power in space is scientifically grounded. Advances in solar panel efficiency, wireless power transmission, and space-based construction techniques make the overall feasibility of the project realistic.
- **Economic Viability**: on the basis of our study, although the initial investment for space-based solar power infrastructure is substantial, the long-term economic benefits are foreseen to overweigh the costs in virtue of the expected energy production. Continued technological advancements and economies of scale could further enhance the economic viability of SBSP.
- **Programmatic Feasibility**: implementing a space-based solar power program requires international collaboration, regulatory frameworks, and strategic planning. Our study underscores the importance of robust international partnerships and comprehensive policies to tackle the complexities of space-based energy generation.

In essence, the technical, economic, and programmatic aspects collectively suggest that space-based solar power holds promise as a sustainable and potentially transformative energy solution. Further research, development, and international cooperation will be key in realizing the full potential of this innovative approach.

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