Architecture Selection Report

Written by	
Di Tommaso Umberto	Written on 03/11/2023 12:45
Verified By	
Massobrio Federico	Verified on 03/11/2023 16:50
Cavaglia' Rosetta	Verified on 03/11/2023 17:10
Di Tommaso Umberto	Verified on 03/11/2023 16:51
Approved By	
Musso Giorgio	Approved on 03/11/2023 17:12
Released By	
Cavaglia' Rosetta	Released on 03/11/2023 17:25

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SBSP Pre-Phase A System Study

Architecture Selection Report

DRL: TN 3

Written by	***Responsibility*** + handwritten signature if no electronic workflow tool
U. Di Tommaso	Author
Verified by	
F. Massobrio	Checker
R. Cavaglià	Configuration Manager
U. Di Tommaso	Systems Engineer
Approved by	
G. Musso	Program Manager
Documentation Manager	
R. Cavaglià	Configuration Administrator

Approval evidence is kept within the document management system

Change Records

ISSUE	DATE	§ CHANGE RECORDS	AUTHOR
01	19/05/2023	Issue 1	SBSP Team
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		Updated §3.4.2.8 in response to ASR RID **VP-06** Updated Table 3-34 in response to ASR RID **SV-08** Updated Table 3-39 in §3.5.1 as per ASR Part 2 presentation (ref. SBSP_ASR_review_presentation_Part2) Moved Chapter 4 (Concept of Operations), Chapter 5 (Functional Analysis) and Annex 2 (DM4/DM5 model + Capella software) to TN4	

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1 Introduction

1.1 Scope and purpose

This document summarizes the trade space exploration of candidate architectures focusing on *how* the SBSP System could be designed to achieve *what* the system must do.

The first issue of this document, released for the SKR, covers the following aspects:

- identification of the trade-offs to be performed;
- definition of the trade-off criteria.

The second issue of this document, released for the ASR, completes the trade-space exploration focusing on the architectural options relevant to the selected reference use-case. The identified trade-offs are executed, one SBSP architecture selected, the ConOps elaborated, and the Functional Analysis performed. The key points of the present study are summurized in Section 3.5.

The third issue of this document, released for the AKR, implements the updates agreed with ESA at ASR Part1 and ASR Part2.

1.2 Applicable documents

Internal code / DRL	Reference	Issue	Title	Location of record
[AD1]			Orbit Analyses for Commercial-Scale Space-Based Solar Power Systems	
[AD2]			ESSB-HB-U-005 Space system Life Cycle Assessment (LCA) Guidelines iss.1.0	
[AD3]			ESA LCA Database	
[AD4]			ECSS-U-AS-10C Rev.1 – Adoption Notice of ISO 24113: Space systems – Space debris mitigation requirements (3 December 2019)	
[AD5]			Study Report(s) from ESA Future Launchers Preparatory Programme activity titled “euroPean Reusable and cOsT Effective heavy lIft transport investigation” (PROTEIN)	
[AD6]			ESA-TECSF-SOW-2022-003590 - Statement of Work Pre-Phase A System Study of a Commercial-Scale Space-Based Solar Power (SBSP) System for Terrestrial Needs	

1.3 Reference documents

Internal code / DRL	Reference	Issue	Title	Location of record
[RD1]			Final Deliverables from Frazer-Nash Consultancy for ESA-funded study titled “Cost-Benefit Analysis of Space-Based Solar Power Generation for Terrestrial Energy Needs” https://ec.europa.eu/eurostat/cache/infographs/energy/bloc-2a.html https://esamultimedia.esa.int/docs/technology/frazer-nash-consultancy-SBSP-cost-benefit-study-full-deliverables.zip	
[RD2]			Final Deliverables from Roland Berger for ESA-funded study titled “Cost-Benefit Analysis of Space-Based Solar Power Generation for Terrestrial Energy Needs” https://esamultimedia.esa.int/docs/technology/roland-berger-SBSP-cost-benefit-study-full-deliverables.zip	
[RD3]			SPS-ALPHA: The First Practical Solar Power Satellite via Arbitrarily Large Phased Array (A 2011-2012 NASA NIAC Phase 1 Project)	
[RD4]			Mankins, John C. "New Developments in Space Solar Power." NSS Space Settlement Journal (2017): 1-30.	

[RD5]			Space Solar Power: An Overview – John C. Mankins (Presentation at ISDC 2022)	
[RD6]			Cash, Ian. "CASSIOPeiA–A new paradigm for space solar power." Acta Astronautica 159 (2019): 170-178. https://doi.org/10.1016/j.actaastro.2019.03.063	
[RD7]			Cash, Ian. "CASSIOPeiA solar power satellite." 2017 IEEE International Conference on Wireless for Space and Extreme Environments (WiSEE). IEEE, 2017. 10.1109/WiSEE.2017.8124908	
[RD8]			UK Patent: GB2571383 - Solar concentrator. https://www.ipo.gov.uk/p-ipsum/Case/PublicationNumber/GB2571383	
[RD9]			UK Patent: GB2563574 - A phased array antenna and apparatus incorporating the same https://www.ipo.gov.uk/p-ipsum/Case/PublicationNumber/GB2563574	
[RD10]			CASSIOPEIA SPS: Advantages for Commercial Power, I Cash (Presentation at ISDC 2022)	
[RD11]			Space Solar Power development in China and MR-SPS, 4th SPS Symposium 2018, Kyoto, Japan https://www.sspss.jp/MR-SPS4.pdf	
[RD12]			Fraas, Lewis M. "Mirrors in space for low-cost terrestrial solar electric power at night." 2012 38th IEEE Photovoltaic Specialists Conference. IEEE, 2012.	
[RD13]			Fraas, Lewis M., Geoffrey A. Landis, and Arthur Palisoc. "Mirror satellites in polar orbit beaming sunlight to terrestrial solar fields at dawn and dusk." 2013 IEEE 39th Photovoltaic Specialists Conference (PVSC). IEEE, 2013.	
[RD14]			Çelik, Onur, et al. "Enhancing terrestrial solar power using orbiting solar reflectors." Acta Astronautica 195 (2022): 276-286.	
[RD15]			Çelik, Onur, and Colin R. McInnes. "An analytical model for solar energy reflected from space with selected applications." Advances in Space Research 69.1 (2022): 647-663.	
[RD16]			ESSB-ST-U-004 ESA Re-entry Safety Requirements iss.1.0	
[RD17]			FNC 011337 53514R Space Based Solar Power End of Life Study Final Report (Frazer-Nash Consultancy) Issue 1	
[RD18]			FNC 011337 53615R Space Based Solar Power End of Life Study Summary Report (Frazer-Nash Consultancy) Issue 1	
[RD19]			Sala, Serenella, et al. "Global normalisation factors for the environmental footprint and life cycle assessment." Publications Office of the European Union: Luxembourg (2017): 1-16	

[RD20]			A. Fikes *et al*., "The Caltech Space Solar Power Demonstration One Mission," *2022 IEEE International Conference on Wireless for Space and Extreme Environments (WiSEE)*, Winnipeg, MB, Canada, 2022, pp. 18-22, doi: 10.1109/WiSEE49342.2022.9926883.	
[RD21]			Venugopal R, Manjunath H. R, Raghu A. V. Overview of Space Based Solar Power. Mat. Sci. Res. India;19(2).	
[RD22]			Steiner M., Bösch A., Dilger A., Dimroth F., Dörsam T., Muller M., Hornung T., Siefer G., Wiesenfarth M., Bett A.W. FLATCON® CPV module with 36.7% efficiency equipped with four-junction solar cells.	
[RD23]			Verduci, R.; Romano, V.; Brunetti, G.; Yaghoobi Nia, N.; Di Carlo, A.; D'Angelo, G.; Ciminelli, C. Solar Energy in Space Applications: Review and Technology Perspectives. Adv. Energy Mater. 2022, 12, 2200125.	
[RD24]			NREL, "Best Research-Cell Efficiency Chart," 04 01 2021. Available: https://www.nrel.gov/pv/cell-efficiency.html	
[RD25]			Office of Energy Efficiency & Renewable Energy, Solar Energy Technologies Office Perovskite Solar Cells https://www.energy.gov/eere/solar/perovskite-solar-cells	
[RD26]			Chaudhary, K., Kumar, D. Satellite solar wireless power transfer for baseload ground supply: clean energy for the future. *Eur J Futures Res* **6**, 9 (2018). https://doi.org/10.1186/s40309-018-0139-7	
[RD27]			Summary of Recent Results from NASA's Space Solar Power (SSP) Programs and the Current Capabilities of Microwave WPT Technology	

1.4 Definitions and Acronyms

Acronym/Abbreviation	Definition
AC	Alternating Current
ACSS	Aluminium Conductor Steel Supported
AOCS	Attitude and Orbit Control System
ARCADIA	ARChitecture Analysis and Design Integrated Approach
ASR	Architecture Selection Review
BTM	Behind The Meter
CAPEX	Capital Expediture
CASSIOPeiA	Constant Aperture, Solid-State, Integrated orbital Phased Array
CCI	Central Plant Controller
CEI	Comitato Elettrotecnico Italiano
DM	Digital Model
EN	European Standards
ESA	European Space Agency
EU	European Union
GNSS	Global Navigation Satellite System
GPS	Ground Power Station
HV	High Voltage
HVAC	Heating, Ventilation and Air Conditioning
IEC	International Electrotechnical Commission
LCA	Life Cycle Assessment
LCOE	Levelized cost of electricity
LEO	Low Earth Orbit
LFP	Lithium Ferro-Phosphate
MAPLE	Microwave Array for Power-transfer Low-orbit Experiment
MBSE	Model Based Systems Engineering
MEO	Medium Earth Orbit
MR-SPS	Multi-Rotary joints SPS
MV	Medium Voltage
MVA	Megavoltampere
MW	Megawatt
NASA	National Aeronautics and Space Administration
O&M	Operations and Maintenance
OPEX	Operating Expenses or Expenditure
PETER	Product Evaluation Tool for Eco-design and Reporting
PF	Package of Functions
PV	Photovoltaic
PVA	Photovoltaic Assembly
RF	Radio Frequency
SBSP	Space-Based Solar Power
SC	SuperCapacitor
SKR	Stakeholder Key-Point Review
SOW	Statement of Work
SPS	Solar Power Satellite
SPS-ALPHA	SPS by means of Arbitrarily Large Phased Array
TAS	Thales Alenia Space
TRL	Technology Readiness Levels
TS	Technical specification
VALCOE	Value-Adjusted Levelised Cost Of Electricity
W	Watt
WPT	Wireless Power Transmission

2 Mission Definition and scope

The Space-Based Solar Power (SBSP) mission objective is to gather solar energy in space and distribute it safely to Earth providing electricity to the grid transmission network 24/7.

The solution proposed by our Consortium consist in distributing it to Earth by means of the wireless power transmission technology whose application in the space domain has been recently proven by Caltech through the MAPLE experiment [RD20].

Other power distribution solutions (e.g., by space mirrors), analyzed as a part of the SBSP concept review and included in the proposal, will not be further investigated.

3 Architecture Trade-Space Exploration

The trade-offs identified in the following paragraphs will be performed with the aim to identify the baseline architecture for the SBSP System which includes the following elements:

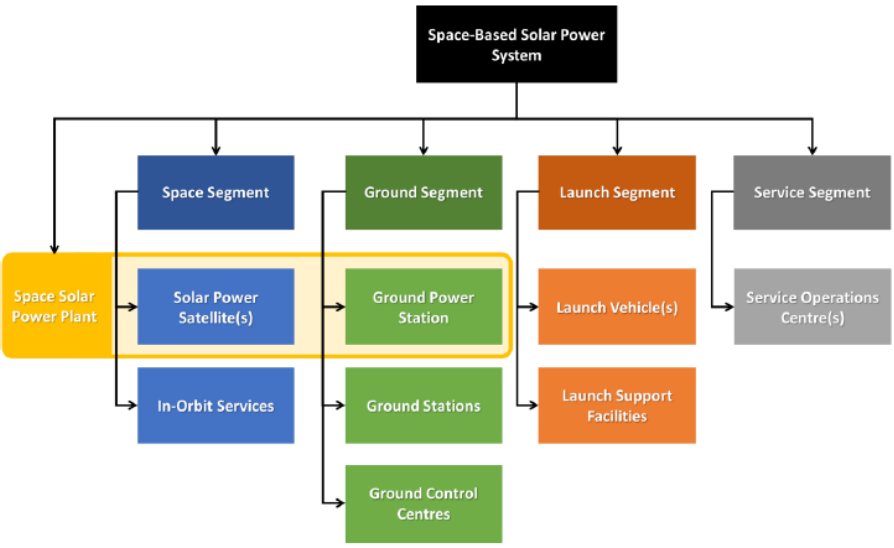


Figure 3-1 SBSP System elements

3.1 Space Segment trade-offs

3.1.1 Orbit selection

Trade-off between GEO and EO (eccentric orbits) reported in AD1 will be performed considering the following parameters:

Parameter
Eclipse duration
Visibility duration (Germany TBC)
Visibility duration (Spain TBC)
Visibility duration (Sweden TBC)
Range
Elevation

Figure 3-2 Orbit selection parameters

For EO analysis will be performed considering the following parameters:

Parameter
Orbit Altitude
Orbit Inclination
Orbit Eccentricity
SPS number

Figure 3-3 Orbit selection parameters for EO

in order to derive the access/range/elevation plots for the 4 synchronous, eccentric orbits at critical inclination.

This output will drive the selection of the baseline orbit for the SPS(s).

3.1.2 SPS system

For the solar power satellite itself a functional level trade-off is proposed, looking at trading of the various top level architectural functions of the system (e.g. collect function, convert function, distribute function etc).

<table>
<tr><th>Feature</th><th colspan="2">Examples of Options</th></tr>
<tr><td rowspan="4">Collect</td><td rowspan="2">Direct – Conversion system pointed at the sun</td><td>Monolithic (1 or few large elements)</td></tr>
<tr><td>Multiple (many smaller elements)</td></tr>
<tr><td rowspan="2">Reflect - Reflectors used to illuminate ground conversion system with the sun</td><td>Monolithic</td></tr>
<tr><td>Multiple</td></tr>
<tr><td rowspan="2">Point</td><td rowspan="2"></td><td>Rotating across electrical Interface</td></tr>
<tr><td>Rotating across optical interface</td></tr>
</table>

	Separate Sun and Earth Pointing	Rotating across transmission interface
	Solid State	Geometric – Beam steering
		Non-constant Illumination
		Redundant elements (collection or transmission)
Convert	Solar Array	Direct sun exposure of the on-orbit PVA
		Reflector and Concentrator used to reflect sun flux on a fixed Solar Array located on orbit
	Thermal (e.g. a Stirling engine, or even a steam generator)	
Distribute (among on-orbit elements)	High Voltage	
	Low Voltage	
	Wireless (RF)	
Transmit	Microwave	
	Laser	

Table 3-1 SPS functional level trade-offs

This could be illustrated with the trade-off tree in Figure 3-4.

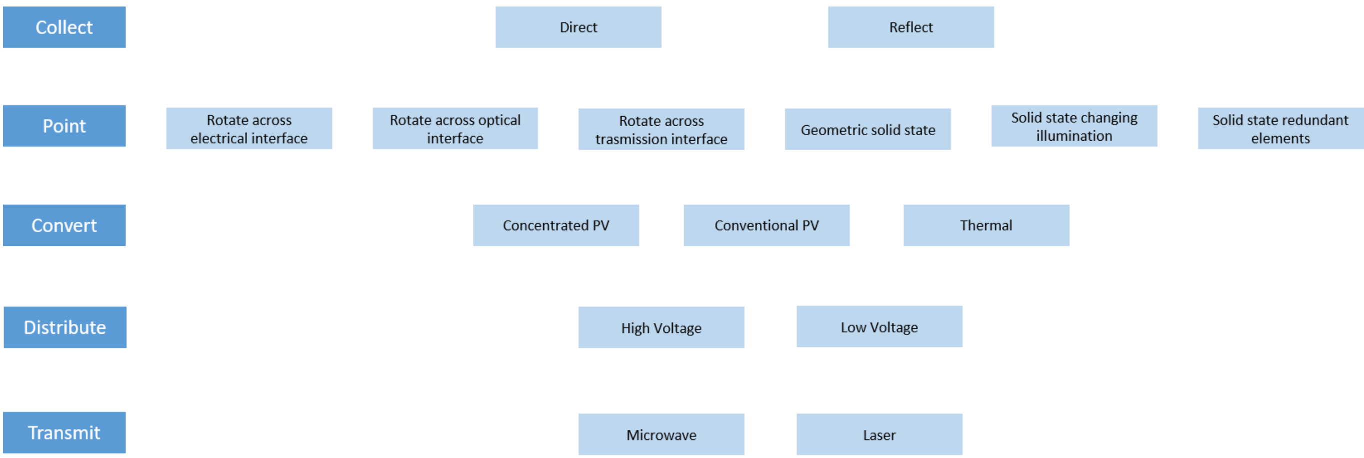


Figure 3-4 SPS trade-off tree

Individual concepts can be represented as routes through the tree from top to bottom.

A CASSIOPeiA type concept:

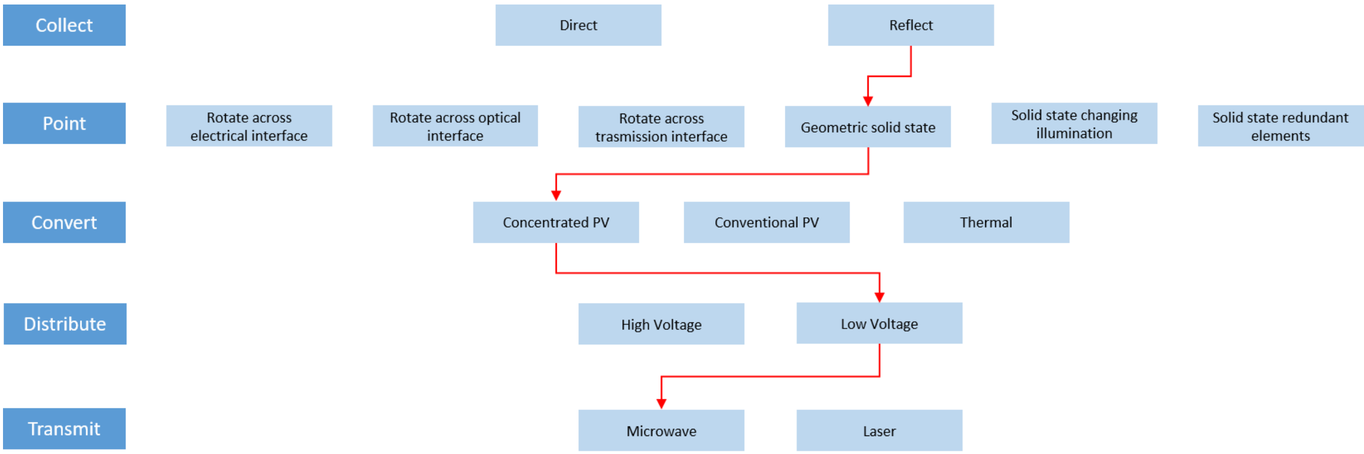


Figure 3-5 CASSIOPeiA type concept

An SPS-Alpha type concept:

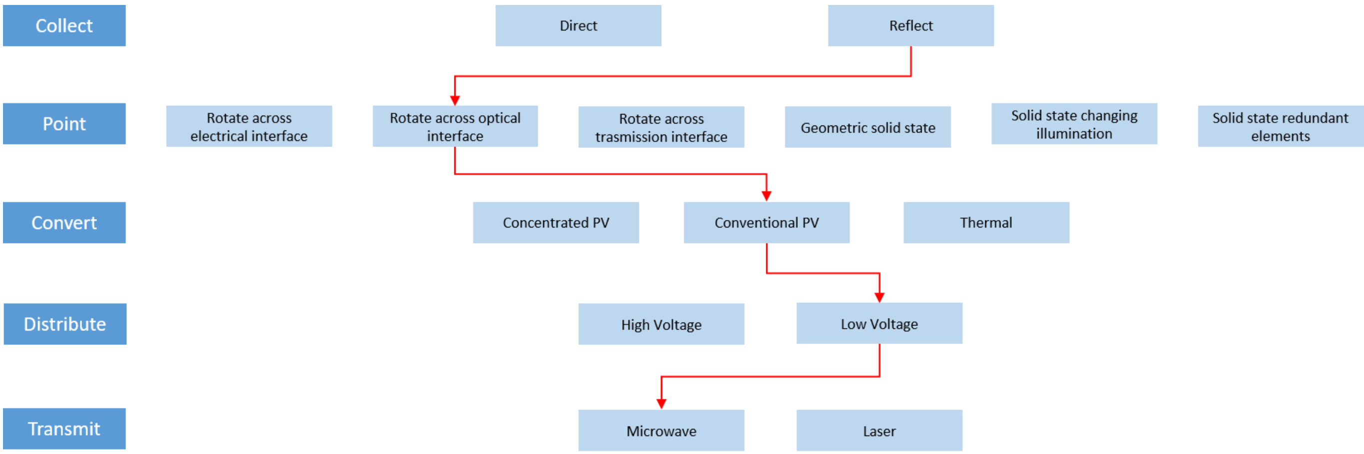


Figure 3-6 SPS-Alpha type concept

A MR-SPS type concept:

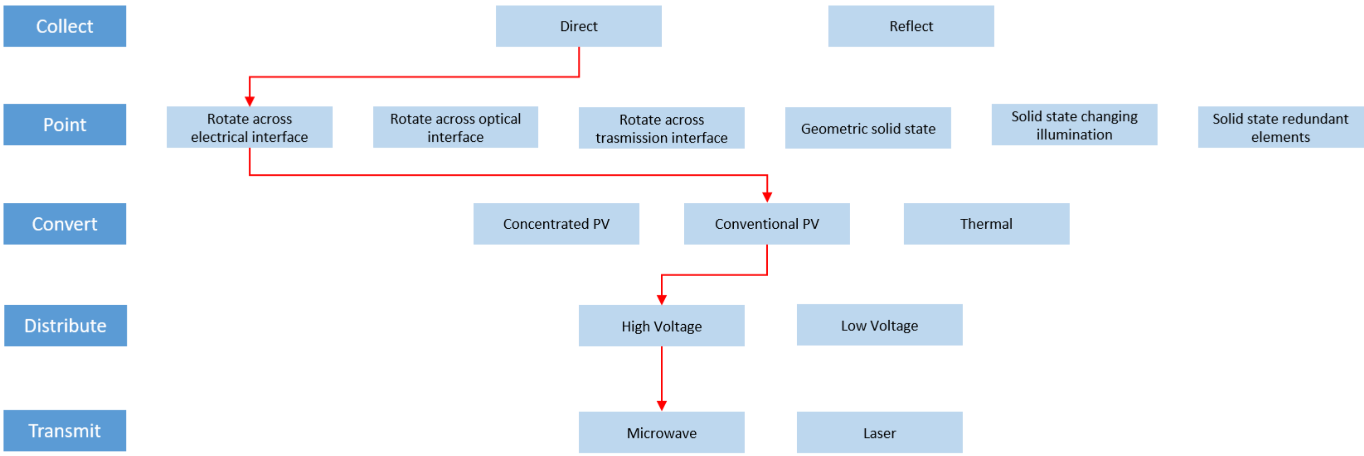


Figure 3-7 MR-SPS concept

Potentially particular “leaves” of the tree can be ruled out initially (e.g. Thermal conversion?) to limit the number of paths, and also particular path sections can be ruled out (e.g. direct illumination cannot rotate across the optical interface). It may also be that the distribution voltage line can be ignored as a particular concept either requires high voltage distribution of not depending of the proximity of the convert to the transmit function.

Then a series of reference concepts can be derived (including perhaps some that haven’t been investigated before) and traded off against each other.

Some concept examples are reported below with their functions broken down as per the trade-off tree.

Concept	Collect	Point	Convert	Transmit	Comment
CASSIOPeiA like	Reflect	Geometric solid state	Concentrated PV	Microwave	Geometry is such that complete convert area is always illuminated and complete antenna can point to ground. PV and transmission very close and modular, so high power distribution not needed
NASA 1979 reference SPS MR-SPS K-SPS	Direct	Rotate across electrical interface	PV	Microwave	Needs high power distribution from remote PV

SPS-Alpha	Reflect	Rotate across optical interface	PV	Microwave	Rotating "heliostats" used to track the sun. Not all are reflecting the sun at anyone time. PV and transmission very close and modular, so high power distribution not needed
"Tin Can" SPS	Direct	Solid state redundant elements	PV	Microwave	Cylindrical PV means no need to rotate to catch sun, but not all PV is illuminated at any one time (hence "redundant"
Tethered SPS (planar)	Direct	Solid state changing illumination	PV	Microwave	Fixed aspect solar arrays means illumination angle changes over orbit (and not illuminated at times).
Space Mirror	Reflect	Rotate across optical interface	PV on ground	None	Rotating space mirror to reflect sunlight directly to ground

Table 3-2 Concepts overview

3.1.3 Wireless power transmission

During the trade-space of candidate architectures the identification of the WPT critical parameters have been performed. By critical parameter we mean the SBSP system performances that are directly impacted by the architecture and design of the WPT system, and the WPT design parameters that are impacting the design parameters of the other SBSP systems.

3.1.3.1 Impacted SBSP system performances

The energy production performance can be evaluated by two performances:

- the **installed power** (peak) in kWp. It is the measurement for the peak output power of the couple Solar Power satellite/Ground Power Station. It is estimated in the optimal or most favourable conditions (beginning of life, clear sky, etc.). It is similar to the "SBSP System Capacity" parameters in Annex C to ESA SOW.
- the **delivered annual energy** in kWh. It is the measurement of the total annual electrical energy (in kWh) that is delivered to the power grid during a particular year by the couple SPS/GPS.

The ratio kWh/kWp is a measure of the yield of the system. It takes into account the effective duration of operation of the SPS/GPS couple, the variations in the efficiencies of the various sub-systems and in particular the WTP. Indeed the availability and the overall efficiency of the WPT are depending more or less on the weather conditions above the Ground Power Station. The achieved efficiency depends on the choice of the electromagnetic wave of the WPT: RF beyond 10 GHz, RF above 10 GHz or infra-red. For example a WPT using a radiofrequency signal above 10 GHz will have its loss (efficiency) highly dependent on rain and water clouds WPT using infrared will be blocked by clouds and therefore will have a poor availability.

We assume that the electricity production in orbit is mainly continuous with the exception of eclipse period. The duration of the eclipse season and the duration of each eclipse (one per orbit) are depending on the orbit characteristics.

The **installed power** (kWp) is constrained by two design parameters:

- the in-orbit harvested power which is depending on the sunlight collecting area of the Solar Power Satellite and the overall efficiency of the light to electricity conversion.
- the maximum overall efficiency of the Wireless Power Transfer system.

The **delivered annual energy** is constrained by

- the availability and overall efficiency of the Wireless Power Transfer system linking a Solar Power Satellite and a Ground Power Station.
- the effective duration of operations. It includes cumulative duration of eclipses during the eclipse season.

3.1.3.2 Architecture & design trading parameters

The functional architecture of the power supply chain of a SBSP is schematically represented in Figure 3-8. It includes:

- ✓ the in-orbit Solar Power Generator (SPG) which is defined by the area of the PV panels and the overall power conversion efficiency.
- ✓ the Wireless Power Transfer (WPT) which is mainly defined by the aperture of the antenna and other two efficiencies: the RF power generation efficiency and the power transmission efficiency.
- ✓ the atmosphere which is defined by its power attenuation
- ✓ the Ground Power Station (GPS) which is defined by the area of the rectenna panels and its overall efficiency.

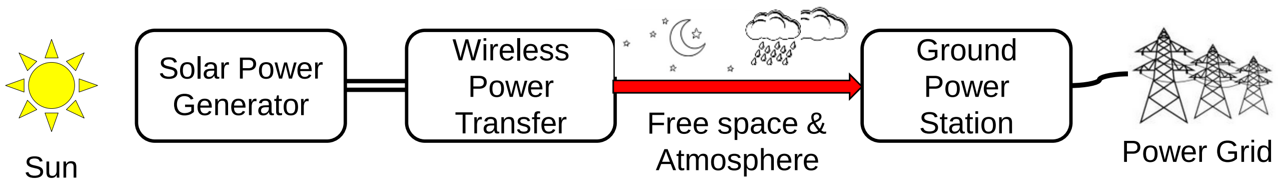


Figure 3-8 : Space based electric power supply chain

The overall efficiencies of the power transmission will be treated in a further section, together with their concrete implementation in a mathematical model used during the trade-space pruning and the frequency selection trade-off.

3.1.4 SPS AOCS

The attitude control architecture for SPS platforms is strictly linked to the selected conjurations between space and ground segment. However the following basic functions can be identified:

- Attitude observer, which means a navigation solution aimed to evaluate the SPS segment attitude w.r.t. ground and sun aimed to maximize the power generation and minimize the loss in transmission due to mispointing. The mentioned navigation solution shall, in addition, integrate a navigation sensors aimed to provide measurement that can be used to determine the SPS attitude.

Typically the sensors used to determine a satellite attitude are the star trackers and sun sensors. Gyroscope can be considered for short duration measurements but due to their bias drift, they need to be calibrate periodically with the star tracker.

- Attitude control is a suite of actuators that shall be implemented to satisfy the pointing requirements since the space segment, as 3-axis stabilized satellite, attitude is subjected by different perturbations, first of all the one provided by the sun wind.

  Different attitude control solutions as:

  - Control Momentum Gyroscopes (CMGs) which act as Reaction weel for large satellite as the ISS
  - Reaction Control Systems accommodated in different position around the SBSP geometrical envelope with different thrust authority

  could be adopted considering the reference space segment geometrical envelope, related mass and orbit.

In this frame the attitude navigation and control solutions trade-off should be considered once the reference mission, aimed to satisfy the power and wireless transmission needs, has been identified.

3.2 Ground Segment trade-offs

3.2.1 Ground Station location

To individuate a location for the station on the earth several parameters must be taken into account. The main point is any case related to cost of the facility since is one of the fundamental driving factors in the energy business. We must also consider the maturity and the development of the technology and the potential impact on all the parameters. Once defined the intrinsic cost of the investment, we must take into account also other parameters as the following:

- Safety of wireless transmission (power density, losses etc)
- Security of the assets (Intrusions, fire, earthquakes etc)
- Environment impact of new infrastructure (construction and interaction with local ecosystems)
- Existing infrastructure utilization (onshore fossil plants and offshore oil&gas platforms)
- Engineering Cost (for example stability criteria and necessity for an offshore station to receive energy from space)
- O&M
- Grids connection
- Trasmission cost
- Trasmission and system reliability

On the basis of these general parameters we can compare the possible solution as reported below:

- Onsite | Off-Grid
  - Islands (with fuel based energy systems)
  - BTM for strategic Military Facilities, Data Centers, Research Centers, Industrial Facilities (i.e. green H_2)
- Offsite | On-Grid
  - Offshore
    - Existing Infrastructure (i.e Wind farm)
    - New Infrastructure
  - Onshore
    - Existing Infrastructure (i.e. Large Substation HV 400 KV grid, Large Renewable plant, Phased Out Coal Plant)
    - Remote location with new interconnection infrastructure

3.2.2 Operational performance

Operational performances is the other fundamental parameter to be considered in the definition of the trade-off with respect to the ground location individuation but it is also a fundamental input to evaluate the investment. Operational performances actually must be well defined in order to correct evaluate the Levelized Cost of Energy (LCOE) that is a common international standard to compare the cost of different energy production methods. Below are reported the main inputs to be defined:

- O&M trade-offs (Capacity Factor | Availability)
  - Maximization of Energy yield vs minimization of long run failure rate
  - Cost effectiveness of intervention for partial outages
- Energy Production Profile:
  - Quasi-Baseload (24x7)
  - Multi-Hour Blocks

3.2.3 Energy delivery to European electricity grids

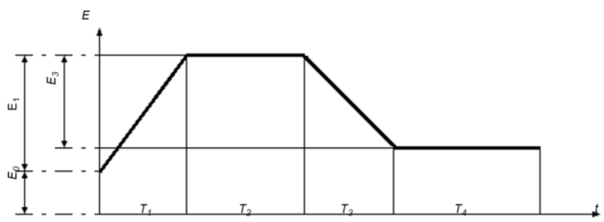
3.2.3.1 Electrical energy storage systems

Stationary and modular electrical energy storage systems (EESS) are already widely adopted for several scenario, including the case of utility EESS (EESS as a component of a utility grid, which exclusively provides services to the utility grid). The series of standards IEC 62933 define terminology, unit parameters, test methods, planning and installation requirements, safety and environmental issues applicable to EESS.

Therefore, several EESS or EESS units connected to the AC MV Busbar of HV/MV substations may be TRL8 or TRL9 independently of the requested power or energy capacity.

As per IEC TS 62933-3-1 recommendation, the EESS requirements have to be specified according to the application during the planning phase at the system level and after the installation site and application has been defined. Therefore, it is crucial to define the characteristics of the application and the installation site. The proposed application sees the EESS as service provider for the integration of a generation plant (in this case with wireless power transfer) in the grid, for example the use of an EESS to mitigate rapid fluctuations in variable power output of renewable energy sources. The EESS is used to absorb or supply power at appropriate times as determined by a control system resulting in a less variable composite power signal at feeder and/or sub-transmission level.

It is also emphasized the role of the expected charging-discharging cycle related to the application. A generic charging-discharging cycle definition is given in following picture (IEC 62933-1).



Key
T_1 is the duration of the charge phase
E_1 is the energy measured during T_1 at the primary POC during the charge phase
T_2 is the duration of the pause after charge
E_2 = 0 (so it is omitted in the figure)
T_3 is the duration of the discharge phase
E_3 is the energy measured during T_3 at the primary POC during the discharge phase
T_4 is the duration of the pause after the discharge
E_4 = 0 (so it is omitted in the figure)
E_0 is the initial stored energy

Figure 3-9 Generic charging-discharging cycle definition

Preliminary assessment follows:

- T_1 is expected to be long, because the energy coming to the space is generally available and there is no reason to fast charges, eclipses and power gaps are also well forecasted and so there is no need to fast recharge the EESS;
- T_3 is expected to be short (0.5 – 1 h) because of the need to compensate just short eclipses, intermittency or power gaps in general;
- T_2 and T_4 are not crucial when there is a slow charge or a slow discharge.

T_3 also give an information about the expected storage duration (energy/power ratio) that is around 0.5 – 1 h; this info can give a preliminary suggestion about the type of accumulation subsystem by using the well know Ragone plot that is used to compare the performance of various devices for energy storage technologies. The following figure is from Kumar, N.; Kim, S.-B.; Lee, S.-Y.; Park, S.-J. Recent Advanced Supercapacitor: A Review of Storage Mechanisms, Electrode Materials, Modification, and Perspectives. Nanomaterials 2022, 12, 3708.

Electrochemical batteries and supercapacitors (electrical storage devices) are indicated as the most adequate for this application and will be trade in the frame of the study.

In order to finally design the accumulation subsystem additional parameters have to be defined, such us:

- Specific Energy [Wh/kg]
- Specific Power [W/kg]
- Round trip Efficiency [%]
- Service Life [Years]
- Service Life [Duty cycles]
- Daily Self Discharge Rate [%]
- Discharge Time [min]
- Environmental Impact
- Energy Cost ($/kWh)
- Power Cost ($/kW)
- Operating and Maintenance cost ($/kW/year)

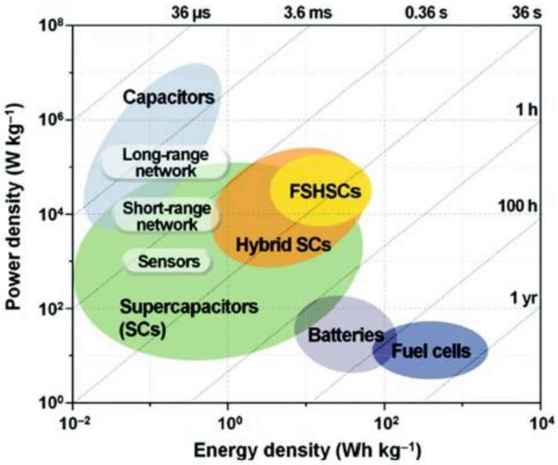


Figure 3-10 Ragone plot

Comparison between Hybrid SuperCapacitors (SC) and Lithium-Ion batteries (Lithium iron phosphate battery LFP) is provided in Advanced Electrical Energy Storage Technologies And Their Applications On Customer Side Christian Noce, Luigi Lanuzza, Martina Radicioni , CIRED2023.

As emphasized SCs are more resilient to temperature and they have a longer service life, moreover the operative costs are less (mainly because of reduced requirements/CAPEX/OPEX for HVAC and firefighting system).

LFP have higher TRL and reduced specific costs.

Features	Hybrid SCs	LIBs LFP
Specific Energy [Wh/kg]	50 – 220	75 – 200
Specific Power [W/kg]	800 – 10000	80 – 300
Round trip Efficiency [%]	60 – 98	78 – 98
Service Life [Years]	8 – 20	5 – 20
Service Life [Duty cycles]	$10^4 – 10^6$	2000 – 8000
Daily Self Discharge Rate [%]	5 – 40	0.036 – 0.33
Discharge Time [min]	10^{-5} – 60	1 – 200
Operative temperatures	0°C – 40°C	-40°C – 65°C
Environmental Impact	Very Low	Medium/Low
Energy Cost ($/kWh)	300 – 2000	200 – 400
Power Cost ($/kW)	100 – 480	900 – 4342
Operating and Maintenance cost ($/kW/year)	6	6 – 12

Table 3-3 Comparison between Hybrid SuperCapacitors (SC) and Lithium Ion batteries

3.2.3.2 Grid connection and remote-control system

According to different EESS and wireless power design and with the aim of ensuring modular and scalable approach, two main criteria will be following explored:

- connection to a primary distribution system (e.g. Enel Grids Italy) able to host up to 10 MVA in MV.
- connection to a sub-transmission network (e.g. Enel Grids Spain) able to host up to 100 MVA in HV.

Both cases will be subject to effective network nodes (power substations) capacity analysis once defined the ground station location and refers to single connection point (bay). Multiple points of coupling could be requested to increase modularity and max power distribution capacity.

Enel Grids owns both rural and urban distribution grids both in Italy and Spain, locations of ground stations should be thus optimized in order to match future and existing energy demand, minimizing network losses and authorization / permitting costs.

3.2.3.2.1 Italian technical connection criteria

For each connection point, it shall be obligatory to provide the Enel Grids with the electrical characteristics of the system components (generating sets, transformers, medium voltage cables, any power factor correction devices, loads, storage systems, etc.) in accordance with formats defined by the Enel Grids and set out in the Operating Rules.

The separation between Enel Grids and Microwaves ground conversion system shall be identified in a physical connection boundary in order to define responsibilities in operation and maintenance of the connecting installation (in accordance with EN 61936).

In case of conventional solutions the connections to Italian HV and MV network will be done in accordance to the applicable standard (i.e. CEI 0-16).

For high voltage connection the technical solutions, being conventional, refer to the most frequent installation situations. In the case of plants with specific solutions, they shall be identified on a case-by-case basis.

Peculiar plant solutions may also be identified in the presence of connection requests for many plants located in the same area.

The actual availability of maximum operating power depends, in general, on the technical standard used, the nominal voltage of the grid to which the system connects and the geographical location of the grid system for connection. On the other hand, the theoretical limit is determined only by the thermal limits of the component and is calculated according to the technical standards in force.

Below, for each standard solution is defined the element of the network system for the connection that identifies the maximum power rate of the connection.

Standard Solution	Nertwork element	Maximum Power rate at 132 kV	Maximum Power rate at 150 kV	Maximum Power rate at 220 kV
HV Single/Radial feeder	Overhead line with AA 585 mm^2 conductors (CEI 11-60)	131 MVA	150 MVA	232 MVA
HV Substation Bay	HV Bay	158 MVA	180 MVA	180 MVA

Table 3-4 Maximum power rate for each standard solution

For MV connection, the maximum operating power generally depends on the technical standard used, the nominal voltage level of the grid to which the system connects and the geographical location of the grid system for connection. It is determined by referring only to the thermal limits of the component and is calculated according to the technical standards in force.

The element of the grid system for the connection that defines the maximum operating power of the connection is the power line.

MV Line Characteristics	Maximum Power Line at 15 kV [kVA]	Maximum Power Line at 20 kV [kVA]
Overhead cable line Al 35 mm2	3.600	4.800
Overhead cable line Al 50 mm2	4.400	5.900
Overhead cable line Al 95 mm2	6.600	8.800
Overhead cable line Al 150 mm2	8.800	11.800
Overhead line in bare conductors ACSS 150 mm^2	9.600	12.800

Underground cable line Al 70 mm^2	4.700	6.250
Underground cable line Al 185 mm^3	8.400	11.250

Table 3-5 MV Line Characteristics

For what concern protection and remote-control system, the generation facility of the conversion and storage system must be designed in coordination with Enel Grids Italy systems and must be equipped with following controllable switches:

- Mainswitch: to exclude the whole plant in case of internal faults
- Interface switch: to separate part of user plant that may operate in island
- Generator switch: to exclude each generator in case of fault into the generator itself

Furthermore CEI-016 v2 network code in Italy has introduced the Central Plant Controller (CCI). The CCI is installed at the Delivery Point and allows Enel Grids Italy to monitor and regulate the power production plant, thereby taking part in the balancing of the grid, in coordination with national power networks backbone operator (Transmission System Operator).

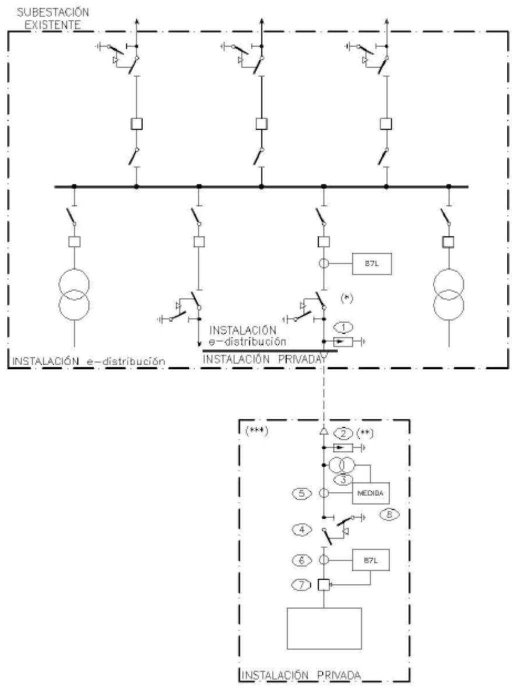
CCI realizes three types of functional services of great interest for a large-scale storage based power plant:

- PF1 mandatory: relates to monitoring and data exchange services;
- PF2 optional: additional functions to perform electrical system support. Optional PF2 relates to the power input limitation and voltage regulation services;
- PF3 optional: functions whose implementation depends on the initiative of the manufacturer. Optional PF3 relates to optimized management of the power plant system and to participate to the Italian Dispatching Ancillary Services Market.

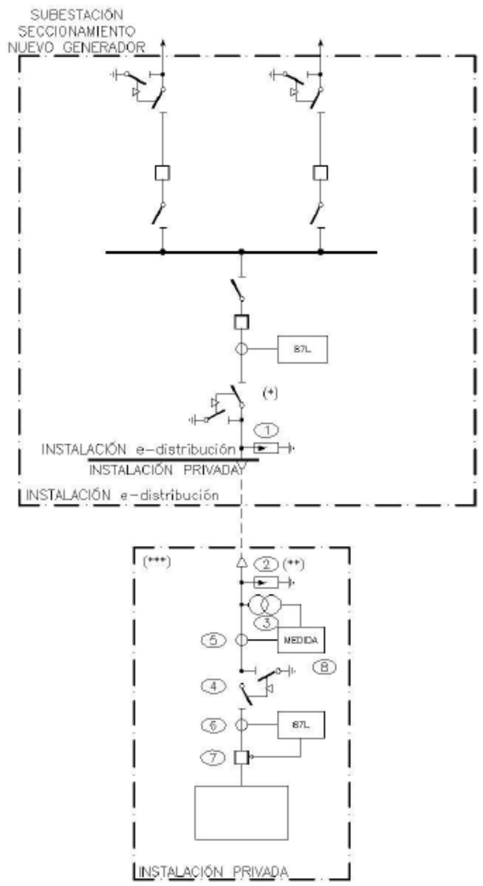
3.2.3.2.2 Spanish technical connection criteria

According to Spanish regulation the generator connection will not be part of the distribution networks. New installations or network extension that will be used by more than one consumer and are carried out directly by the applicant producer, must be transferred to the power distribution utility that will be responsible for its operation and maintenance, safety and quality of supply. Furthermore, the connection position to an existing power substation must be financed by generators and transferred to the utility who owns the substation, which will receive for the same exclusively remuneration for operation and maintenance.

Additionally, the point of connection in the network is the physical point in which is located the border of responsibility of the power distribution company (according to Orden ECO/797/2002). The boundary between the Enel Grids Spain facilities and the private facilities is indicated in the following diagrams of connection:



Connection to an existing Substation



Connection to an existing HV line

Figure 3-11 Enel Grids Spain facilities vs. private facilities

Existing network nodes hosting capacity are always up to date and published at https://www.edistribucion.com/en/red-electrica/Nodos_capacidad_acceso.html

Main Technical parameters:

Nominal Voltage Un (kV)	Maximum hosting capacity per bay (MW)
132	100
110	100
66	60
45	40

Table 3-6 Maximum access capacity to existing facilities

Enel Grids Spain will calculate the values of short-circuit currents between phases and to ground foreseen for the connection point for the purposes of choosing appropriate switchgears and design of the installation.

The facilities will be designed to withstand the maximum short-circuit currents expected, under the most unfavourable operating conditions and taking into account the existing network and the planned development.

Antenna receiver, conversion system and Storage facilities protection systems should be designed in order to ensure the coordination with the Enel Grids Spain network systems, complying with current EU and national legislation, and must be selective with the Enel system. The fine tuning of the protection systems will be defined in each case on a proposal of Enel X / TAS that will be validated by Enel Grids Spain.

Based on regulatory requirements, criteria of reliability and quality of service and for optimal management of the network, all the Enel Grids Spain switch-disconnectors coupled with the ground receiver and storage installation will be remote controlled. Metering system of the generation facility will be designed according to “NRZ104 EP” requirements.

3.3 Trade-offs criteria

The proposed trade-offs will be evaluated on the basis of the following criteria.

3.3.1 General Criteria

- Cost – Relative cost of the proposed solution, VALCOE, LCOE
- Energy expenditure – Energy Returned on Energy Invested across the system lifetime
- Social acceptance – People acceptance of the proposed solutions
- Environmental impact – Carbon footprint of the proposed solutions

3.3.2 Technical Criteria

- Mass / Area / Volume – Physical dimensions of the analysed solutions will be assessed and quoted
- Design Complexity – Streamline of proposed design
- Deployment complexity – How difficult would it be to launch and assemble the SBSP system
- Operational complexity – How difficult would it be to operate, maintain and decommission the SBSP system
- Failure Tolerance – Capability of the solution to withstand to failure and performance degradation
- Capacity factor – How much power can be provided by the solution
- Modularity – Capability of the analyzed solution to be realized with separate parts that, when combined, form a complete whole
- Scalability – Capability of the analyzed solution to be scalable in performance
- TRL / Heritage – Technology maturity of the proposed solution
- Lifetime – Capability of the analyzed solution to comply with the speficified functionalities for the entire lifetime minimizing the maintainability

3.4 Trade-offs execution

This section contains the trade-offs executed and the relevant justifications leading to the reference architecture presented in Section 3.5.

At this stage we have purposely focused on simple solutions that meet the mission requirements, avoiding complexity, as much as possible.

These solutions, mainly based on existing real-world scenarios (e.g., ISS), are expected to include any advantageous improvement deriving from technology evolution in the upcoming years.

3.4.1 Scoring guideline and weight factors

The following scoring guideline has been used for the trade-offs execution:

Criteria	Input value					Description
	1	2	3	4	5	
Cost	Very Bad	Bad	Medium	Good	Very Good	Relative cost of the proposed solution, VALCOE, LCOE
Energy expediture	Very Bad	Bad	Medium	Good	Very Good	Energy Returned on Energy Invested across the system lifetime
Social acceptance	Very Bad	Bad	Medium	Good	Very Good	People acceptance of the proposed solutions
Carbon footprint	Very Bad	Bad	Medium	Good	Very Good	Carbon footprint of the proposed solutions
Mass / Area / Volume	Very Bad	Bad	Medium	Good	Very Good	Physical dimensions of the analysed solutions will be assessed and quoted
Design Complexity	Very Bad	Bad	Medium	Good	Very Good	Streamline of proposed design
Deployment complexity	Very Bad	Bad	Medium	Good	Very Good	How difficult would it be to launch and assemble the SBSP system
Operational complexity	Very Bad	Bad	Medium	Good	Very Good	How difficult would it be to operate, maintain and decommission the SBSP system
Failure Tolerance	Very Bad	Bad	Medium	Good	Very Good	Capability of the solution to withstand to failure and performance degradation
Capacity factor	Very Bad	Bad	Medium	Good	Very Good	How much power can be provided by the solution
Modularity	Very Bad	Bad	Medium	Good	Very Good	Capability of the analyzed solution to be realized with separate parts that, when combined, form a complete whole
Scalability	Very Bad	Bad	Medium	Good	Very Good	Capability of the analyzed solution to be scalable in performance
TRL / Heritage	Very Bad	Bad	Medium	Good	Very Good	Technology maturity of the proposed solution
Lifetime	Very Bad	Bad	Medium	Good	Very Good	Capability of the analyzed solution to comply with the speficified functionalities for the entire lifetime minimizing the maintainability
Industrial capability/scalability	Very Bad	Bad	Medium	Good	Very Good	In terms of logistic (technological reasons vs. geopolitical location) and industrial supply

Table 3-7 Trade-offs scoring guideline

The following weight factors have been used for the trade-offs execution:

Weight factors		
Criteria	**Weight factor value**	**Justification**
Cost	5	Cost are considered important for mission feasibility but less critical than other criteria (e.g. social acceptance) ref. TN1
Energy expediture	3	This is linked with cost and the same weight factor has been applied
Social acceptance	5	This criterion was indicated by all the stakeholders as the most critical for SBSP applications (see TN1)
Carbon footprint	5	High criticality has been assigned to carbon footprint considering the size of the system. Environmental impact importance has been highlighted both by ESA SoW and by the stakeholders
Mass / Area / Volume	5	The SBSP mission feasibility is strongly dependend on this criterion which depends on the architecture and technologies selected
Design Complexity	3	All the SBSP concepts exhibit considerable design complexity. This complexity need to be minimized but has been considered of medium criticality, provided that the feasibility is granted
Deployment complexity	3	The SBSP system deployment is considered highly critical for mission feasibility. There is a strong impact in terms of launcher performances
Operational complexity	3	The operational complexity has been considered critical in particular for safety reasons
Failure Tolerance	2	The failure tolerance has not been considered particularly critical since an highly reliable and efficient support IOS system is foreseen
Capacity factor	4	The power provided by the solution has been considered important by the stakeholders and for economical feasibility
Modularity	4	The modularity has been considered quite critical considering the size of the system and the need of assembling it in-orbit
Scalability	4	The scalability of the performance has been considered quite critical considering the need to develop a demonstrator
TRL / Heritage	1	Considering only the scalability required of already existing technologies and the timeframe available for technology improvements the TRL has been considered not critical
Lifetime	4	Lifetime has been considered critical for the required operations of 30 years and the competition with alternative energy solutions
Industrial capability and scalability	3	The industrial capability and scalability have been considered of medium criticality

Table 3-8 Weight factors

3.4.2 Space Segment trade-offs

3.4.2.1 Trade tree pruning and development

The trade-off tree presented in Section 3.1.2 (previously introduced in SKR, derived from a first functional analysis) serves as an excellent initial framework for outlining the trade-space. However, it was necessary to carry out a preliminary pruning to facilitate subsequent development work on possible design paths.

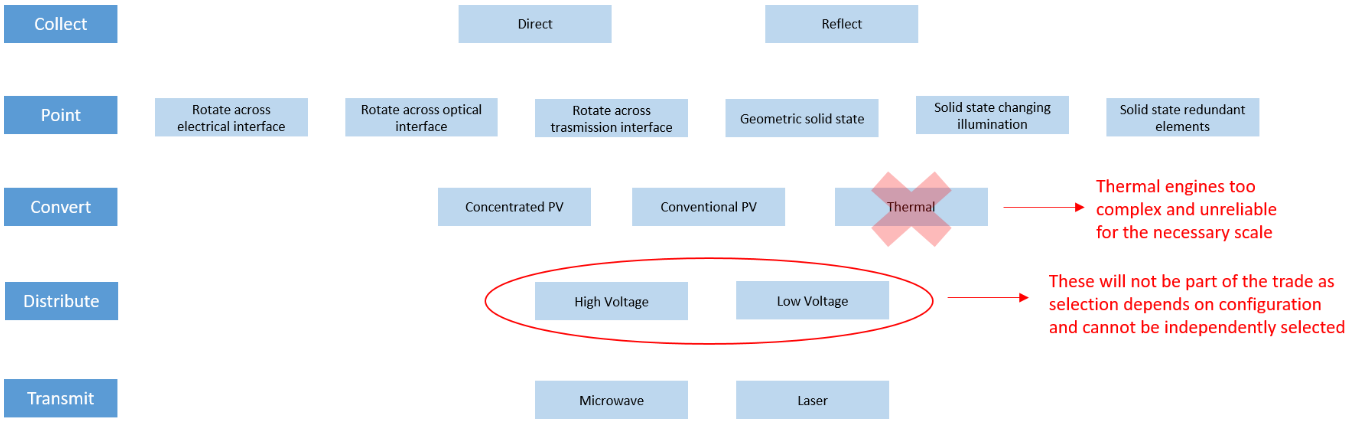


Figure 3-12 Trade tree preliminary pruning

Three different trees will be subsequently proposed based on the viable paths and traded-off (with the goal to select in Section 3.5 the proposed baseline tree).

For the selection of the transmission function, the following considerations hold. Two options are essentially possible for the wireless power transmission, i.e., either microwave or laser. The laser option is discarded for the following well-known disadvantages that affect laser power beaming [see, e.g., RD21]:

- The laser option is affected by climatic conditions, like rain and clouds, and hence it is unable to deliver continuous electricity thus violating the SBSP system requirement UR-REQ-0110 (constant power provision), reported in Section 2.4 of TN1 - Stakeholder Expectation Report
- The laser option has a limited conversion efficiency and requires massive battery storage systems
- If not properly treated the laser presents high risks, in terms of skin and eye damage

According to the updated trade-off tree, all possible combinations were analysed following a secondary pruning of technically incompatible alternatives. This approach allows a high-level observation of all possible solutions to obtain a complete picture of the SBSP architecture trade-space.

Collect	Point	Comment
Direct	Across Electrical	MR-SPS type
	Across Optical	No optical interface with direct illumination
	Across Transmission	Abacus type
	SS Electrical	e.g. "end on" CASSIOPeiA
	SS Changing Illumination	Flat panel concepts
	SS Redundant	Tin can and others
Reflect	Across Electrical	Theoretically possible, no extant designs
	Across Optical	SPS Alpha type
	Across Transmission	Theoretically possible, no extant designs
	SS Electrical	CASSIOPeiA
	SS Changing Illumination	Difficult to think of a geometry. Would imply illumination of reflector is changing, but this means reflectance angles keep changing and therefore convert system would need to keep moving relative to reflector, so not SS (becomes rotation across optical)
	SS Redundant	SPS Alpha has elements of this, as its reflectors are redundant. As with changing illumination, fixed reflectors can't be redundant as changing illumination would change reflection angle necessitating PV to move. If sun pointing with constant illumination, cant reflect onto an earth pointing surface.
Convert	**Point**	**Comment**
CPV	Across Electrical	Possible - No extant designs. Probably requires sun pointing with 3 DoF
CPV PV	Across Optical	Possible but complex. Probably needs 3 DoF reflector steering. For instance, SPS-Alpha has non-constant illumination of the PV due to differing angles of the heliostats (?). SPS-Alpha solution with CPV not possible as reflector diameter is much larger than convert diameter meaning there will always be an angle of incidence on the convert from heliostats outside the diameter of the convert panel.
	Across Transmission	Possible, probably requires 3 DoF
	SS Electrical	CASSIOPeiA
	SS Changing Illumination	Changing illumination angle makes CPV infeasible
	SS Redundant	Possible is redundant element is the phased array antenna. Not possible with redundant PV
	Across Electrical	MR-SPS type
PV	Across Optical	SPS-Alpha
	Across Transmission	Abacus
	SS Electrical	CASSIOPeiA normal PV option
	SS Changing Illumination	Flat panel solutions
	SS Redundant	Tin can

Table 3-9 First tree couplings pruning

The red boxes highlight the technically unfeasible couplings in order to have a deeper look only on possible paths of the tree.

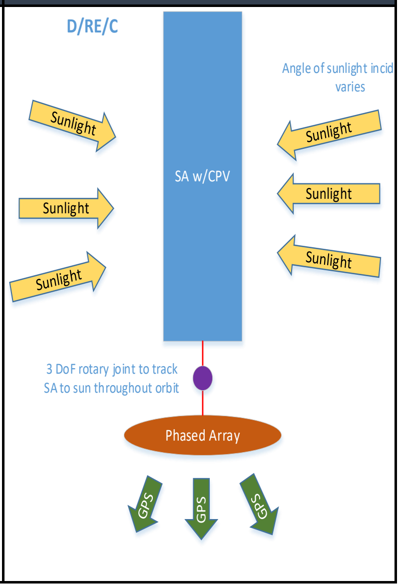
Every feasible tree path was then developed (as shown in the next table) and all the corresponding final solutions result in a comment with possible advantages and problems of that concept type. Furthermore, for each possible development, it is specified whether a concept already exists, whether it could be a probable solution or whether there is currently no solution with clear feasibility.

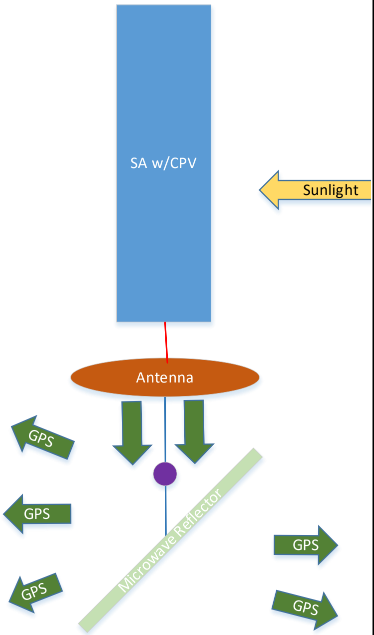
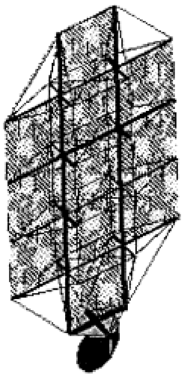
Solutions are described with specific reference to a couple of key system aspects that can affect the feasibility, namely:

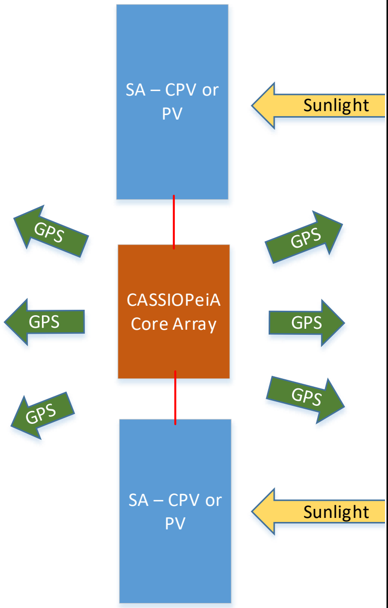
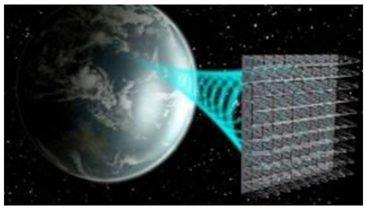
- If the concept is likely to require the use of high voltage (HV) distribution or can make use of low voltage (LV) distribution
- If the system overall can be considered Sun aligned or Earth aligned. This can have an impact on whether a system can be gravity gradient stabilised

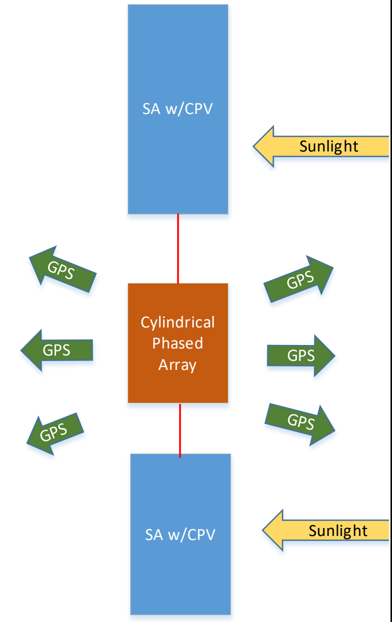
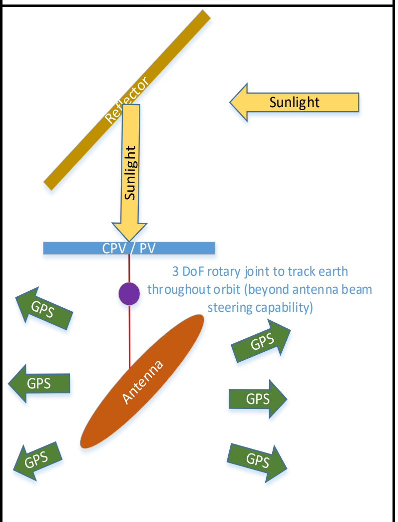
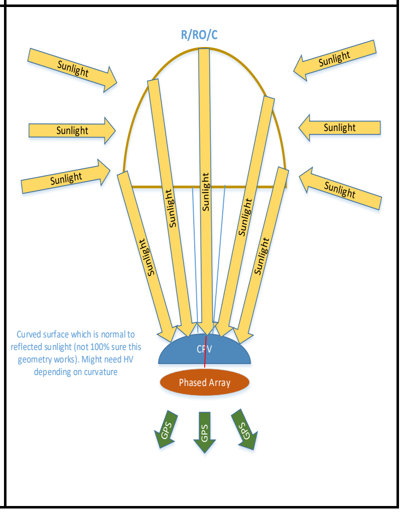
It is important to note that the diagrams in the table illustrate a possible solution for the concept. There may be other solutions as well, but these are illustrated to show that there is at least one concept that can be constructed. Each concept is given an hybrid ID indicating its combination of tree elements.

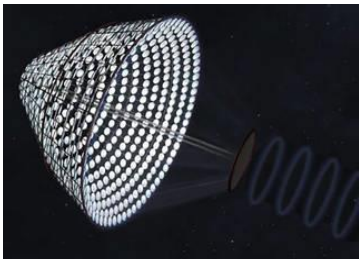
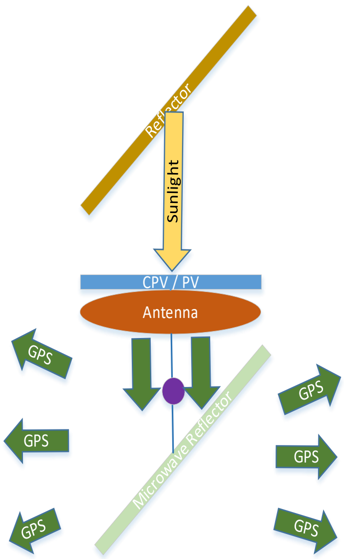
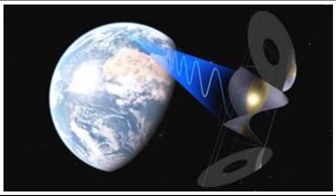
	Extant Solution	
	Probable Solution	
	No clear solution (not traded now)	

Collect	Point	Convert	ID	Example	Comment	
(D) Direct	**(RE) Across Electrical**	**CPV**	D/RE/C		Consider a MR-SPS type concept (or solar tower type), kept aligned with the sun within the acceptance angle of the CPV throughout orbit (i.e. create 100% "illumination efficiency"). It would need 3 DoF steering to maintain pointing. High Voltage (HV) distribution is always needed as large directly illuminated panels need to consolidate electrical supply across the rotation interface so supply the antenna. Alignment needs to keep the antenna aligned with the Earth and the PV well aligned with the sun	

		PV	D/RE/P	MR-SPS / SailTower / NASA 1979	HV always needed as large directly illuminated panels need to consolidate electrical supply across the rotation interface so supply the antenna. For alignment, the rotational aspect tries to keep the PV aligned with the Sun and the antenna aligned with the Earth. For a simple system with fewer degrees of freedom, the guiding alignment is likely to be the Earth, with the PV at varying angles to the sun throughout the orbit	
	(RT) Across Transmission	**CPV**	D/RT/C		Similar to rotation across electrical, this would need a microwave reflector with 3 DoF to keep CPV pointed directly at the sun. As with rotation across electrical, direct illumination requires large solar arrays the output of which needs to be consolidated in a single antenna, resulting in long distance power transmission and HV distribution. Unclear if phased array can be used with microwave reflector (as reflection might destroy phase coherence). Even if it can, it will probably make retrodirective steering impossible, so will need very high accuracy knowledge and control of position, attitude and GPS direction	
		PV	D/RT/P	Abacus	Abacus would need HV distribution, as with CPV, direct illumination like this requires long transmission. The alignment philosophy here keeps the bulk of the system aligned with the sun, and the microwave reflector points the beam towards the Earth	

	(SE) SS Electrical	**CPV**	D/SE/C		This could be seen as a side illuminated CASSIOPeiA. 360° steerable antenna but with PV oriented 90° to antenna base panels. TBD if there is a workable configuration like this. An obvious feasible config is a CASSIOPeiA antenna, with reflectors replaced by solar arrays with HV distribution to the antenna. Earth pointing is done electrically in this scheme so the platform as a whole would be sun aligned.	
		PV	D/SE/P		As above, but with regular PV panels.	
	(SC) SS Changing Illumination	**PV**	D/SC/P	Tethered SPS / USA Caltech	The whole system is sun aligned and illumination angles wrt sun are allowed to evolve as the system orbits the Earth. Low Voltage (LV) distribution is possible as the whole design could be one flat panel with PV on one side and antenna on the other	
	(SR) SS Redundant	**PV**	D/SR/P	Tin Can	An alternative solution to a Tin Can type is to have a redundant antenna instead of redundant PV. Cylindrical phased array with flat solar array pointed at the sun. In directly illuminated form this needs HV distribution as the two elements need to be separate. Alignment depends on which element is redundant. LV could be possible in a totally redundant scenario where PV and antenna are colocated on a cylinder, but HV in other scenarios	

		CPV	D/SR/C		Needs to be redundant phased array rather than redundant photovoltaics as CPV illumination angle needs to be constant and Sun pointed.	
(R) Reflect	**Across Electrical**	**CPV**	R/RE/C		These solutions probably need to be Sun pointed with steerable antenna. Need to use reflector to create a collimated light beam onto a CPV surface, both of which have fixed relationship with the sun. Antenna can then be steered towards GPS. Consolidation of electrical link across rotaing interface needs HV	
		PV	R/RE/P		Would be very similar solutions to above but with regular PV instead of CPV	
	(RO) Across Optical	**CPV**	R/RO/C		Earth Pointed. Need to use steerable reflectors to create a collimated light beam onto a CPV surface and antenna that is fixed wrt the Earth. Like SPS alpha but collimated. More specific SPS alpha comparison would be to replace flat SPS alpha PV array with domed (or otherwise shaped) surface whose surface is at a normal to the reflected light beams. TBD if this kind of alteration is possible. Could in theory retain LV power distribution.	

		PV	R/RO/P	SPS Alpha	SPS is Earth aligned with the sun tracked by heliostats. The combination of PV and phased array in one place allows for LV distribution.	
	Across Transmission	**CPV**	R/RT/C		Sun pointed. Can envisage a CASSIOPeiA type arrangement with PV/Antenna panel(s) illuminated by 45° reflector. Centre of the CASSIOPeiA core is replaced by a 360° steerable reflector. PV and antenna colocated for LV power. Feasibility of maintaining phase of reflected beam TBD as noted in the direct illumination solutions. As transmitter doesn't need to be electrically steerable, could use a parabolic antenna, but this would create very stringent mechanical steering constraints.	
		PV	R/RT/P		As above but with PV instead of CPV	
	SS Electrical	**CPV**	R/SE/C	CASSIOPeiA	CASSIOPeiA is sun aligned. Co-location of PV and antenna elements allows LV distribution	
		PV	R/SE/P	CASSIOPeiA	CASSIOPeiA variant with PV instead of CPV	
	SS Redundant	**CPV**	R/SR/C		Reflector onto flat CPV/PV panel which is then connected to a cylindrical phased array (redundant).	

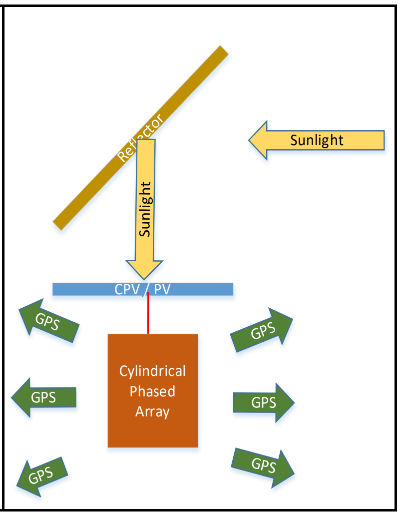
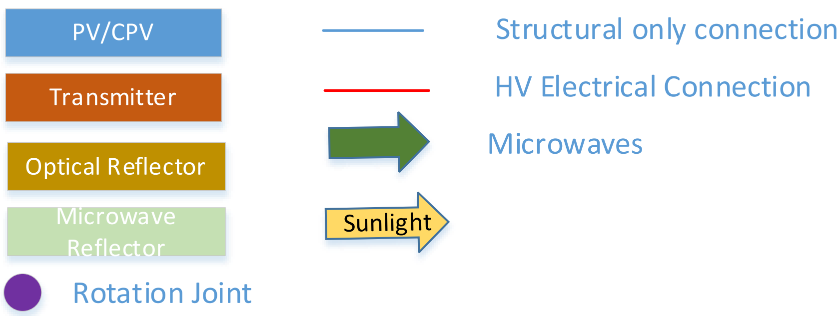
		PV	R/SR/P		Like CASSIOPeiA but with a cylindrical phased array and the PV collapsed into a circle at either end of the helix. This is likely to require HV distributions and is Sun aligned.	

Table 3-10 Trade tree development

The diagrams in Table 3-10 use the following conventions to help highlight the particular features



- **Cost**: Relative CAPEX assessed cost with respect to known benchmarks in literature that are in the trade-space. Concepts are assessed as likely to be more costly / less costly than existing baselines based on specific similarities / differences. Note this trade is **not** done wrt to LCOE, as relative assessments are complex, and take into account e.g. mass / capacity factor, which would mean double counting. LCOE comparative costs are expected to be captured by the trade-off as a whole, as the relative assessments are done at a fixed energy level (1GW)
- **Energy expenditure**: Not distinguishing between solutions at this level – at this concept level its not feasible to directly assess the energy required to design, manufacture, launch and build a particular SPS, so it would be done by proxy via mass and complexity assessments. These are captured in dedicated criteria.
- **Social acceptance**: Not distinguishing between solutions, all elements are space based and don't imply different ground infrastructure or frequencies that may significantly affect social acceptance.
- **Carbon footprint**: At this level of concept definition, amount of launches drives this, and is therefore mostly related to mass and deployment complexity. These are captured as specific criteria.
- **Mass / Area / Volume**: In this case, assumed mass of an individual solution relative to known masses within the trade-space (i.e. more massive than / less massive than)

- **Design Complexity**: Complexity of technologies involved to be developed for each concept. This is assessed through assessing the number of complex elements a solution has, and then scoring accordingly.
- **Deployment Complexity**: Relative complexity of deployment for different concepts. Driven by overall scale of a concept, and the geometry. Scale is benchmarked against known concept values in literature, as with mass and cost.
- **Operational Complexity**: For SPS alone, this is measured as the pointing and alignment challenges. Namely, how difficult it is to align the concept PV with the sun, how difficult it is to align the antenna with the GPS (assuming some degree of electronic steering in some solutions) and how difficult is any internal alignment required to maintain operation.
- **Failure tolerance**: How many elements does the concept have that may have higher failure rates / lower lifetimes. Broadly elements that affect this are; moving parts, potential redundancy of those moving parts, use of high voltage elements that have the potential to degrade faster.
- **Capacity factor**: Can the solution provide continuous power at a consistent level (excepting for eclipses that will be common to all concepts)
- **Modularity:** Do particular concepts lend themselves to modularization better than others? Factors that affect this are regularity of structures, simple geometries, nuber of distinct different functional elements (e.g solutions that combine PV and antenna into one modular structure score well, those with separate PV / antennas / reflectors score lower)
- **Scalability**: Ability to scale from low powers (MWs) to high powers (GWs), this has two contributions, one from the ability to simple scale the system physically, the other to operate in different orbits (as it is not feasible to e.g. operate a MW system from GEO due to beam powers and geometries)
- **TRL / Heritage**: Do the concepts carry more heritage? This is assed with respect to the number of identified low TRL technologies per concept and scored accordingly.
- **Lifetime**: Not assessed separately here as covered by Failure tolerance, i.e. a good failure tolerance means higher lifetime
- **Industrial capability/ scalability**: Not assessed at this level, as rational for scoring is the same as modularity rather than capability for individual components

Table 3-11 SPS shows the summary of the trade-off for all 19 concepts.

Criteria	Applicability [N/A= 0, Applicable = 1]	Weight Factor [1-5]	Applicability * Weight Factor	OPTION 1		OPTION 2		OPTION 3		OPTION 4		OPTION 5		OPTION 6		OPTION 7		OPTION 8		OPTION 9	
				D/RE/C		D/RE/P		D/RT/C		D/RT/P		D/SE/C		D/SE/P		D/SC/P		D/SR/P		D/SR/C	
				Input [1- 5]	Value [Weight Factor * Input]	Input [1- 5]	Value [Weight Factor * Input]	Input [1- 5]	Value [Weight Factor * Input]	Input [1- 5]	Value [Weight Factor * Input]	Input [1- 5]	Value [Weight Factor * Input]	Input [1- 5]	Value [Weight Factor * Input]	Input [1- 5]	Value [Weight Factor * Input]	Input [1- 5]	Value [Weight Factor * Input]	Input [1- 5]	Value [Weight Factor * Input]
Cost	1	5	5	1	5	3	15	1	5	1	5	3	15	4	20	5	25	2	10	2	10
Energy expediture	0	3	0																		
Social acceptance	0	5	0																		
Carbon footprint	0	5	0																		
Mass / Area / Volume	1	5	5	2	10	3	15	1	5	1	5	4	20	4	20	2	10	3	15	3	15
Design Complexity	1	3	3	2	6	3	9	1	3	3	9	2	6	3	9	5	15	5	15	3	9
Deployment complexity	1	3	3	5	15	4	12	5	15	4	12	2	6	1	3	4	12	2	6	2	6
Operational complexity	1	3	3	3	9	4	12	1	3	2	6	4	12	4	12	5	15	3	9	5	15
Failure Tolerance	1	2	2	2	4	2	4	1	2	1	2	3	6	4	8	5	10	4	8	4	8
Capacity factor	1	4	4	5	20	5	20	5	20	5	20	5	20	5	20	0	0	5	20	5	20
Modularity	1	4	4	5	20	5	20	4	16	4	16	3	12	3	12	5	20	4	16	4	16
Scalability	1	4	4	5	20	5	20	3	12	3	12	4	16	4	16	2	8	3	12	3	12
TRL / Heritage	1	1	1	4	4	5	5	2	2	3	3	2	2	3	3	5	5	2	2	3	3
Lifetime	0	4	0																		
Industrial capability/scalability	0	3	0																		
TOTAL SCORE					3.32		3.88		2.44		2.65		3.38		3.62		3.53		3.32		3.35

Criteria	Applicability [N/A= 0, Applicable = 1]	Weight Factor [1-5]	Applicability * Weight Factor	OPTION 10		OPTION 11		OPTION 12		OPTION 13		OPTION 14		OPTION 15		OPTION 16		OPTION 17		OPTION 18		OPTION 19	
				R/RE/C		R/RE/P		R/RO/C		R/RO/P		R/RT/C		R/RT/P		R/SE/C		R/SE/P		R/SR/C		R/SR/P	
				Input [1- 5]	Value [Weight Factor * Input]	Input [1- 5]	Value [Weight Factor * Input]	Input [1- 5]	Value [Weight Factor * Input]	Input [1- 5]	Value [Weight Factor * Input]	Input [1- 5]	Value [Weight Factor * Input]	Input [1- 5]	Value [Weight Factor * Input]	Input [1- 5]	Value [Weight Factor * Input]	Input [1- 5]	Value [Weight Factor * Input]	Input [1- 5]	Value [Weight Factor * Input]	Input [1- 5]	Value [Weight Factor * Input]
Cost	1	5	5	1	5	1	5	2	10	4	20	1	5	1	5	3	15	4	20	3	15	4	20
Energy expediture	0	3	0																				
Social acceptance	0	5	0																				
Carbon footprint	0	5	0																				
Mass / Area / Volume	1	5	5	3	15	3	15	2	10	3	15	2	10	2	10	4	20	4	20	3	15	3	15
Design Complexity	1	3	3	1	3	2	6	2	6	4	12	1	3	2	6	2	6	3	9	1	3	2	6
Deployment complexity	1	3	3	4	12	5	15	1	3	1	3	5	15	5	15	4	12	4	12	4	12	4	12
Operational complexity	1	3	3	2	6	3	9	2	6	3	9	1	3	2	6	2	6	3	9	2	6	3	9
Failure Tolerance	1	2	2	1	2	1	2	3	6	4	8	2	4	2	4	5	10	5	10	4	8	4	8
Capacity factor	1	4	4	5	20	5	20	5	20	5	20	5	20	5	20	5	20	5	20	5	20	5	20
Modularity	1	4	4	2	8	2	8	3	12	4	16	3	12	3	12	2	8	2	8	2	8	2	8
Scalability	1	4	4	3	12	3	12	3	12	4	16	2	8	2	8	3	12	3	12	5	20	5	20
TRL / Heritage	1	1	1	2	2	3	3	2	2	3	3	1	1	2	2	2	2	3	3	2	2	3	3
Lifetime	0	4	0																				
Industrial capability/scalability	0	3	0																				
TOTAL SCORE					2.50		2.79		2.56		3.59		2.38		2.59		3.26		3.62		3.21		3.56

Table 3-11 SPS concept trade-off summay

For further details on concept trade-off refer to A.1.

Table 3-12 simplifies the concept ranking and highlights the concept against the extant solutions

D/RE/P	3.88	MR-SPS / NASA 1979 / Sun tower
D/SE/P	3.62	side illuminated CASSIOPeiA with regular PV
R/SE/P	3.62	CASSIOPeiA with PV
R/RO/P	3.59	SPS-Alpha
R/SR/P	3.56	
D/SC/P	3.53	Tethered-SPS / Caltech / Virtus Solis?
D/SE/C	3.38	
D/SR/C	3.35	
D/RE/C	3.32	
D/SR/P	3.32	
R/SE/C	3.26	
R/SR/C	3.21	
R/RE/P	2.79	
D/RT/P	2.65	
R/RT/P	2.59	
R/RO/C	2.56	
R/RE/C	2.50	
D/RT/C	2.44	
R/RT/C	2.38	

Table 3-12 SPS concept ranking

The outcome of the trade-off points towards a conceptual solution similar to those developed as part of the NASA architectural studies and the Chinese MR-SPS solution, that is an array of non-concentrator solar panels, rotated mechanically to track the sun, with an Earth pointed phased array antenna, electrically steered to point the beam to the GPS.

There is however, a reasonably close grouping at the top of the table that covers also a CASSIOPeiA and an SPS-Alpha type concepts

This is telling, as these 3 types of solutions are ones with the most study history and heritage within the SPS trade-space, indicating that perhaps they have advanced to their current prominence because they **do** represent the best solutions out of the defined trade-space. This result gives confidence to the outcome of the trade. Argument could be made that they rise to prominence here simply because they are the best defined solutions with the most reference material available, but this doesn't necessarily imply they would score highly, as more detailed dives into concepts often turn up more issues than immediately apparent, so they could just as easily have sunk lower in the rankings due to more detailed definition.

Closer inspection of the trade results shows some of the sensitivity of the selection to the various scorings and weightings within the trade. Understandably, the critical ratings are for the cost / mass criteria, and so the outcome is highly sensitive to the relative masses of the concepts. Of the 4 highest scoring solutions, R/SE/P solutions (CASSIOPeiA like) are understood to have the lowest mass / kW based on available information. The mass of the D/RE/P type (NASA/ MR-SPS) is usually understood to be the highest of the 3 solutions. The key here is that it has been assessed as part of this study that it is likely that the mass of a D/RE/P type could feasibly be reduced down to something that matches an R/RO/P type (SPS-Alpha), whilst the lack of available information on R/SE/P solution mass breakdown doesn't lead to confidence that the mass of that type of solution won't significantly increase. Adjustment of the scoring to better reflect the publically available mass numbers (i.e. reducing D/RE/P to 2 instead of 3 for mass and cost) makes the trade inconclusive as D/RE/P, R/SE/P and R/RO/P are separated by a score of only 0.02.

Sensitivity to the weightings is limited, as the heaviest weightings are already applied to mass and cost, where D/RE/P is the lowest scoring of the top scoring selection, so reducing the weighting of this with respect to other criteria will only strengthen the distinctions between the solutions at the top of the table.

It's worth noting that CPV based solutions scored lower. This is possibly because there is uncertainty in each solution as to the benefit to mass / cost / scale for each different concept from the increased complexity, and so the relative costs of CPV are captured better, and more frequently throughout the trade, than the relative benefits it brings. For the selected concept, CPV should not therefore be completely dismissed, but the increased complexity added to designs that require mechanical sun pointing for CPV mean PV is likely to be the best option in these instances. In contrast, for a solid state solution like D/SE/C, the fixed relationship between the platform and the sun makes the introduction of CPV more a mass vs. efficiency trade than an added complecity one.

As a result of this trade, three architectures, illustrated with their corresponding tree path, are defined:

- **Architecture 1a**

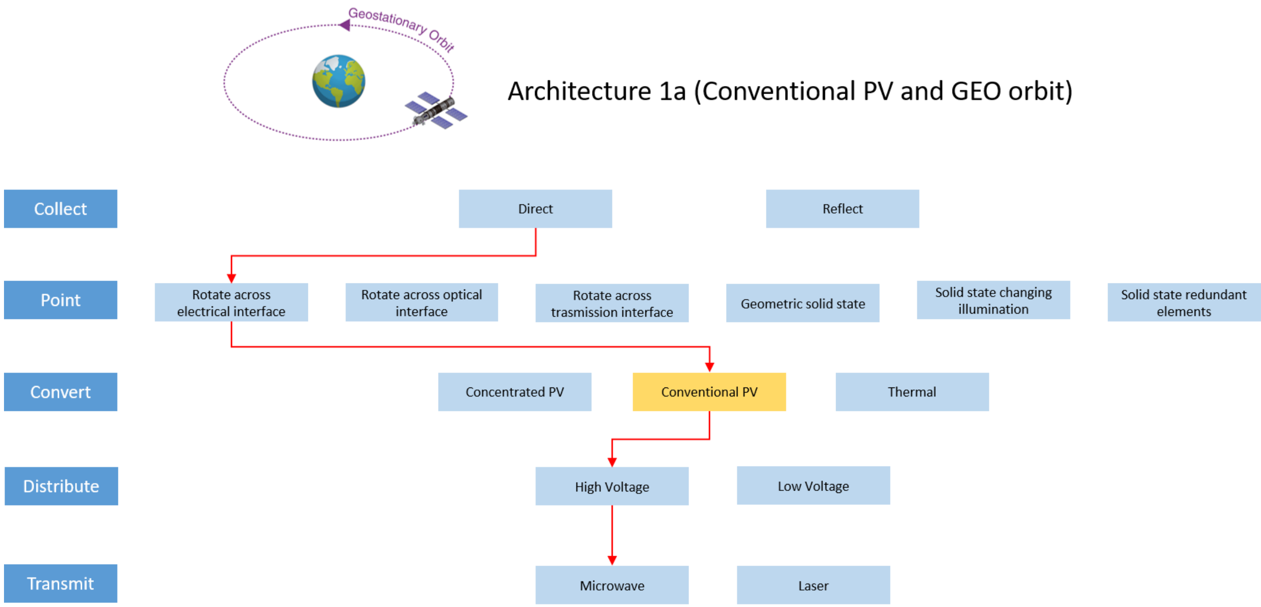


Figure 3-13 Trade tree path for Architecture 1a

- **Architecture 1b**

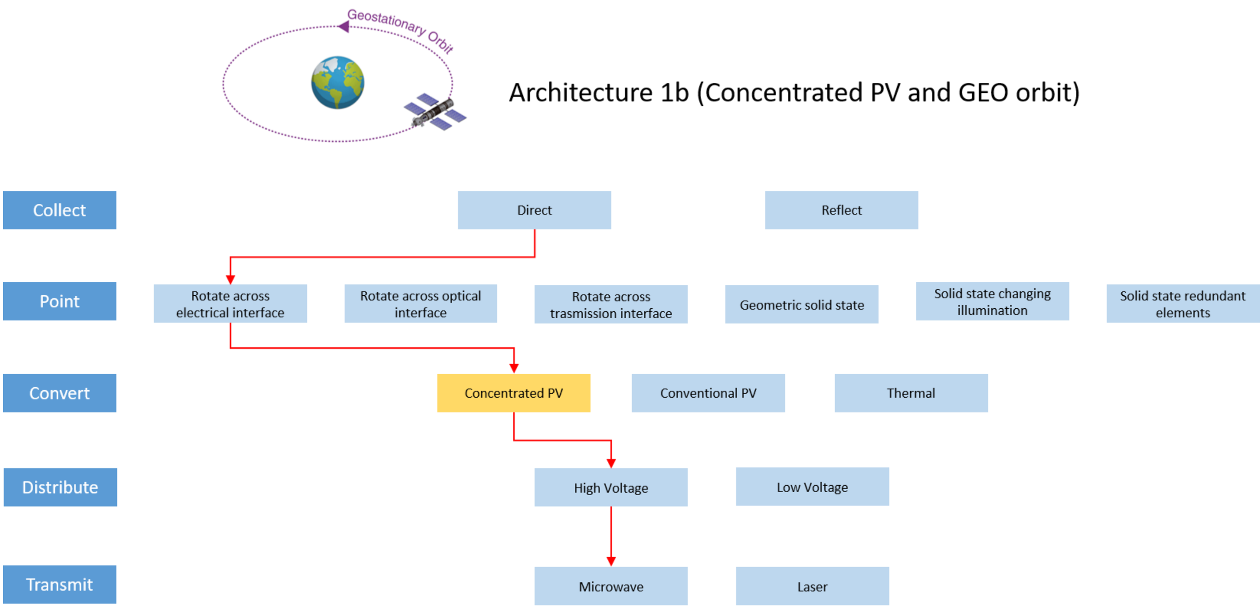


Figure 3-14 Trade tree path for Architecture 1b

- **Architecture 2**

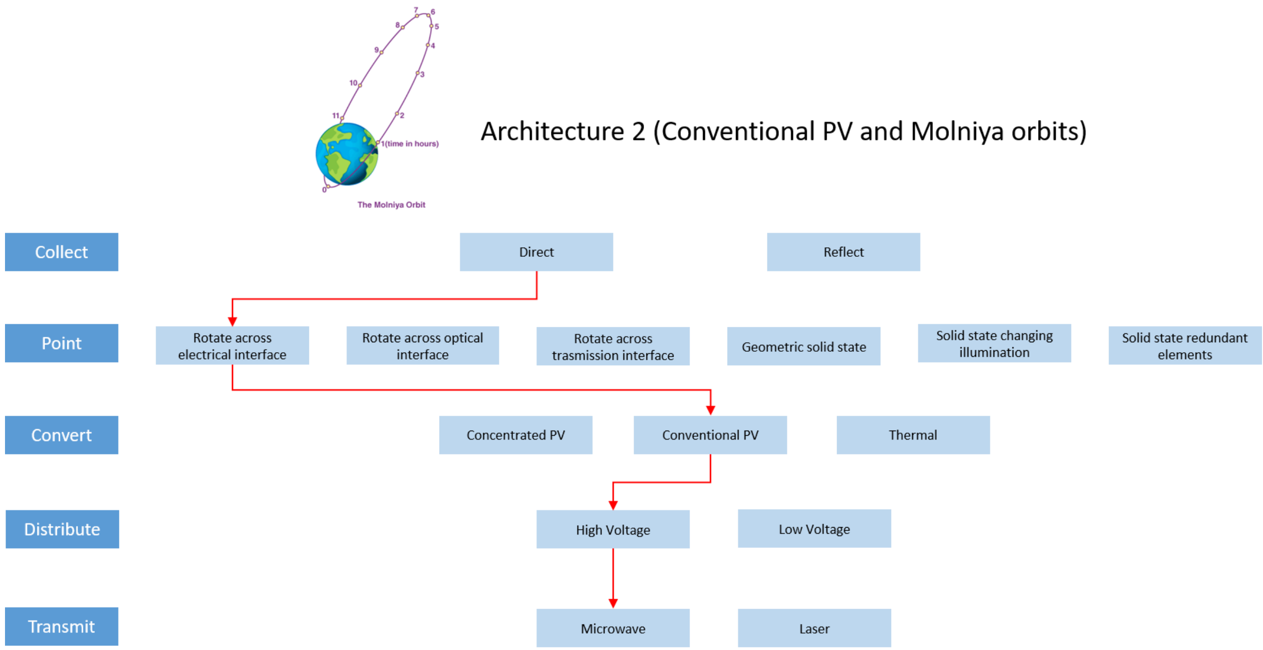


Figure 3-15 Trade tree path for Architecture 2

The following trade-offs were performed to define the best architecture for the purpose and in order to better delineate some high-level aspects (space segment and ground segment) of the selected one.

3.4.2.2 Overall approach and mathematical model

The sizing of the structures is of the uttermost importance due to the huge dimensions involved. All the energy production chain has been inserted and evaluated through an optimization model in order to minimize the GPS, SPG and antenna areas considering constraints of energy production and safety.

The efficiencies considered are the ones listed in Table 3-13. They take into account the power loss at every step.

Solar power generator efficiency	η_{SPG}
WPT efficiency	η_{WPT}
GPS efficiency	η_{GPS}

Table 3-13 Efficiencies in the energy production chain

At every step the energy transmitted is decreased by the factor specified by these efficiencies

$$P_{AC} = \eta_{SPG}\eta_{WPT}\eta_{GPS}G_{SC}A_{PV},$$

where P_{AC} is the output power of the ground power station, G_{SC} is the solar constant of $1361\ W/m^2$ and A_{PV} is the solar panels area.

The efficiencies can be further split into several different factors:

- **SPG efficiency**
  - **Photovoltaic (solar) cell efficiency:** the efficiency of a photovoltaic cell is the percentage of incident power that the cell can convert into electricity

    The efficiency can be reduced by several phenomena:

    1. Modification in efficiency due to voltage variation with the cell temperature. The hotter, the lower the efficiency.
    2. Reduced efficiency with space radiation doses.
    3. Degradation of certain photovoltaic cell technologies by UV light.
    4. Degradation by micro-meteors.

    In the model we considered this value to be 0.36, but it could vary depending on the technology chosen.
  - **Solar panel surface efficiency:** the solar panel is the structural element which mechanically supports the photovoltaic cells and which mechanically interfaces with the other solar panels. The panel also supports the first electrical wiring connecting the cells. This efficiency is the ratio of the area of all photovoltaic cells to the total area of the solar panel. It takes into account the surface of the panel which is lost according to the shape and the type of assembly of the cells on the panel. We estimated it to be about 0.86.
  - **Illumination efficiency:** this is the ratio of the surface intercepting the solar flux on the surface of the panel. It depends of the angle of arrival (or elevation) of the solar rays on the panels. This parameter characterizes the good orientation of the solar panels towards the sun. It is a variable parameter over time. We will take an average value over a year. In GEO, we assume that the Solar Power Generator (solar panels) revolves around the North/South axis to always face the sun. It rotates at the rate of one full rotation per day. The Solar Power Satellite being in the celestial or equatorial equator, the perpendicular to the plane of the solar panels is in the equatorial plane, the angle of arrival of the sun rays is then the sun declination. The ecliptic plane is the orbital plane of Earth around the Sun; it is inclined to the equatorial plane by an angle of 23.4°. Consequently the angle of arrival of the sun's rays on the solar panels varies with the declination of the sun. The average value is about 0.96.
  - **Power line efficiency:** this loss is due to

    1. an electrical wiring that connects the photovoltaic cells inside a solar panel,
    2. another electrical wiring connecting the solar panels to the Solar Power Generator interface,
    3. a third electrical wiring that connects the SPG and the Wireless Power Transfer.

    We considered it to be about 0.99.

- **Power conditioning efficiency:** to reduce the losses in all the electrical wirings, we can choose different types of current (DC or AC), voltages and intensities to transmit electrical power in each wiring. Power conversion and conditioning devices are cleverly installed in the wiring assemblies. Current/voltage converters (DC/DC, DC/AC or AC/DC) can be implemented between the three wirings to conduct electricity with different voltage and type of current. This allows to reduce the ohmic losses, to optimize the mass and section of the wires. This is the global efficiency of power conversion and conditioning that could take place inside the Solar Power Generator. We set it to be 0.98.

- **WPT efficiency**
  - **Efficiency of the power distribution network**: This is the power line efficiency of the power distribution network inside the WPT. The electric power distribution network feeds the EPC of the EM power generators with the electric power provided by the Solar Power Generator. We estimated it to be about 0.98.
  - **Antenna efficiency:** Antenna efficiency is the ratio of the power radiated by an antenna to the power fed to the port of the antenna. It includes the ohmic and matching losses of the radiating element or sub-antenna. We estimated it to be about 0.99.
  - **RF power generator efficiency (DC-RF):** this is the efficiency of the EM power generator. It is the ratio of the EM generated power and the consumed DC power. The EM power generators generate EM power from the electrical power provided by the Solar Power Generator. We considered in the mathematical model adopted the SSPA technology which can provide an efficiency around 0.83-0.87, but that can change slightly with the frequency of the RF (also considering an additional efficiency of around 0.95 for the correspondant EPC)
  - **Beam efficiency:** this takes into account the diffraction effect and the consequent shape of the intensity profile on the ground. Indeed, SBSP operating at frequencies under 10 GHz (2.45, 5.8 GHz) requires a very large antenna. Diffraction generates secondary lobes or beams in the pattern. The intensity profile is given by the formula:

$$I(D_{tx}, D_{rx}, \lambda, d) = \frac{P_0 \pi D_{tx}^2}{4\lambda^2 d^2} \left[\frac{2J_1\left(\frac{\pi D_{rx} D_{tx}}{2\lambda d}\right)}{\frac{\pi D_{rx} D_{tx}}{2\lambda d}} \right]^2,$$

where D_{tx} and D_{rx} are the diameters of the GPS and of the antenna, λ is the wavelength, d is the distance between the antenna and the GPS, P_0 is the total power that reaches the ground and $J_1(x)$ is a Bessel function of the first kind of first order (“*Principles of Optics”, M.Born, E.Wolf, Cambridge University Press, 1999)*. It is plotted in Figure 3-16.

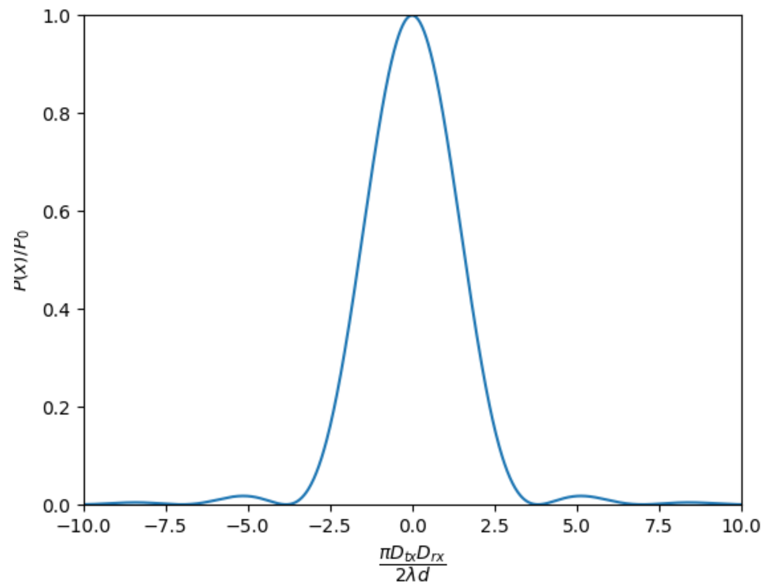


Figure 3-16 Intensity profile due to diffraction

The power distribution in the lobes is given by the following formula:

$$P(x) = P_0\,[1 - J_0^2(x) - J_1^2(x)],$$

where $x = \frac{\pi D_{rx} D_{tx}}{2\lambda d}$ and J_0 is a Bessel function of the first kind of order zero. It is plotted in Figure 3-17.

The intensity of the beam is maximum at the centre and it decreases as we move far from it, until we reach a point where it drops to zero: this is the first null. Then it increases and decreases again, reaching a second null and so on.

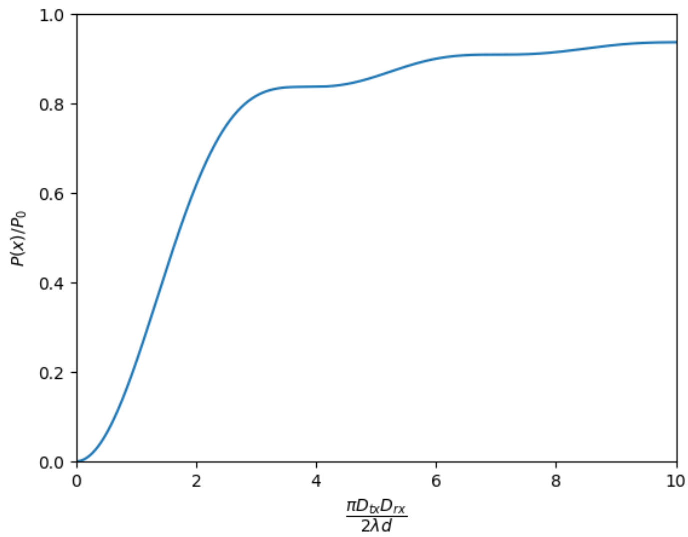


Figure 3-17 Power distribution in the beam

Therefore, the main (first) beam includes 83.8% of the total transmitted power, the second beam includes 7.2%. So the beam efficiency depends on the dimensions of the GPS and of the antenna, as well as on the frequency and the distance. The intensity describes a diffraction patterns on the GPS as can be seen in Figure 3-18.

Considering taking the power till the first null of the Bessel function (83.3% of the total power) the following formula applies:

$$D_{Tx}\, D_{Rx} = 2.44\ \lambda d$$

where λ is the wavelength (m) and d is the orbit altitude (m).

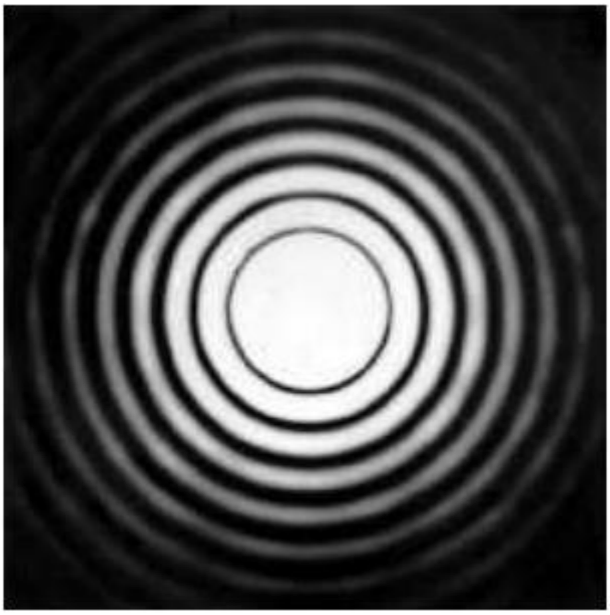


Figure 3-18 Diffraction pattern on the GPS

- **Atmospheric attenuation:** we are interested only in the effects of the atmosphere on the radio waves which cause an attenuation of the signal strength (loss of power). There are two types of atmospheric effects: effects causing permanent loss (not depending on weather conditions) and effects causing random loss depending on weather conditions above the Ground Power Station:
  1. Gaseous absorption is due to gas molecular absorption bands (mainly water vapour H_2O and oxygen O_3) and it causes permanent loss of power.
  2. Attenuation by precipitation and clouds depends mainly on frequency, elevation angle, altitude and on the statistical occurrence and intensity of clouds and rain showers at the GPS location.

  Following the ITU (International Telecommunication Union) prescription, we can find that at frequencies below 10 GHz these attenuation are very low: around 0.98 for the gaseous absorption and 0.99 or higher for the rain attenuation depending on the intensity. If the frequency increases over 10 GHz then the attenuation profile becomes very irregular and very high: we would have high losses due to the atmosphere and almost an interruption of service during rain showers.

- **GPS efficiency**
  - **Rectenna panel surface efficiency:** this is the surface efficiency of the rectenna panels. It is the ratio of the capture area of the rectenna to the total area of the ground panel. This parameter takes into account the surface of the panel which is lost according to the shape

and the type of assembly of the individual rectenna on the panel. We consider it to be 0.99.

- **Power line efficiency:** this takes into account two losses (0.98 overall):
  1. An electrical wiring that connects the rectenna inside a rectenna panel
  2. An electrical wiring connecting the rectenna panels to the GPS interface device connecting the Power Grid.
- **Power conditioning efficiency:** this is the efficiency of the current converters (DC to AC) that are required to deliver the electrical power to the Power Grid. We estimate it to be 0.95.
- **Rectenna efficiency:** this takes into account the conversion from RF to DC through a rectenna. The conversion efficiency depends on the power intensity reaching the rectenna as can be seen in figure. In order to compute this efficiency in the model we considered an average intensity over the GPS.

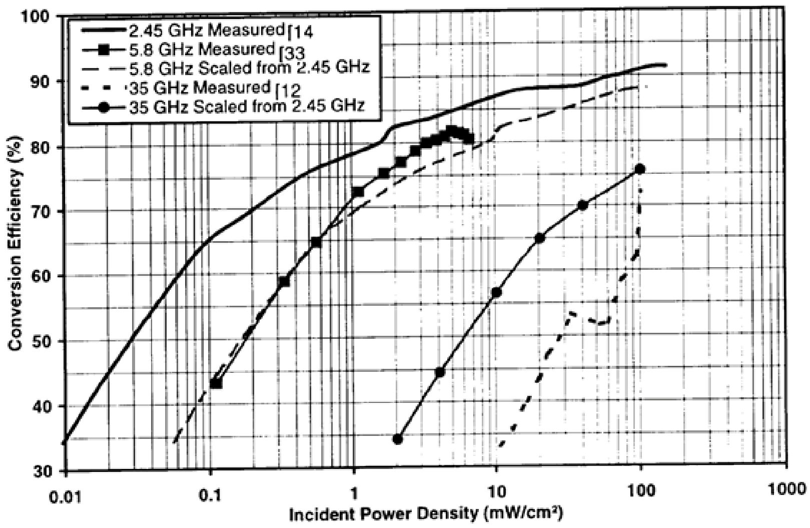


Figure 3-19 Conversion efficiency for rectennas

Furthermore, when considering the GPS area, we must take into account that in case of GEO SPS and a circular RF power beam, the footprint of the power beam is elliptical with a ratio between the minor axis (b) and the major axis (a) equal to sin(elev), elev is the elevation angle of the rectenna antenna pointing the SPS. The major axis is aligned with the direction of the SPS.

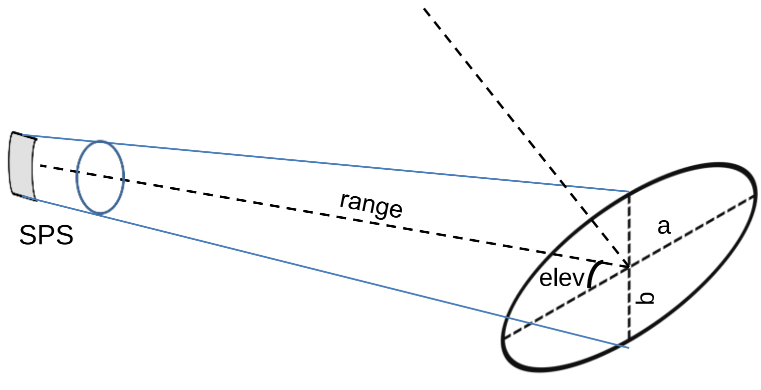


Figure 3-20 Power beam geometric configuration

These are all the efficiency that we expect at the moment to have an impact on the energy production. We do not exclude the possibility that the list and the numbers will be updated in a next and more detailed analysis. Everything has been inserted in the optimization model. It minimizes the GPS, SPS and antenna areas with appropriate weights while being compliant with some constraints:

1. Total power delivered in the grid at least 1 GW

$$\eta_{SPG}\eta_{WPT}\eta_{GPS}G_{SC}A_{PV} \geq 1\ GW,$$

where the symbols used are explained at the beginning of this section.

2. Average power intensity on the GPS not over 50 W/m^2

$$\eta_{WPT}\eta_{GPS}G_{SC}A_{PV}/A_{GPS} \leq 50\ W/m^2,$$

where A_{GPS} is the area of the GPS. Depending on the latitude of the location the shape is distorted into an ellipse for a GEO SPG.

3. Peak power at the centre of the GPS not over 250 W/m^2

$$\eta_{atm}\eta_{rain}\eta_{GPS}G_{SC}A_{PV}\frac{\pi D_{tx}^2}{4\lambda^2 d^2} \leq 250\ W/m^2,$$

where η_{atm} and η_{rain} are the efficiencies due to the atmosphere and the rain and the other symbols are explained in the *Beam efficiency* section.

The optimization has been implemented in MATLAB and makes use of a multi-start approach with a sequential quadratic programming algorithm as non-linear optimization method.

The model gives as output the minimized values for the three areas and the chosen frequency.

3.4.2.3 Orbit trade-off

For the orbit selection, the following configuration have been evaluated: Low Earth Orbits, Medium Earth Orbits, Molniya orbits and Geosynchronous Earth Orbit. Each option has been analysed and pros and cons derived in order to perform a preliminary orbit pruning.

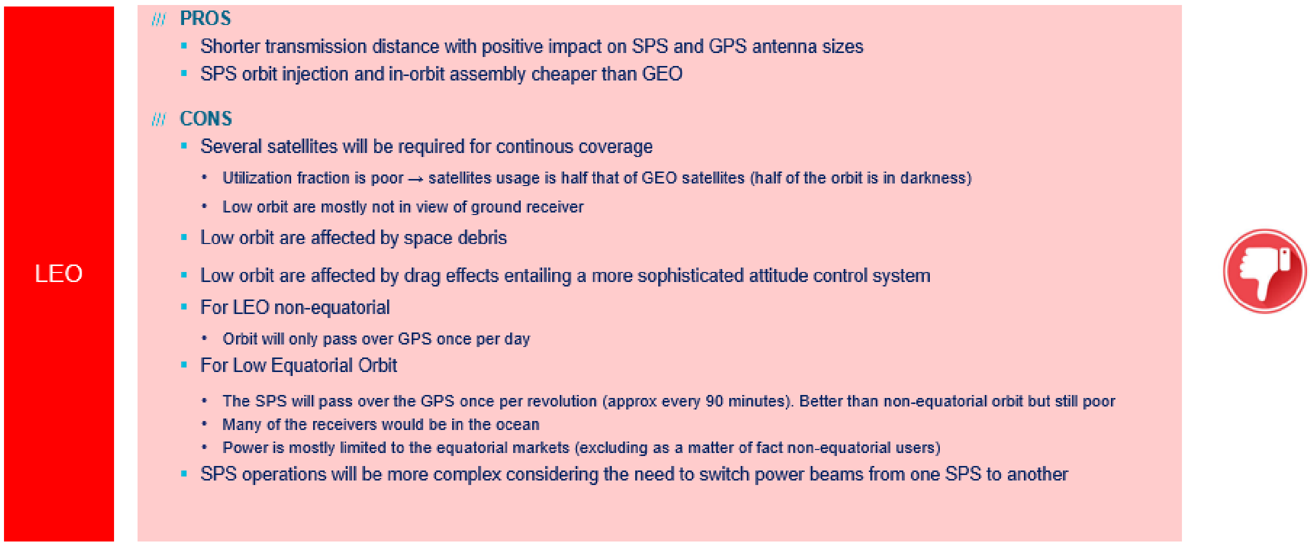


Figure 3-21 Orbit preliminary considerations (LEO)

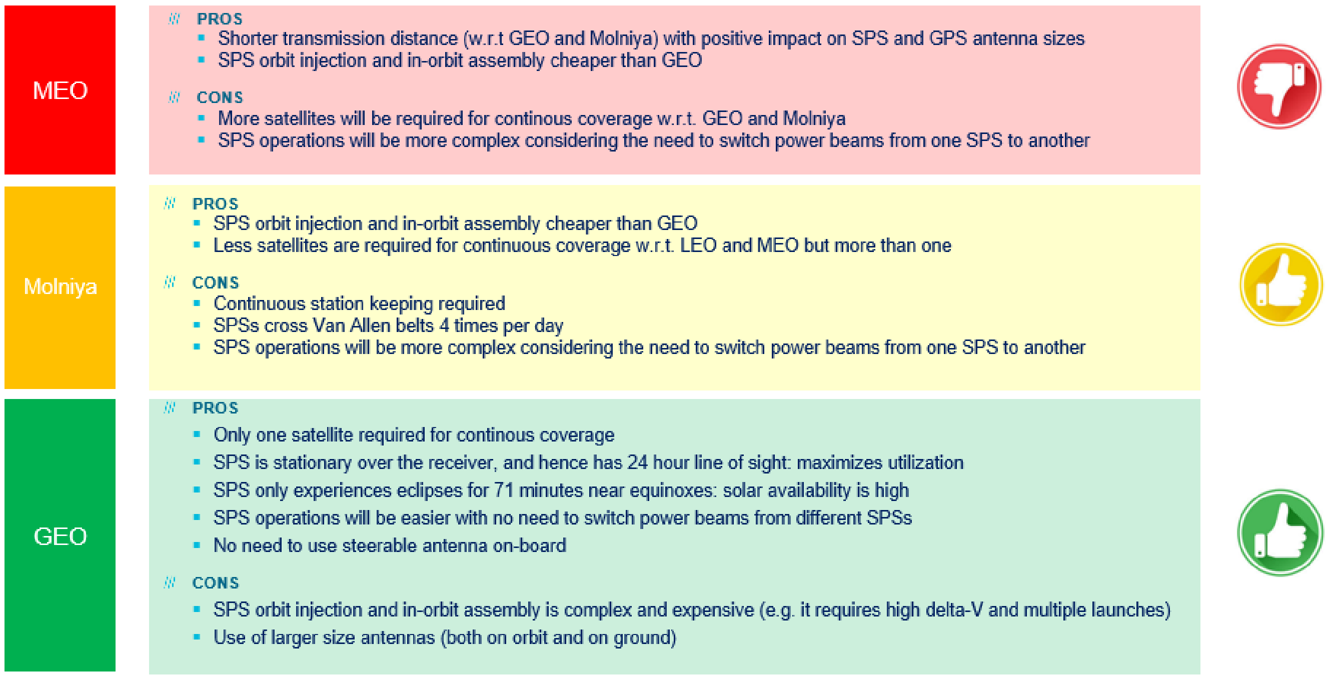


Figure 3-22 Orbit preliminary considerations (MEO, Molniya, GEO)

As a result of this activity, two options have been considered more suitable for our scope: geostationary orbits and high eccentricity – critically inclined orbits. Details on the criteria used for the orbit trade-off are provided below:

- **Cost**: Overall mission cost, including amount of launches and satellites and station-keeping
- **Energy expenditure**: Not applicable
- **Social acceptance**: Area that the energy transmission beam will cover during an orbit

- **Carbon footprint**: Amount of launches
- **Mass / Area / Volume**: Amount of satellites
- **Design Complexity**: Station-keeping and control/monitoring of one or multiple satellites
- **Deployment Complexity**: Delta V required to an orbit insertion
- **Operational Complexity**: Difficulty to keep the pointing of the antenna to the GPS
- **Failure tolerance**: Difficulty to insert an In-Orbit servicer satellite to the SPS orbit and power delivery in case of a satellite failure
- **Capacity factor**: Eclipse duration
- **Modularity** Not applicable
- **Scalability**: Not applicable
- **TRL / Heritage**: Not applicable
- **Lifetime**: Stationkeeping required during lifetime
- **Industrial capability/ scalability**: Dependent on GPS chosen, thus not applicable

The Geostationary orbit has the main advantage to require only one satellite and has a constant elevation angle between SPS and GPS. Considering the satellite located above the same longitude of the chosen GPS, the elevation angle for each GPS considered in AD1 is reported in Table 3-14.

GPS	Spain	Germany	Sweden
Elevation angle	47 deg	34 deg	18 deg

Table 3-14 Elevation angle in GEO

The results shows the advantage of having the GPS in Spain considering that the beam's projection increase with the decrease in elevation angle.

The main disadvantage of GEO lies in the high orbit's semi-major axis, thus high delta V is required to bring the satellite in orbit, as well as possible future in-orbit servicing satellites for construction and repairing. Another disadvantage is the eclipse duration during equinoxes up to 72 minutes per day that will have to be covered by batteries inside the GPS. Moreover, the antennas' dimension increase with the increase in slant range.

The Eccentric Orbits solve some of the Geostationary orbit problems, thanks to little to no eclipse during operation time and lower semi-major axes. The main disadvantages lies in the requiring of at least 3 satellites, all of which shall be able to deliver the 1 GW of energy required back to Earth, and that will be useful for a fraction of the time they are in orbit as only for part of it the satellite would be above the GPS. By not being geostationary, each satellite would require continuous pointing adjustments w.r.t. GEO, both in terms of antennae and of solar panels. Moreover, a greater number of station-keeping manoeuvres are required and each satellite would pass inside the Van Allen radiation belt twice per orbit.

To evaluate costs and carbon footprint, it is worth noticing how, for the eccentric orbits, the amount of satellites required increases with the increase in synchronicity, but the Delta V required for the insertion is lower, thus the amount of payload per launch increases. As launcher capability is still unknown, a rough estimate of the amount of launches required can be done comparing the transportable payload in GEO and in Geosynchronous Transfer Orbit, or GTO, as the GTO has a semi-major axis comparable to the EO.

For example, considering a LEO injection orbit at 500 km and an Orbital Tug to bring a module to the target orbit, the required delta V are the following:

Geostationary orbit	Eccentric orbit with 2:1 synchronicity	Eccentric orbit with 3:1 synchronicity	Eccentric orbit with 4:1 synchronicity	Eccentric orbit with 6:1 synchronicity
3.82 km/s	2.96 km/s	2.87 km/s	2.80 km/s	2.65 km/s

Table 3-15 Required Delta V to bring a module from transfer orbit to target orbit

As at least three SPS are required for an eccentric orbit to have continuous coverage, even considering the best scenario of 1.9 km/s for the eccentric orbit, the cumulative delta V for a single module per SPS is 7.95 km/s for an eccentric orbit and 3.82 km/s for the GEO, making this last one as the cheaper in terms of delta V, thus propellant.

Orbit selection				OPTION 1		OPTION 2		OPTION 3		OPTION 4		OPTION 5	
				Geostationary orbit		Eccentric orbit with 2:1 synchronicity		Eccentric orbit with 3:1 synchronicity		Eccentric orbit with 4:1 synchronicity		Eccentric orbit with 6:1 synchronicity	
Criteria	Applicability [N/A= 0, Applicable = 1]	Weight Factor [1-5]	Applicability * Weight Factor	Input [1-5]	Value [Weight Factor * Input]	Input [1-5]	Value [Weight Factor * Input]	Input [1-5]	Value [Weight Factor * Input]	Input [1-5]	Value [Weight Factor * Input]	Input [1-5]	Value [Weight Factor * Input]
Cost	1	5	5	5	25	3	15	2	10	1	5	1	5
Energy expediture	0	3	0		0		0		0		0		0
Social acceptance	1	5	5	5	25	3	15	2	10	2	10	1	5
Carbon footprint	1	5	5	5	25	4	20	3	15	2	10	1	5
Mass / Area / Volume	1	5	5	5	25	4	20	3	15	2	10	1	5
Design Complexity	1	3	3	5	15	2	6	3	9	2	6	1	3
Deployment complexity	1	3	3	1	3	4	12	3	9	4	12	5	15
Operational complexity	1	3	3	5	15	2	6	3	9	2	6	1	3
Failure Tolerance	1	2	2	1	2	5	10	3	6	4	8	5	10
Capacity factor	1	4	4	3	12	5	20	4	16	4	16	4	16
Modularity	0	4	0		0		0		0		0		0
Scalability	0	4	0		0		0		0		0		0
TRL / Heritage	0	1	0		0		0		0		0		0
Lifetime	1	4	4	4	16	2	8	2	8	2	8	2	8
Industrial capability/scalability	0	3	0		0		0		0		0		0
TOTAL SCORE					**4.18**		**3.38**		**2.74**		**2.33**		**1.92**

Table 3-16 Orbit trade-off

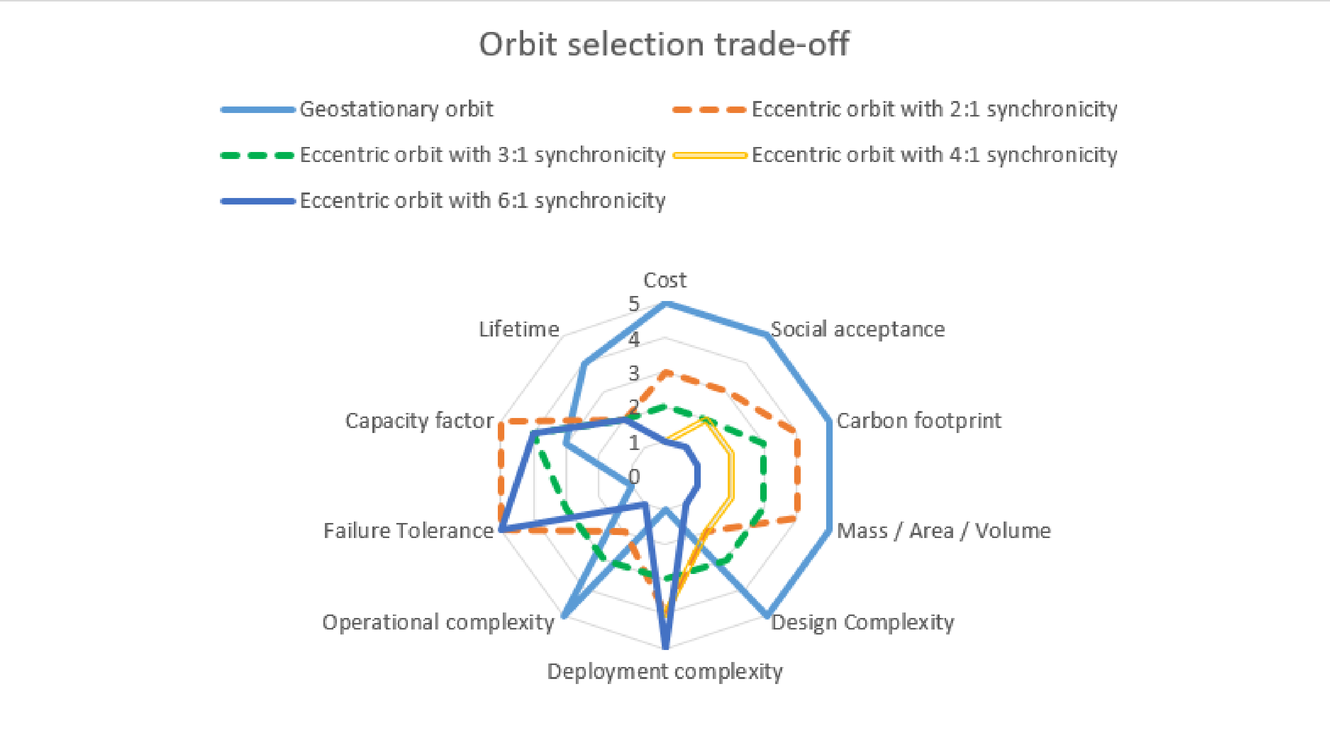


Figure 3-23 Orbit selection trade-off summary graph

The trade-off analysis clearly shows that GEO is the most suitable orbit for the scope of the mission, mainly for the possibility of using only one satellite and for having a fixed beam towards Earth, at the cost of a bigger GPS due to the slant range. Among the EO, the 2:1 synchronicity stands out as it has the least amount of satellites w.r.t. the other configurations and the least amount of eclipse of all the configurations.

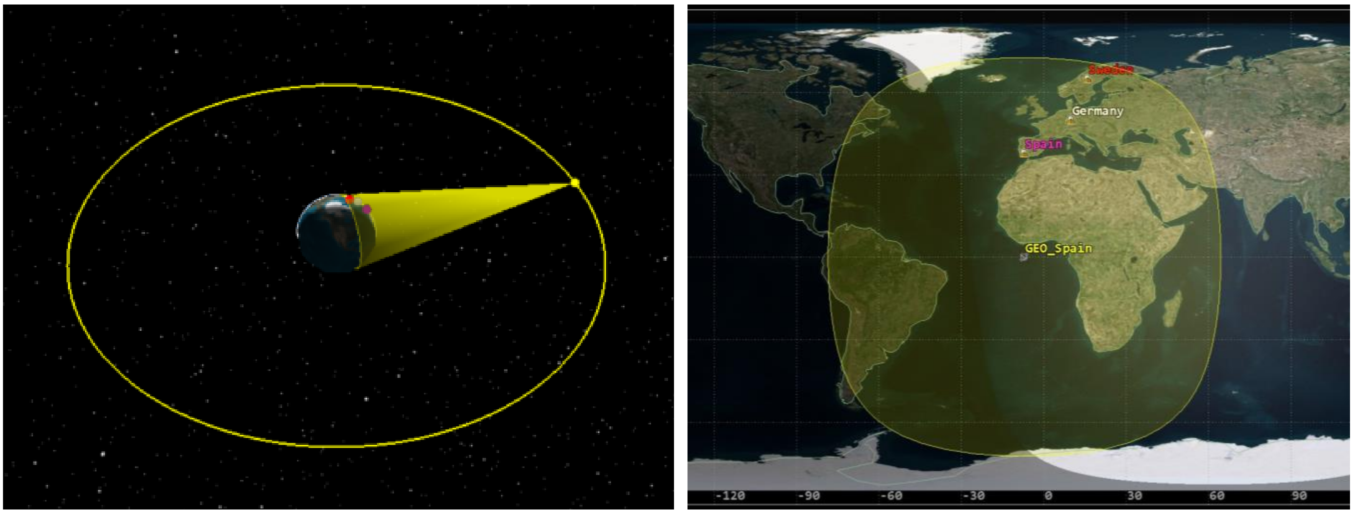


Figure 3-24 Orbit (left) and Coverage (right) of a GEO satellite

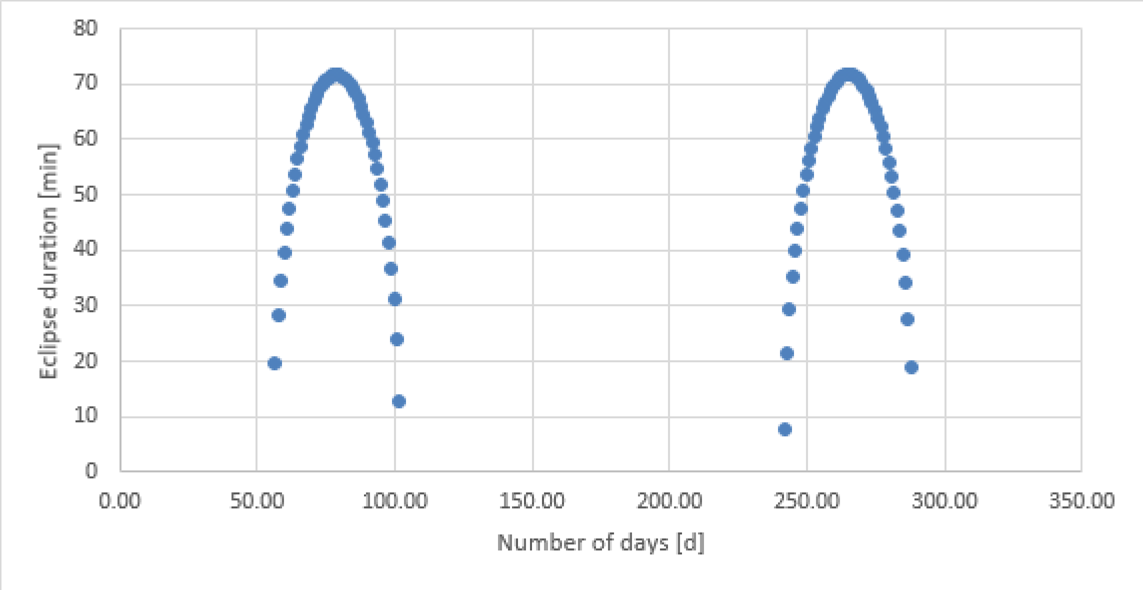


Figure 3-25 Penumbra eclipse duration for a GEO satellite at 7 [deg] west longitude

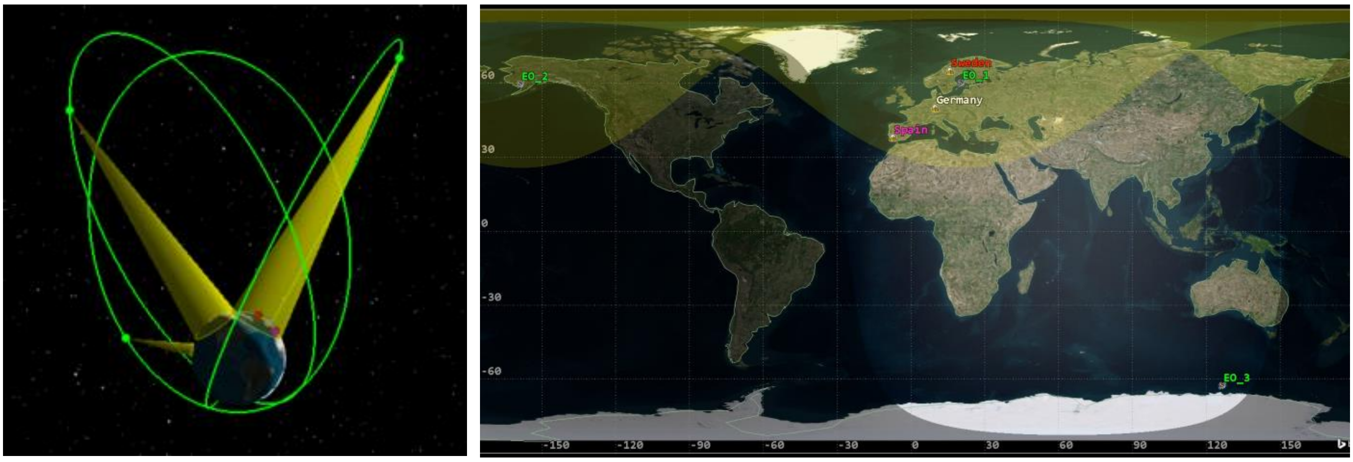


Figure 3-26 Orbit (left) and Coverage (right) of a EO 2:1 synchronicity constellation

3.4.2.4 Case study analysis

Following the orbit trade-off which sees GEO orbit as the winning option (with a GPS in Spain favourable), it was decided to build a precise case study for the mathematical model presented before. In particular, assuming a GEO orbit and a latitude of 40.45 degree (Spain), analysis have been performed firstly to have a preliminary overview of the numbers in play for the three main system areas (GPS, antenna and solar panels) and then to put a solid base to develop the operating frequency trade off.

More precisely two separate analysis have been performed considering the available ISM frequencies in a specific range (1 GHz – 24 GHz) and considering that frequencies over 10 GHz shall be discarded for atmospheric attenuation reasons (too high to assure a 24/7 baseload power) :

- 2.45 GHz
- 5.8 GHz

As mentioned in the model description the tool gives the possibility to the user to set different weight factors for the optimization of the three areas considered. In fact, in order to have a more detailed investigation, both analysis have been performed with different combinations of weight factors for space segment areas (antenna and solar panels) and ground segment area (GPS). This was done to control the possible variation of the optimum point chosen by the tool for the areas dimensions.

The main assumption (in this two analysis) is the use of 3 junction PV cells with an expected efficiency of 36%. However, as detailed later on in the section, additional analysis have been performed in order to evaluate the difference in area and weight of overall panel arrays changing the PV cell technology.

The preliminary results obtained by the model considering different weight factor combinations are presented below:

- 2.45 GHz

Weight factors (GPS area - antenna area - Solar panels area)	GPS area [km2]	Antenna area [km2]	Solar panels area [km2]
1 1 1	23.66	1.87	5.19
1 10 10	28.5	1.66	5.11
1 20 20	41.77	1.29	5.04
1 30 30	51.6	1.11	5.02
1 40 40	59.55	1.01	5.02
1 50 50	66.34	0.93	5.02

Table 3-17 Preliminary tool results obtained for 2.45 GHz

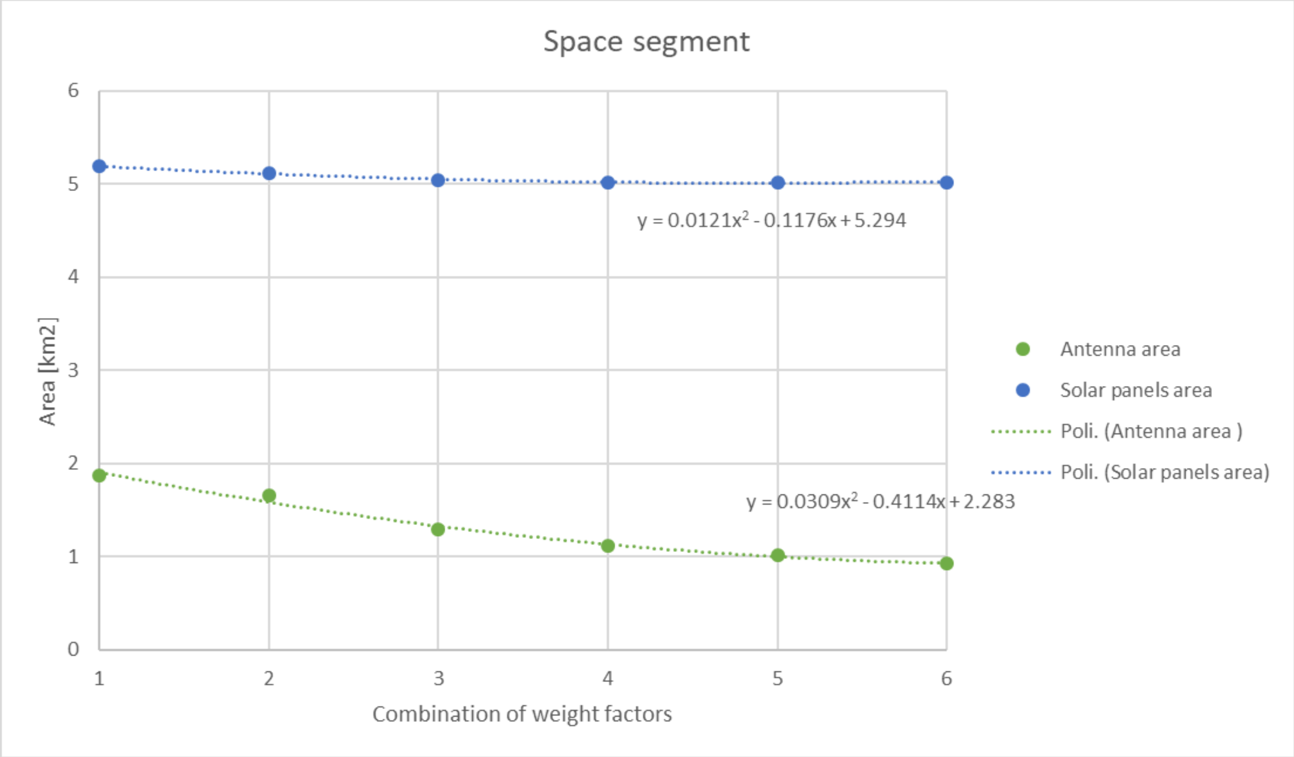


Figure 3-27 Antenna and solar panel areas varying with the space segment weight factors increase for 2.45 GHz

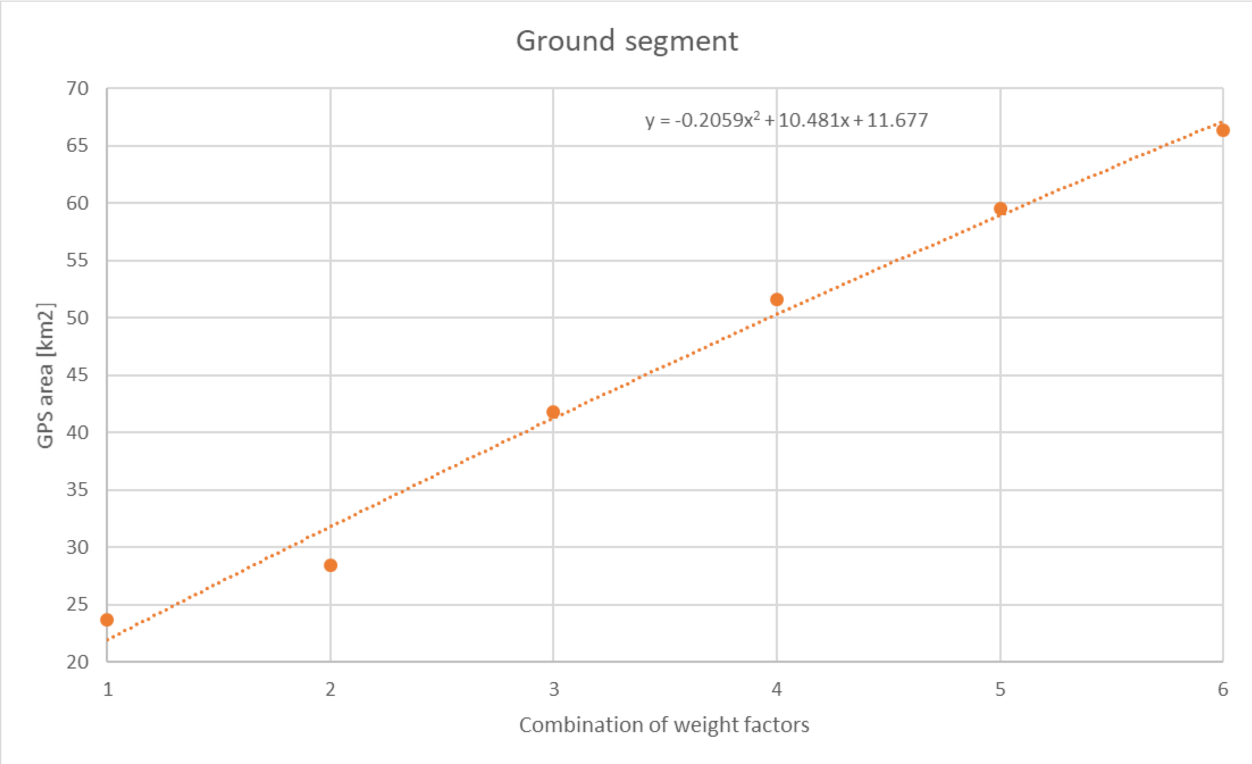


Figure 3-28 GPS area varying with the space segment weight factors increase for 2.45 GHz

- 5.8 GHz

Weight factors (GPS area - antenna area - Solar panels area)	GPS area [km2]	Antenna area [km2]	Solar panels area [km2]
1 1 1	23.34	0.45	4.97
1 10 10	23.34	0.45	4.97
1 20 20	24.27	0.44	4.94
1 30 30	25.48	0.44	4.91
1 40 40	26.22	0.44	4.905
1 50 50	26.74	0.44	4.9

Table 3-18 Preliminary tool results obtained for 5.8 GHz

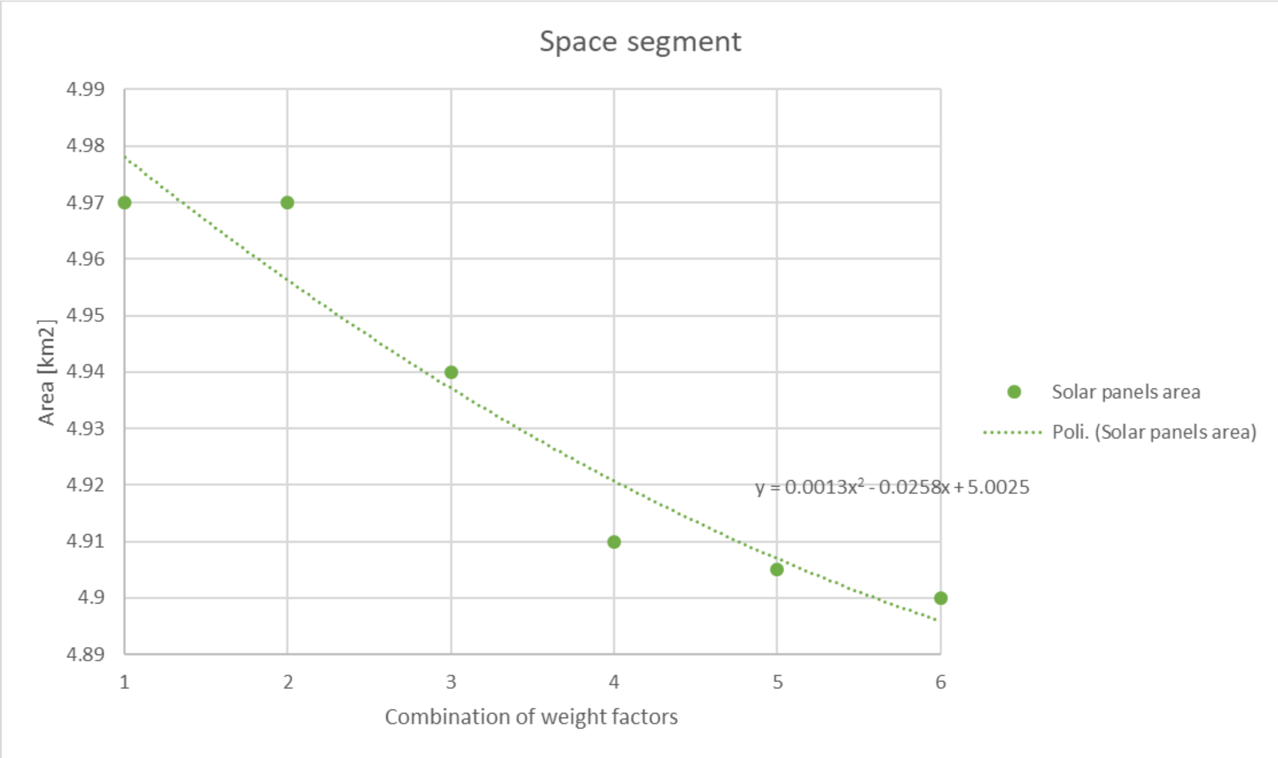


Figure 3-29 Solar panels area varying with the space segment weight factors increase for 5.8 GHz

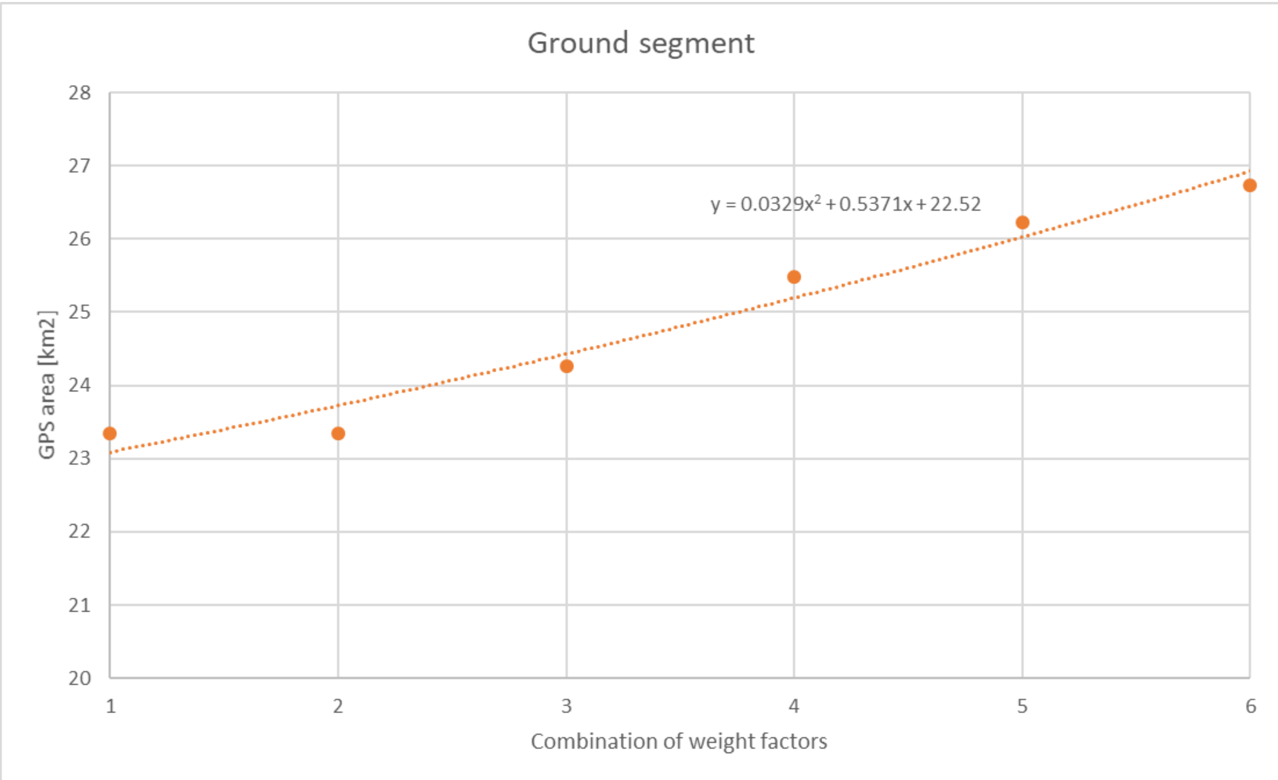


Figure 3-30 GPS area varying with the space segment weight factors increase for 5.8 GHz

As previously stated, the analyses were conducted based on a cell efficiency of 36%, yielding realistic expected cell efficiencies for triple junction technologies. Nevertheless, to address cost and weight considerations, which will be elaborated in Section 3.4.2.6, the obtained model results (for 5.8 GHz) need to be compared with an alternative analysis using a lower cell efficiency of 29%. This efficiency is particularly relevant when considering thin film cell types and represents a more realistic scenario for this technology.

Weight factors (GPS area - antenna area - Solar panels area)	Solar panels area (3j/4j conventional cells) [km2]	Solar panels area (thin film cells) [km2]
1 1 1	5.19	6.28
1 10 10	5.11	6.27
1 20 20	5.04	6.21
1 30 30	5.02	6.19
1 40 40	5.02	6.17
1 50 50	5.02	6.17

Table 3-19 Solar panels area varying with the space segment weight factors increase for 5.8 GHz considering two different cell efficiencies (36% and 29%)

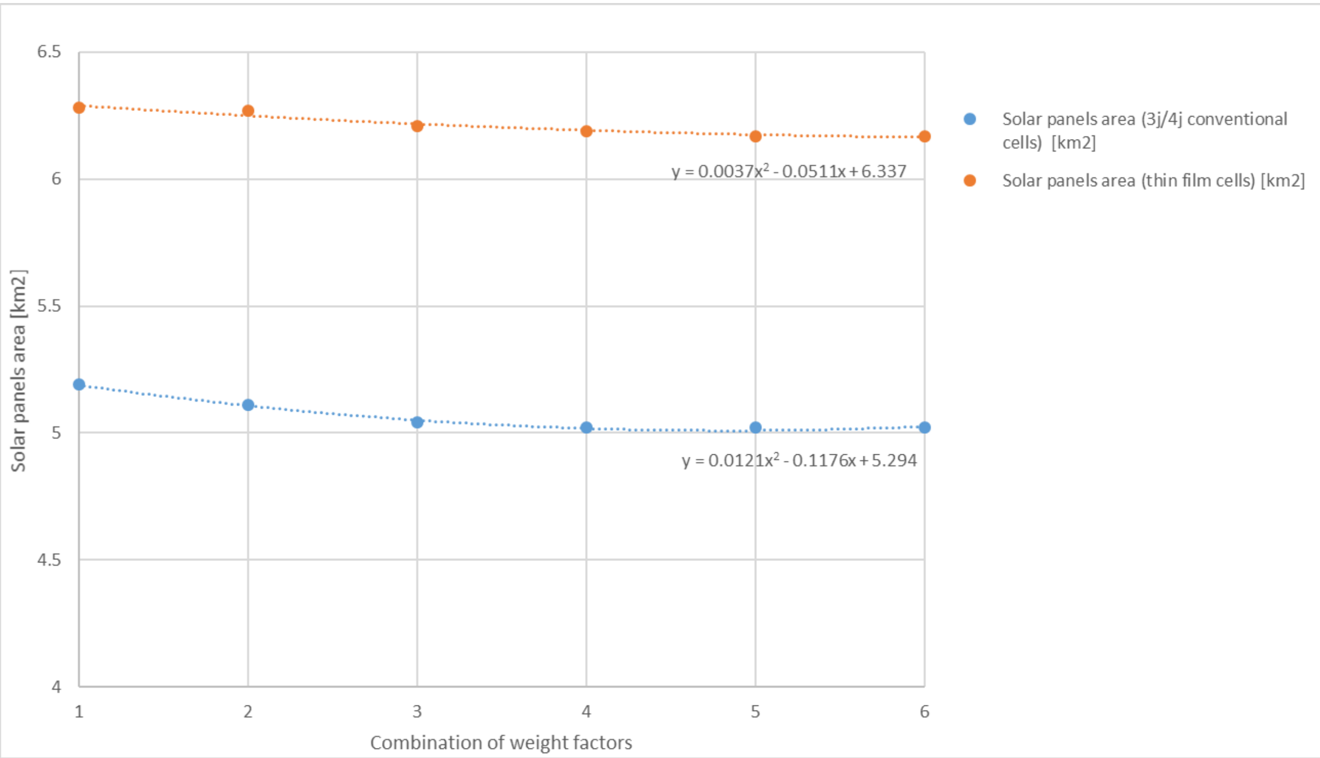


Figure 3-31 Visual trend of solar panels area varying with the space segment weight factors increase for 5.8 GHz considering two different cell efficiencies (36% and 29%)

It is worth noting how the solar panels area increases when considering a lower cell efficiency. The choice of a cell technology will be further discussed in Section 3.4.2.6 in order to highlight the impact on mass of the thin film cell technology considering their high power density.

3.4.2.5 WPT operating frequency trade-off

Frequency choice is one of the critical points of SBSP system concept. As mentioned in TN2 and in the case study analysis it is plausible to consider a range of operative frequencies between 1 and 24 GHz (in particular considering the ISM frequencies available).

However, frequencies above 10 GHz are strongly affected by the atmosphere. Consequently the availability of the power link and its power capacity (losses) will depend on weather conditions (rain, snow, fog, etc.) above the GPS so this is not compliant with the 24/7 baseload use case considered.

For this reason, and considering the available ranges of ISM band, the two remaining alternatives are 2.45 GHz and 5.8 GHz.

The following choice of the frequency is based on the results showed before, obtained with the model, mainly considering 4 factors which vary with the operative frequency:

- ✓ the optimization of the 3 main areas of the SBSP system: solar panels area, on board antenna area and GPS area.
- ✓ the atmospheric loss (so related to the "capacity factor" criteria). The higher the frequency, the higher is the loss (but the difference is almost negligible in this case between the two options considered).
- ✓ the efficiency of the DC to RF (space) and RF to DC (ground) power conversions, which varies with the frequency considered. In particular the efficiencies, at the moment, decrease with the frequency rising.
- ✓ the TRL level of DC-RF conversions for a particular frequency: in fact, an higher TRL (for the efficiencies we are considering valuable for the project) is expected for lower frequencies. In fact, more researches and studies now are performed for lower ranges such as 2.45 GHz, but in the future the same TRL (for the target efficiency) could be expected for 5.8 GHz too.

At the end, the final decision depends mainly on the Mass/Area/Volume attribute for this trade-off. In fact, the majority of other applicable criteria result to be direct consequences of this (for example, at least for this trade off, cost is only a direct consequence of the 3 main project areas we are considering such as deployment and operational complexity too).

For this reason, observing the tool results shown before, we notice how for 5.8 GHz we obtain a reduction of the on board antenna area of 1/3 with respect to 2.45 GHz solution, while having only a small arise of the solar panels area. Since reducing the antenna area could be a great advantage not only for mass/volume criteria, but also for cost and design complexity reasons, the choice is an operative frequency of 5.8 GHz.

Operating frequency

Criteria	Applicability [N/A= 0, Applicable = 1]	Weight Factor [1-5]	Applicability * Weight Factor	OPTION 1		OPTION 2	
				2.45 GHz		5.8 GHz	
				Input [1- 5]	Value [Weight Factor * Input]	Input [1- 5]	Value [Weight Factor * Input]
Cost	1	5	5	2	10	3	15
Energy expediture	0	3	0		0		0
Social acceptance	0	5	0		0		0
Carbon footprint	0	5	0		0		0
Mass / Area / Volume	1	5	5	2	10	4	20
Design Complexity	1	3	3	1	3	1	3
Deployment complexity	1	3	3	2	6	3	9
Operational complexity	1	3	3	2	6	3	9
Failure Tolerance	0	2	0		0		0
Capacity factor	1	4	4	5	20	4	16
Modularity	1	4	4	2	8	2	8
Scalability	1	4	4	2	8	2	8
TRL / Heritage	1	1	1	3	3	2	2
Lifetime	0	4	0		0		0
Industrial capability/scalability	0	3	0		0		0
TOTAL SCORE					**2.31**		**2.81**

Table 3-20 Operating frequency trade-off

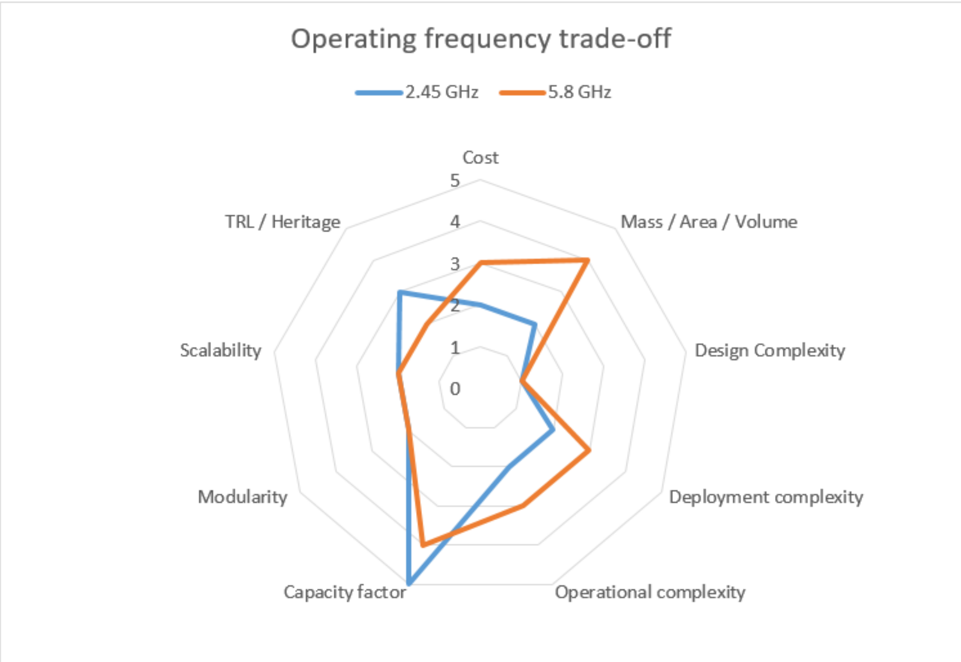


Figure 3-32 Operating frequency trade-off summary graph

3.4.2.6 PV vs CPV trade-off and cells technology selection

As already pointed out in TN2, PV cells could be combined with solar concentrators in order to have higher cell efficiencies and lower PV cell area (lowering the costs).

Concentrators are devices comprising various optical elements that focus light, typically sunlight, onto a single central point where a solar cell is located. These concentrator photovoltaics (CPV) are quantified in terms of the intensity of concentration, expressed as the number of Suns or ratios. If the light intensity on the solar cell exceeds 10 Suns, passive cooling of the PV cell becomes necessary, categorizing the system as a low-concentration photovoltaic system (LCPV), where silicon solar cells can still be utilized. However, when the light intensity surpasses 100 Suns, active cooling with a cooling fluid is required, classifying it as high-concentration photovoltaics (HCPV). The specific value may vary across different literature sources.

Concentrator designs come in various forms, including Fresnel lenses, reflectors, parabolic mirrors, or luminescent concentrators.

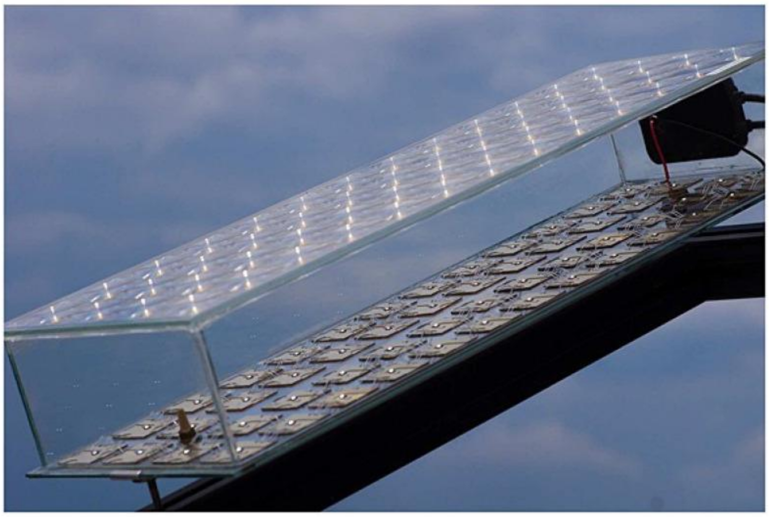


Figure 3-33 FLATCON® CPV module with 52 four-junction solar cells (see [RD22])

Since a direct-across electrical interface concept has been chosen for the study, after having discarded the Architecture 2 solution, now the purpose is to go deeply in the PV and CPV solutions.

To do this, the tables below summarize some pros and cons of the two solutions (considering always a direct-across electrical interface option):

PV Pros	PV Cons

Lower overall complexity (also for deployment and assembly on orbit)	For the same cell technology a single PV panel has higher cost w.r.t. CPV panel. This not imply a cost reduction for the overall system considering the higher complexity of this solution
No need of 3 DoF pointing system for solar arrays (maybe 1 or 2 are required for the selected concept)	Lower maximum experimental lab tested cell efficiencies (at the moment) with respect to CPV
High TRL	

Table 3-21 Pros and cons of PV implementation

CPV Pros	CPV Cons
For the same cell technology a single CPV panel has lower cost w.r.t. PV panel (expensive semiconductor cell areas are replaced with less expensive lenses, but other factors, such as additional cost for adding mass and complexity due to lens structures, need to be taken into account)	Very high termal loads to be managed (with respect also to Conventional PV) with also the impossibilty to radiate some of the heat to the outer space (because of the lens which blocks it)
Higher cell efficiencies (but it is not sure whether this corresponds to an actual decrease in panel areas in the overall system)	Major complexity and probably less reliablity due to different lens and particular structures needed
	In case of Direct option solar arrays with 3 DoF pointing are needed (to be compliant also with on board antenna requirement to be always Nadir pointing). Not needed when considering reflectors at platform level (e.g., CASSIOPeiA concept)

Table 3-22 Pros and cons of CPV implementation

Different criteria have been analyzed to perform the trade-off:

Different criteria have been analyzed to perform the trade-off:

- **Cost – Estimated cost savings at PV level considering one or the other solution** : one of the primary benefits of Concentrated Photovoltaics (CPV) lies in its ability to lower costs at the Photovoltaic Array (PVA) level, as compared to traditional Photovoltaics (PV). This cost reduction primarily stems from the option to replace costly solar cell area with lenses/reflectors, which are inherently more affordable. By focusing on this aspect alone, it's conceivable to achieve a significant 25-30% reduction in overall costs. Nonetheless, accurately assessing the potential increase in secondary costs associated with the heightened complexity of the system using CPV remains challenging during this phase.
- **Mass/Area/Volume – Mass and area of the SPS** : Exploring the CPV alternative, there aren't significant advantages in terms of total area savings when compared to traditional PV panels. Nevertheless, when we focus on the utilization of thin film 3-junction solar cells (with a specific power density of approximately 1 W/g), adopting CPV technology could indeed yield advantages in terms of Photovoltaic Array (PVA) mass. In fact, researchers at Caltech are currently in the process of validating a CPV technology with a relatively low concentration factor (ranging from 4 to 10). This advancement has the potential to decrease the PVA mass by a remarkable factor of 4, owing to its higher specific power density, around 4 W/g. However, achieving this reduction in mass could also be feasible by transitioning to different types of solar cells. For instance, emerging technologies like CIGS and Perovskite, which are presently unsuitable for CPV applications, could be considered. As for the financial aspect, accurately evaluating the potential rise in secondary costs linked to the increased intricacy of a CPV system remains a formidable task at this stage.

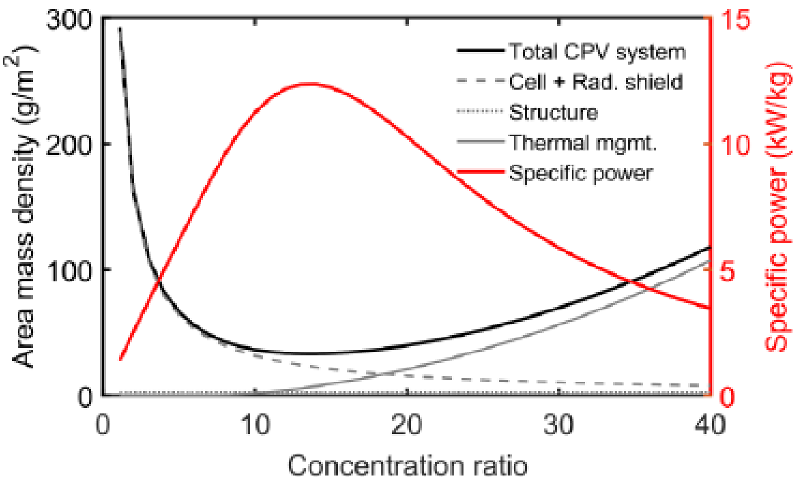


Figure 3-34 Concentration ratio 1/2

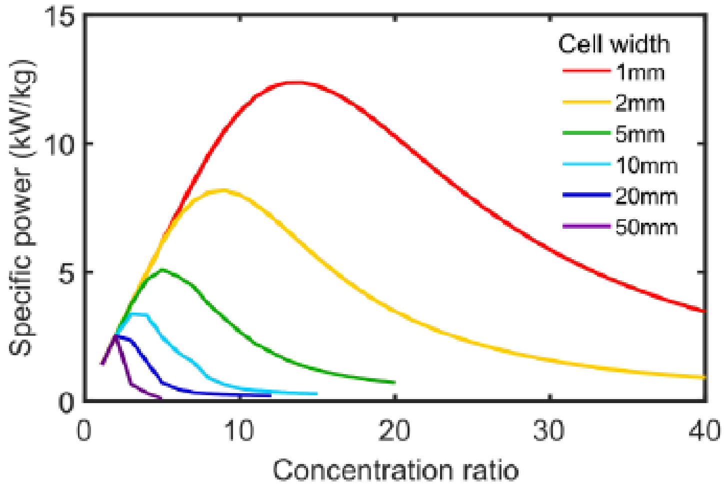


Figure 3-35 Concentration ratio 2/2

- **Design complexity :** Considering the CPV option, this undoubtedly introduces greater complexity to the overall system design. Notably, subsystems like the thermal control system and, specifically, sun-tracking mechanisms pose heightened challenges in comparison to the implementation of traditional PV systems.
- **Deployment complexity :** When contemplating the integration of CPV, the adoption of roll-out or deployable structures for the Photovoltaic Array (PVA) unquestionably introduces a significant layer of complexity. The utilization of micro-CPV or more extensive deployable lens/reflector units would become preferable, in contrast to the straightforwardness associated with PV systems serving the same purpose.

Operational complexity: this criteria is the main problem for the CPV implementation on SPS. Infact, adding this type of technology has lots of drawbacks for what concerns overall system complexity:

- the biggest advantage and principal reason for the usage of CPVs for satellite platforms are to create a more suitable alternative in terms of cost compared to the conventional flat plate system by decreasing the number of expensive solar cells. However, CPVs using these cells cannot operate at the optimum performance because of the difficulty of the use of the active cooling system, which is required for high temperatures that occur at high concentration ratios, on satellite platforms.
- the CPVs need to be developed with a relatively light structure which shall also be resistant to mechanical effects that may occur from its production throughout its mission period in the orbit. Applications in which mechanical influences have not been sufficiently taken into account resulted unsuccessful. This should be seen as one of the most important indicators of the difficulty of the design process.
- the development of highly precise tracking systems needed to ensure the necessary focus without affecting the payload involves great difficulties due to satellite platform limitation. For the elimination of these problems, the tolerance angles of CPVs should be increased to reduce the tracking sensitivity.

Failure tolerance: Major complexity in the overall systems implies also lower reliability when considering CPV implementation. Moreover, according to the AIAA standards, all mission/applications apart from SCARLET-II among CPVs have failed, demonstrating the low reliability of the technology at the moment.

TRL/Heritage: As previously noted, the conventional application of PV in space undeniably holds a more established track record compared to CPV. Consequently, when referring to identical cell technologies, PV boasts a higher Technology Readiness Level (TRL) in comparison to CPV.

Lifetime : Thus far, CPV has exhibited elevated degradation rates in contrast to conventional PV cells. This discrepancy primarily arises from the augmented temperatures resulting from solar concentration. Additionally, the heightened degradation could potentially necessitate more frequent on-board maintenance or cell replacements—a supplementary layer of complexity for the entire system.

A quantified trade-off for PV vs CPV is reported in Table 3-23.

SPS convert							
				OPTION 1		OPTION 2	
				Concentrated PV		Conventional PV	
Criteria	Applicability [N/A= 0, Applicable = 1]	Weight Factor [1-5]	Applicability * Weight Factor	Input [1- 5]	Value [Weight Factor * Input]	Input [1- 5]	Value [Weight Factor * Input]
Cost	1	5	5	3	15	2	10
Energy expediture	0	3	0		0		0
Social acceptance	0	5	0		0		0
Carbon footprint	0	5	0		0		0
Mass / Area / Volume	1	5	5	3	15	2	10
Design Complexity	1	3	3	2	6	3	9
Deployment complexity	1	3	3	2	6	3	9
Operational complexity	1	3	3	1	3	4	12
Failure Tolerance	1	2	2	2	4	3	6
Capacity factor	0	4	0		0		0
Modularity	0	4	0		0		0
Scalability	0	4	0		0		0
TRL / Heritage	1	1	1	1	1	3	3
Lifetime	1	4	4	2	8	3	12
Industrial capability/scalability	0	3	0		0		0
TOTAL SCORE					**2.23**		**2.73**

Table 3-23 SPS convert trade-off

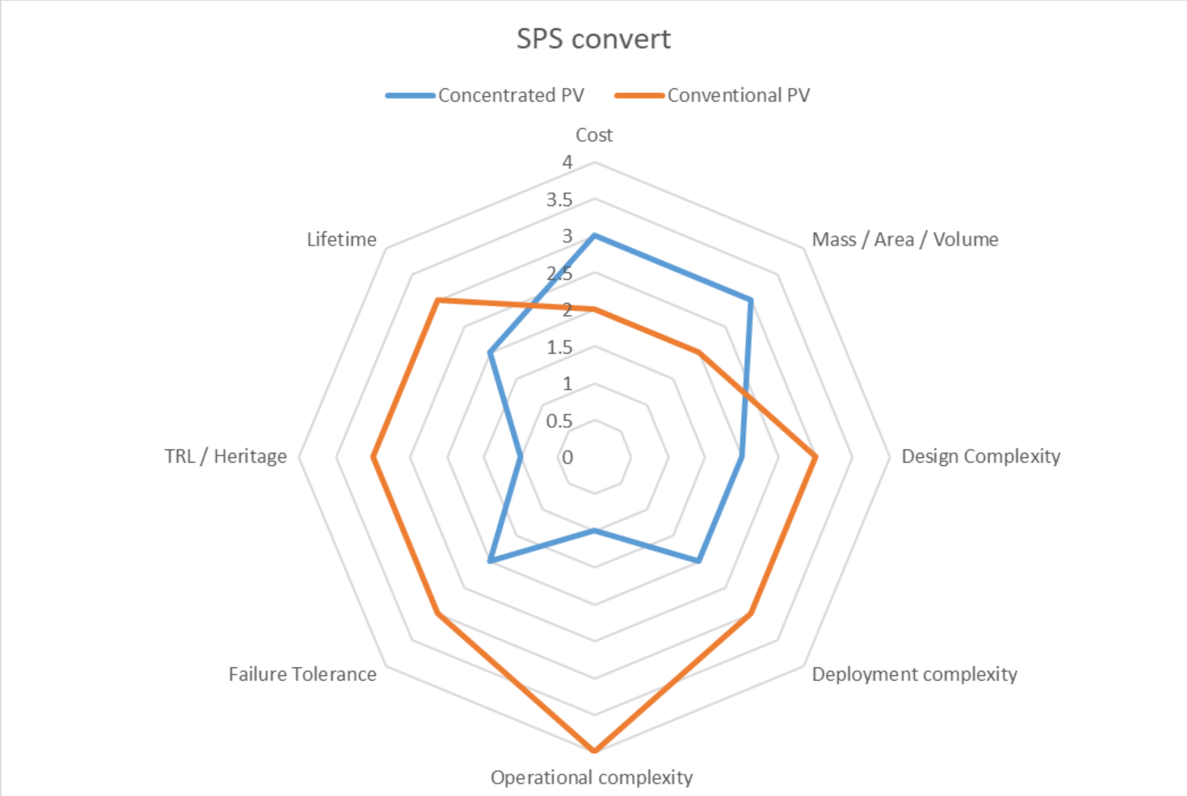


Figure 3-36 SPS convert trade-off summary graph

Although the potential benefits in terms of mass and PVA costs when implementing CPV are acknowledged (albeit uncertain in terms of scalability due to secondary impacts from higher overall complexity), factors such as operational and design complexities lean towards favouring the implementation of conventional PV cells, which are selected as baseline.

For what concerns the PV cell technologies (see TN2), many different technologies are available (or will be) for space applications.

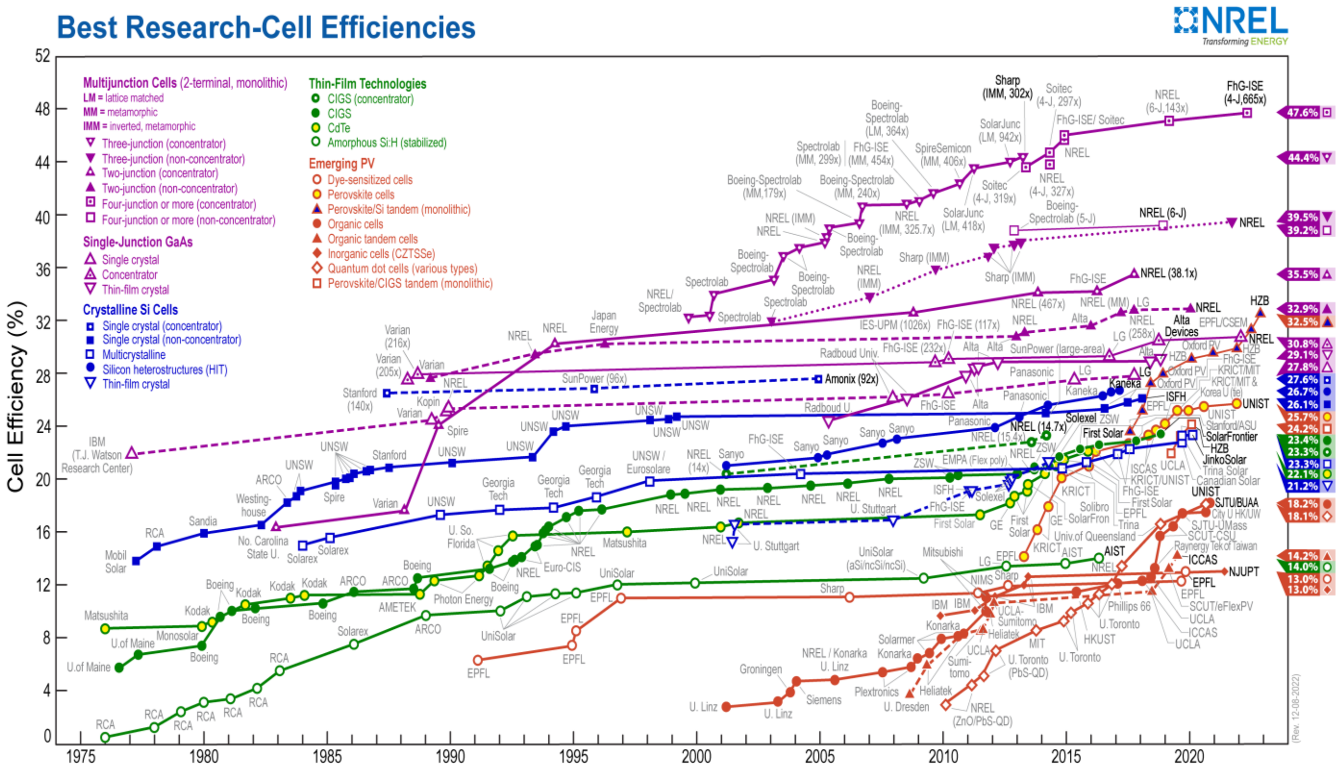


Figure 3-37 Cell efficiencies state of art (see [RD24])

A precise selection of cell technologies applicable to SPS, considering up-to-date PV cells data are reported in Table 3-24:

	Conventional Multijunction 3j/4j (e.g., XTG)	Thin film InGaP/GaAs/Ge (e.g., 3G30-C)	Thin film single junction GaAs	Thin film CIGS	Perovskite cells
Module efficiency (proved in space applications)	32%	29%	/	/	/
Max lab proved efficiency	/	/	29%	23.4%	26%
Expected module efficiency (2050) with adequate funding	40%	36%	32%	29%	29%
Technology TRL	9	9	5-6	4 -5	3-4
Specific power density [W/g]	0.47	0.8	3	3	23
Mass/area [kg/m2] under 1 Sun	2.9	2.05	0.5	0.5	0.07

	Conventional Multijunction 3j/4j (e.g., XTG)	Thin film InGaP/GaAs/Ge (e.g., 3G30-C)	Thin film single junction GaAs	Thin film CIGS	Perovskite cells
Manufacturing cost (expected)	High	High	Medium	Low	Low
Degradation rate (expected in future applications)	0.5-1.5 %/year	0.5-1.5 %/year	0.5-1 %/year	0.1-0.5 %/year	0.1-0.5 %/year

Table 3-24 Possible cell technologies that could be implemented in a SPS (see [RD2], [RD23], [RD24])

Among the selected options, thin film InGaP/GaAs/Ge cells (e.g., 3G30-C) and Perovskite cells stand out as the two most promising choices, each offering distinct advantages. The first technology excels in terms of efficiency and Technology Readiness Level (TRL), while the second one demonstrates cost-effectiveness and high specific power density (the best among all the cell technologies at the moment). Perovskite cells laboratory test are reported in Table 3-25.

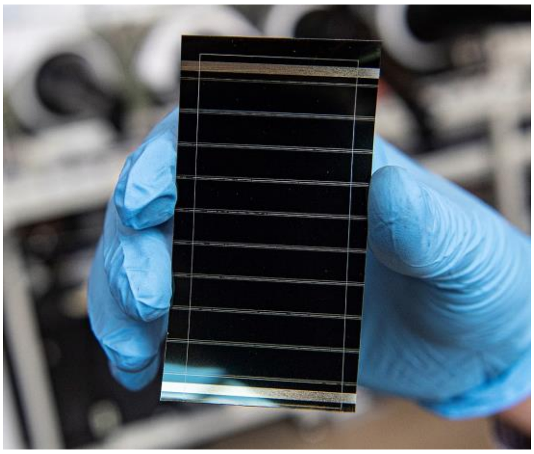


Figure 3-38 Perovskite solar cell (see [RD25])

Measurement Date	Eff. Chart Cell Type	Group(s)	Revised/New Efficiency (%)	Combined efficiency (%)	Uncertainty (%)	Area (cm^2)	V_{OC} (V)	Revised/ New Jsc (mA/cm2)	FF (%)	Suns	Accredited Testing Centers
01/05/2013	Perovskite cells	EPFL	14.1	14.1	0.3	0.2090	1.007	21.34	0.657	1	Newport
01/12/2013	Perovskite cells	KRICT	17.9	17.9	0.8	0.0938	1.109	19.6	0.742	1	Newport
01/04/2014	Perovskite cells	KRICT	17.9	17.9	0.8	0.0937	1.1142	21.8	0.736	1	Newport
01/11/2014	Perovskite cells	KRICT	20.1	20.1	0.4	0.0955	1.059	24.65	0.77	1	Newport
01/02/2015	Perovskite cells	NIMS	15.0	15.0	0.6	1.017	1.09	20.61	0.668	1	AIST
01/06/2015	Perovskite cells	NIMS	15.6	15.6	0.6	1.02	1.074	19.29	0.751	1	AIST
01/12/2015	Perovskite cells	KRICT/UNIST	20.1	20.1	0.4	0. 0955	1.059	24.65	0.77	1	Newport
01/03/2016	Perovskite cells	KRICT/UNIST	22.1	22.1	0.7	0.0946	1.105	24.97	0.803	1	Newport
01/03/2016	Perovskite cells	KRICT/UNIST	19.7	19.7	0.6	0.9917	1.104	24.67	0.723	1	Newport
01/07/2017	Perovskite cells	KRICT	22.7	22.7	0.8	0.0935	1.144	24.92	0.796	1	Newport
01/07/2017	Perovskite cells	KRICT	20.9	20.9	0.7	0.991	1.125	24.92	0.745	1	Newport
18/05/2018	Perovskite cells	ISCAS, Beijing		23.3		0.074	1.791	25.24	0.784	1	Newport
01/09/2018	Perovskite cells	ISCAS, Beijing	23.7	23.7	0.8	0.0739	1.1697	25.40	0.798	1	Newport

01/01/2019	Perovskite cells	KRICT/MIT	24.2	24.2	0.8	0.0955	1.1948	24.16	0.84	1	Newport
01/06/2019	Perovskite cells	ANU	21.6	21.6	0.6	1.0235	1.193	21.64	0.836	1	CSIRO
01/07/2019	Perovskite cells	KRICT/MIT (tied w/ Korea U)	25.2	25.2	0.8	0.0937	1.1805	24.14	0.848	1	Newport
01/12/2019	Perovskite cells	Nanjing Univ	24.2	24.2	0.8	1.041	1.986	15.93	0.766	1	JET
28/07/2020	Perovskite cells	UNIST	25.5	25.5	0.8	0.095	1.189	25.68	0.83	1	Newport
03/12/2021	Perovskite cells	UNIST	25.7	25.7	3.2	0.096	1.179	25.8	84.6	1	Newport
16/11/2022	Perovskite cells	UNIST	25.8	25.8	3.1	0.0959	1.1797	25.77	84.9	1	Newport
01/03/2023	Perovskite cells	IoS/CAS	26.0	26.0	1.9	0.0746	1.19	26.00	84	1	JET
10/05/2023	Perovskite cells	U. of Science and Technology of China	26.1	26.1	2.2	0.05127	1.2	25.7	84	1	NPVM

Table 3-25 Laboratory tests of Perovskite cells from 2013 till 2023 (RD[24])

Considering the provided expected module efficiencies and the results from the previous tool analysis, it becomes evident that Perovskite cells require larger solar panel areas compared to thin film InGaP/GaAs/Ge cells. However, when factoring in specific power density, the advantages of choosing Perovskite cells become relevant, despite their current low TRL.

	Thin film InGaP/GaAs/Ge (e.g.,3G30-C)	Perovskite cells
Expected module efficiency (2050) with adequate funding	36%	29%
Solar panels area required [km2]	4.9	6.2
Specific power density [W/g]	0.8	23
Mass/area [kg/m2] under 1 Sun	2.05	0.07
Overall PV mass [tons]	≈ 10 000 *	≈ 500 *

Table 3-26 Comparison between the two final options

* Not considering support structures or deployment mechanisms

From the above considerations it becomes clear that the implementation of Perovskite cells for the SPS is more advantageous.

In conclusion, while thin film InGaP/GaAs/Ge cells hold their own in terms of efficiency and TRL, Perovskite cells prove to be a compelling option due to their cost-effectiveness and impressive specific power density, even considering their current lower TRL status (which is an attribute with low value in the project decisional logic). Moreover, as showed in Table 3-25, this technology shows an incredible rise in efficiencies in the last 10 years, from 14% in 2013 to 26% in 2023 (lab tested). For this reason (with adequate funding needed for further research to increase lifetime, crystal stability and overall TRL) Perovskite cells could result as the most promising option for future SPS applications.

Therefore, Perovskite PV cells are selected as baseline.

3.4.2.7 DC to RF power conversion trade-off

We consider four possible power amplifier technologies: SSPA based on semi-conductor components, TWTA, Klystrons based on vacuum tube or valve and Magnetrons (see TN2). The efficiency of the DC to RF power conversion depends mainly on the frequency. Typically SSPA are suited for low power amplification up to 10 GHz. A high power (>50W) SSPA consists of the paralleling of high power transistors or transistor strips (~1 to 10W each. SSPA requires simple EPC, which could reach fair efficiency (~0.95). SSPA are well suited for phased array because of their compactness and low weight.

TWTA are used in the Ku to Q/V bands (10GHz to 50 GHz). They offer high power (200 to 500W) with a fair PAE of about 70%. The routing (waveguide, coaxial, circulator) of the RF power to the input port of the antenna generates losses, which reduces the end to end effectiveness of as much. TWTA requires several power sources including high voltages; the EPC will have a lower efficiency (~90%).

Klystrons operate in a large frequency range but presents some problems for mass/volume. Like TWTA, klystron requires to route (waveguide, coaxial, circulator) the RF power to the antenna input which generates losses (>0.5 dB / 0.89). Klystrons can operate directly as frequency generators.

While unlike other vacuum tubes, such as klystrons or traveling-wave tubes (TWTs), the magnetron cannot operate alone as an amplifier to increase the intensity of an applied microwave signal, it can, however, be converted into a two-port amplifier. This converted magnetron is capable of delivering over 30 dB of gain while remaining phase-locked to the input signal across a wide frequency range. This transformed use of the magnetron is known as the MDA (Magnetron Directional Amplifier).

SSPA could represent a different approach (using semi-conductor component and not electron tubes) which could permits some advantages both in antenna integration (no wave guide needed) and in operational complexity (lower thermal loads on the structure and possibility to have electronically steerable antenna).

Details on the criteria used for the orbit trade-off are provided below:

- **Cost**: Possible costs of the group of DC-RF converters needed for the application
- **Energy expenditure**: Not applicable
- **Social acceptance**: Not applicable
- **Carbon footprint**: Not applicable
- **Mass / Area / Volume**: Number, mass and volume of DC-RF converters needed for the same amount of power.
- **Design Complexity**: Possible integration issues in the satellite structure or in the phased array antenna (particular waveguide structure needed)
- **Deployment Complexity**: Not applicable
- **Operational Complexity**: Possible thermal loads that need to be dissipated (depend on the technology efficiency) and possibility to not have mechanical steering
- **Failure tolerance**: Possibility to have failure of a single DC-RF converter and its consequences on the system.
- **Capacity factor**: Not applicable
- **Modularity** : Possibility to divide the DC-RF overall circuit in more possible sub-parts (whit lowest possible dimensions)
- **Scalability**: Possibility to scale the technology for a lower amount of power needed for example for demonstrators
- **TRL / Heritage**: TRL of the technology for the expected efficiency range (70-80%)
- **Lifetime**: Real and prospected lifetime of the technology

- **Industrial capability/ scalability**: Possibility to scale up the production of this technology

<table>
<tr><th colspan="2">Technical Criteria</th><th>Comments</th></tr>
<tr><th>Criteria</th><th>Description</th><th>Comparison of the 4 options</th></tr>
<tr><td>Cost</td><td>Possible cost of the entire group of converters needed</td><td>The cost of the single DC-RF converter is not the main problem, which drives the choice. However, the difference in costs become relevant when we consider the industrial scalability (the possibility to scale up the production of these converters). For this reason surely the mass production of millions of semiconductor chips (SSPA) could be more affordable than the other three technologies , in particular with respect to Klystron ones (very high mass and power for every converter)</td></tr>
<tr><td>Mass/Area/Volume</td><td>Number, mass and volumes required for the technology to handle the required power conversion</td><td>In order to satisfy the request of power conversion, every type of technology has a different fraction of mass/power (kg/kW). Here are some numbers for these technologies (see [RD27]) which permits to understand the problem of weight for electron tubes like technologies (in contrast to SSPA)
<table>
<tr><th>Transmitter</th><th>Type</th><th>Klystron</th><th>Magnetron</th><th>Solid-State</th></tr>
<tr><td>Maximum converter P_{out} (W CW)</td><td></td><td>26,000</td><td>5,000</td><td>59</td></tr>
<tr><td>Converter operating voltage (V_{dc})</td><td></td><td>28,000</td><td>6,000</td><td>80</td></tr>
<tr><td>Converter mass (kg)</td><td></td><td>14.15</td><td>1</td><td>0.001</td></tr>
<tr><td>No. of converters in 500-m diameter antenna (example)</td><td></td><td>209,863</td><td>~400,000</td><td>84,001,536</td></tr>
<tr><td>Total mass of converters (kg)</td><td></td><td>~3,000,000</td><td>~400,000</td><td>~84000</td></tr>
<tr><td>Transmitter specific mass (kg/m²)</td><td></td><td>40.4</td><td>32</td><td>33.9</td></tr>
</table></td></tr>
<tr><td>Design complexity</td><td>Integration problems of the technology in the satellite and the phased array antenna</td><td>The electron tube technologies such as Klystrons and TWTA require a waveguide structure with respect to SSPA. In fact, unlike the slotted waveguide array where a tube would feed many radiating slots, the solid-state transmitter places a power amplifier and phase shifter behind every radiating element.
Moreover, technologies such as Klystron have an output frequency that depends a lot on manufacturing process. This, in a large mass production, could result in a series of slightly different Klystrons with a slightly different frequency. The consequence would be (when we consider the overall antenna integration and operation) a noisier signal with respect using SSPA technologies.</td></tr>
<tr><td>Operational complexity</td><td>Possible difficulties to manage thermal load deriving from the inefficiencies of the DC-RF technology and possibility to avoid mechanically steerable antennas</td><td>TWTA, Magnetron and Klystron technologies could have two operational difficulties with respect to SSPA when we are considering the overall antenna integration:
More concentrated heat loads to be dissipated (high temperatures in more disparate areas)
Necessity to have mechanically steerable antenna (while the use of SSPA permits an electronically steerable antenna, lowering the operational complexity of the system)</td></tr>
<tr><td>Failure Tolerance</td><td>Possibility to have failure of a single converter and the consequences on the overall system operation</td><td>Obviously considering that for SSPA we are talking about millions of different components in series it is immediately consequent that a failure of a SSPA could have lower implications on the overall system (with respect to electron tubes technologies where a failure of only a small part of converters could imply a relevant lowering of the power output).</td></tr>
</table>

Technical Criteria		Comments
Modularity	Capability of the analyzed solution to be realized with separate parts that, when combined, form a complete whole	Being a very high number (million) of equal components needed, using the SSPA technology results surely as the most modular solution with respect to Klystron, Magnetron and TWTA.
Scalability	Capability of the analyzed solution to be scalable in power performance	Every SSPA as a very small max power output with respect to Magnetron, TWTA and in particular Klystron (as showed before in mass/area/volume comment). For this reason, using SSPA could permit to have an infinite possibilities of overall output power depending on what is needed.
TRL / Heritage	Technology maturity of the proposed solution	TWTA and SSPA are the technologies with already lots of applications in space (with efficiencies near what we expect for this application). In fact, at the moment, magnetrons and especially klystrons are used mainly in particle accelerator or other applications (where less efficiency is needed)
Lifetime	Capability of the analyzed solution to comply with the specified functionalities for the entire lifetime minimizing the maintainability	Similar lifetime are expected for all the four technologies (15-25 years) with small advantages for SSPA (which are the simplest solution in terms of lower failure probability), which could also have the easier feasibility to have maintenance in space (if a single converter has a failure or a major degradation).
Industrial capability/scalability	Possibility to scale up the production of the technology	Obviously considering that for SSPA we are talking about millions of different components in series it is immediately consequent that industrial scalability could be easier for this technology with respect to electron tube technologies (which require a lower number of converters for the same overall output value)

Table 3-27 Technical criteria notes for DC-RF technology trade-off

Note also that the choice of the technology for the conversion of DC into RF depends on many design elements of the WPT: frequency, type and size of the antenna, power to be transmitted. At this moment the SSPA could be chosen for the proposed range of frequencies.

WPT antenna architecture / DC to RF power conversion				OPTION 1		OPTION 2		OPTION 3		OPTION 4	
				SSPA		TWTA		Magnetron		Klystron	
Criteria	Applicability [N/A= 0, Applicable = 1]	Weight Factor [1-5]	Applicability * Weight Factor	Input [1-5]	Value [Weight Factor * Input]	Input [1-5]	Value [Weight Factor * Input]	Input [1-5]	Value [Weight Factor * Input]	Input [1-5]	Value [Weight Factor * Input]
Cost	1	5	5	3	15	2	10	2	10	1	5
Energy expediture	0	3	0		0		0		0		0
Social acceptance	0	5	0		0		0		0		0
Carbon footprint	0	5	0		0		0		0		0
Mass / Area / Volume	1	5	5	4	20	1	5	2	10	1	5
Design Complexity	1	3	3	4	12	2	6	2	6	2	6
Deployment complexity	0	3	0		0		0		0		0
Operational complexity	1	3	3	3	9	1	3	1	3	1	3
Failure Tolerance	1	2	2	3	6	2	4	2	4	2	4
Capacity factor	0	4	0		0		0		0		0
Modularity	1	4	4	3	12	1	4	1	4	1	4
Scalability	1	4	4	4	16	2	8	2	8	2	8
TRL / Heritage	1	1	1	2	2	3	3	1	1	1	1
Lifetime	1	4	4	3	12	2	8	2	8	2	8
Industrial capability/scalability	1	3	3	4	12	2	6	2	6	1	3
TOTAL SCORE					3.41		1.68		1.76		1.38

Table 3-28 DC to RF power conversion trade-off

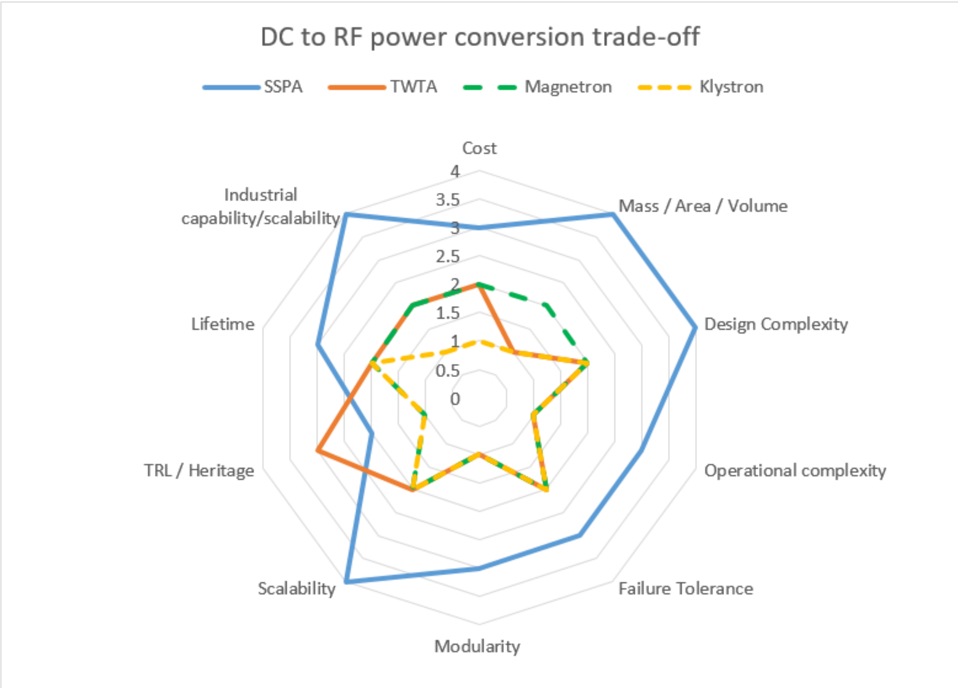


Figure 3-39 DC to RF power conversion trade-off summary graph

3.4.2.8 AOCS trade-off

The AOCS trade-off is carried on studying different solution for AOCS architecture .

These solutions are divided in two branches: Sensor suite and Actuator suite .

For sensor suite we could trade among the following elements:

1. Sun-sensor + Star tracker + Accelerometer + Gyroscope
2. Sun-sensor + Star tracker + Accelerometer + Gyroscope + Lidar
3. Sun-sensor + Star tracker + Accelerometer + Gyroscope + GNSS
4. Sun-sensor + Star tracker + Accelerometer + Gyroscope + Ground tracking

Note: GNSS or Lidar or Ground tracking are sensors to be used for monitoring the relative position with the ground stating

For actuator suite we could trade among the following elements :

1. CMGs + RCS Thrusters
2. CMGs + magnetometer + Thrusters

A further trade-off on thruster technology is performed to implement the Attitude control function and station keeping

For Attitude Control function the following option to trade are

1. Cold gas Thruster
2. Bi-propellant Hypergolic Thruster
3. Mono-propellant Thruster

For station keeping function the following option to trade are

1. Bi-propellant Hypergolic Thruster
2. Electric Thrusters

Note: according with a preliminary evaluation the solar pressure in GEO is such to generate on the Solaris concept an equivalent perturbation force of 40-60 N that shall be compensated in order to prevent a phasing between space segment and ground segment.

AOCS sensor suite				OPTION 1		OPTION 2		OPTION 3		OPTION 4	
				Sun-sensor + Star tracker + Accelerometer + Gyroscope		Sun-sensor + Star tracker + Accelerometer + Gyroscope + Lidar		Sun-sensor + Star tracker + Accelerometer + Gyroscope + GNSS		Sun-sensor + Star tracker + Accelerometer + Gyroscope + Ground tracking	
Criteria	Applicability [N/A= 0, Applicable = 1]	Weight Factor [1-5]	Applicability * Weight Factor	Input [1- 5]	Value [Weight Factor * Input]	Input [1- 5]	Value [Weight Factor * Input]	Input [1- 5]	Value [Weight Factor * Input]	Input [1- 5]	Value [Weight Factor * Input]
Cost	1	5	5	2	10	3	15	3	15	2	10
Energy expediture	1	3	3	2	6	3	9	3	9	3	9
Social acceptance	0	5	0		0		0		0		0
Carbon footprint	0	5	0		0		0		0		0
Mass / Area / Volume	1	5	5	1	5	2	10	2	10	1	5
Design Complexity	1	3	3	4	12	2	6	2	6	4	12
Deployment complexity	1	3	3	4	12	2	6	2	6	4	12
Operational complexity	1	3	3	2	6	2	6	2	6	2	6
Failure Tolerance	1	2	2	5	10	5	10	5	10	5	10
Capacity factor	0	4	0		0		0		0		0
Modularity	1	4	4	5	20	5	20	5	20	5	20
Scalability	1	4	4	5	20	5	20	5	20	5	20
TRL / Heritage	1	1	1	5	5	5	5	5	5	5	5
Lifetime	1	4	4	5	20	5	20	5	20	5	20
Industrial capability/scalability	1	3	3	5	15	5	15	5	15	5	15
TOTAL SCORE					**3.53**		**3.55**		**3.55**		**3.60**

Table 3-29 AOCS sensor suite trade-off

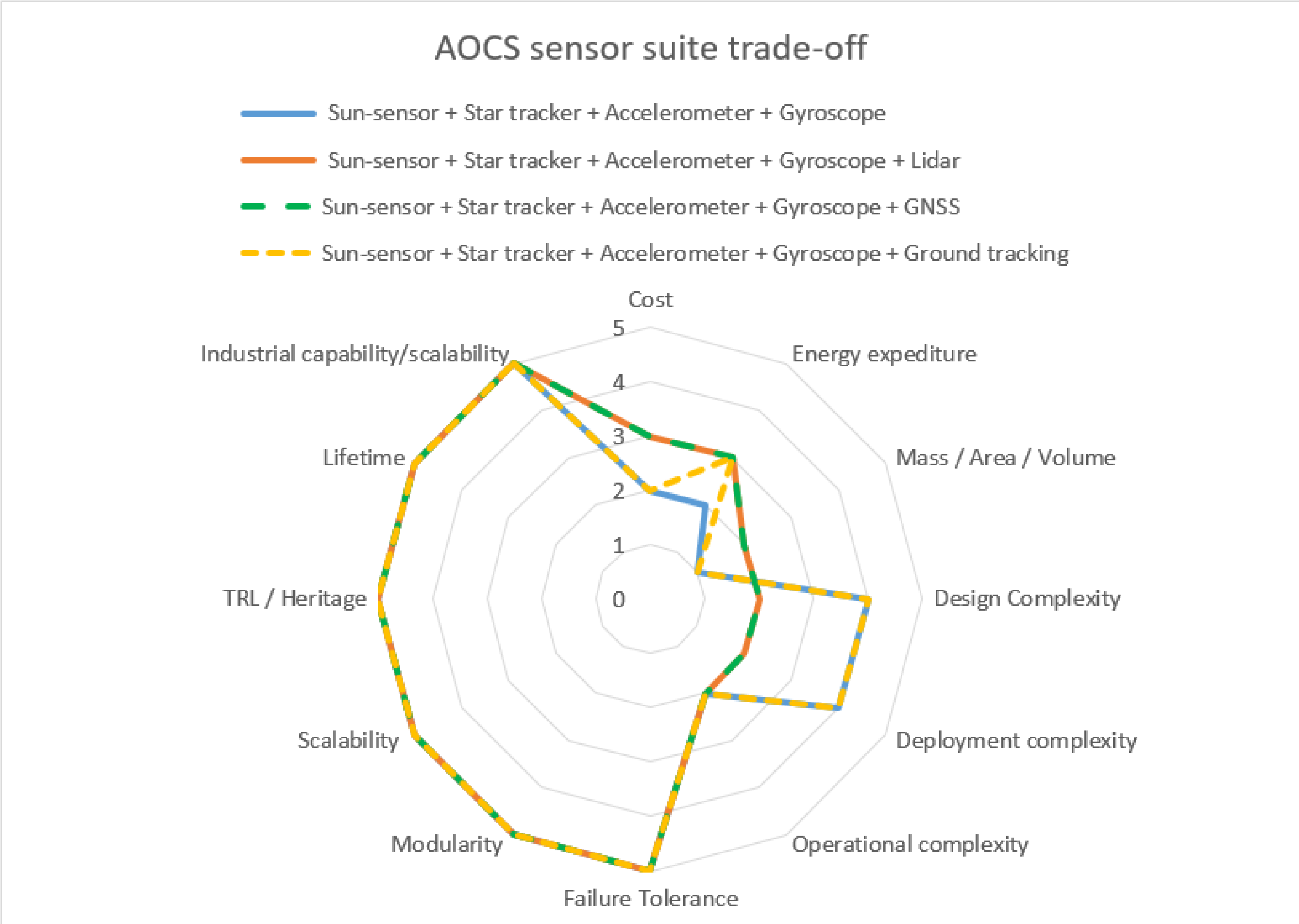


Figure 3-40 AOCS sensor suite trade-off summary graph

AOCS Actuator suite				OPTION 1		OPTION 2	
				CMGs + RCS Thrusters		CMGs + magnetometer + Thrusters	
Criteria	Applicability [N/A= 0, Applicable = 1]	Weight Factor [1-5]	Applicability * Weight Factor	Input [1- 5]	Value [Weight Factor * Input]	Input [1- 5]	Value [Weight Factor * Input]
Cost	1	5	5	3	15	2	10
Energy expediture	1	3	3	2	6	3	9
Social acceptance	0	5	0		0		0
Carbon footprint	0	5	0		0		0
Mass / Area / Volume	1	5	5	3	15	2	10
Design Complexity	1	3	3	3	9	2	6
Deployment complexity	1	3	3	3	9	2	6
Operational complexity	1	3	3	3	9	2	6
Failure Tolerance	1	2	2	2	4	3	6
Capacity factor	0	4	0		0		0
Modularity	1	4	4	3	12	3	12
Scalability	1	4	4	3	12	3	12
TRL / Heritage	1	1	1	5	5	5	5
Lifetime	1	4	4	5	20	5	20
Industrial capability/scalability	1	3	3	5	15	5	15
TOTAL SCORE					**3.28**		**2.93**

Table 3-30 AOCS actuator suite trade-off

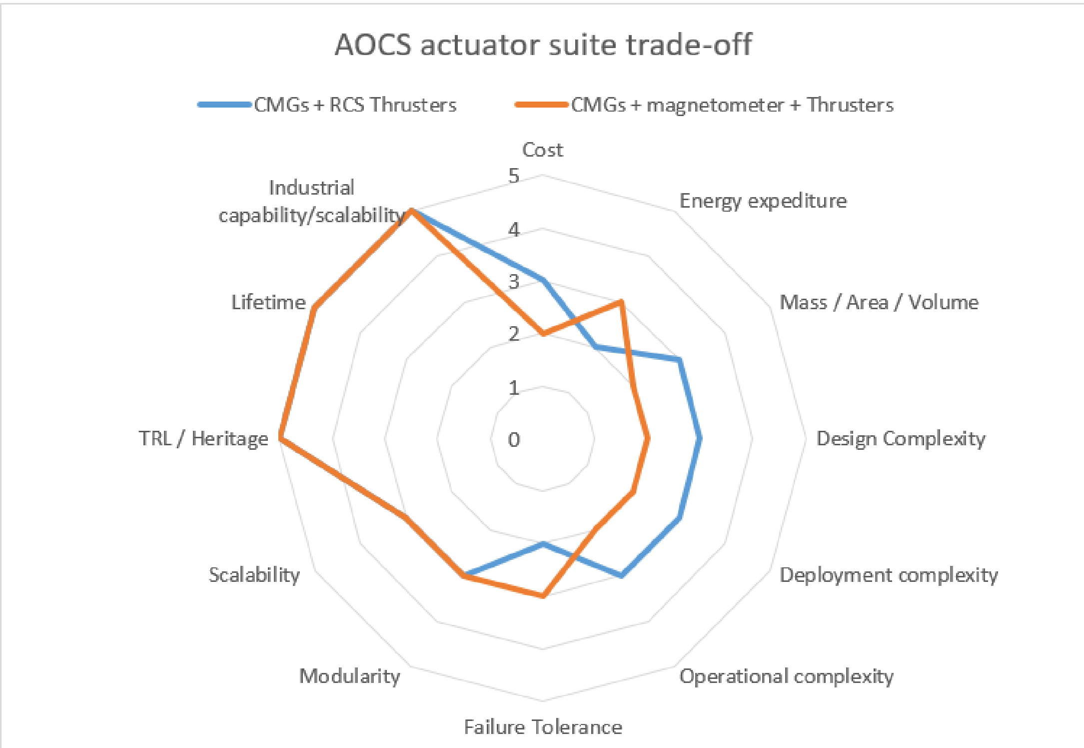


Figure 3-41 AOCS actuator suite trade-off summary graph

AOCS Attitude control thruster				OPTION 1		OPTION 2		OPTION 3	
				Cold gas Thruster		Bi-propellant Hypergolic Thruster		Mono-propellant Thruster	
Criteria	Applicability [N/A= 0, Applicable = 1]	Weight Factor [1-5]	Applicability * Weight Factor	Input [1- 5]	Value [Weight Factor * Input]	Input [1- 5]	Value [Weight Factor * Input]	Input [1- 5]	Value [Weight Factor * Input]
Cost	1	5	5	3	15	5	25	4	20
Energy expediture	1	3	3	3	9	3	9	3	9
Social acceptance	0	5	0		0		0		0
Carbon footprint	1	5	5	4	20	3	15	4	20
Mass / Area / Volume	1	5	5	2	10	3	15	4	20
Design Complexity	1	3	3	2	6	4	12	3	9
Deployment complexity	1	3	3	2	6	4	12	3	9
Operational complexity	1	3	3	2	6	3	9	4	12
Failure Tolerance	1	2	2	4	8	4	8	4	8
Capacity factor	0	4	0		0		0		0
Modularity	1	4	4	5	20	5	20	5	20
Scalability	1	4	4	5	20	5	20	5	20
TRL / Heritage	1	1	1	5	5	5	5	5	5
Lifetime	1	4	4	5	20	5	20	5	20
Industrial capability/scalability	1	3	3	5	15	5	15	5	15
TOTAL SCORE					**3.56**		**4.11**		**4.16**

Table 3-31 AOCS thruster trade-off

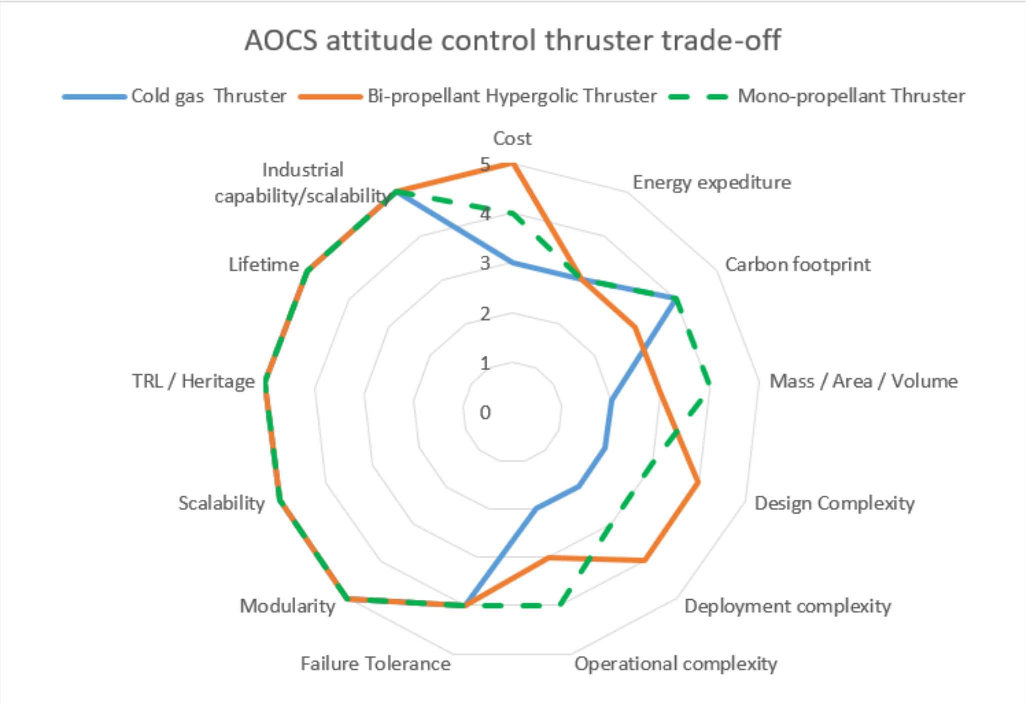


Figure 3-42 AOCS attitude control thruster trade-off summary graph

AOCS station keeping thruster				OPTION 1		OPTION 3	
				Mono-propellant Thruster		Electric Thruster	
Criteria	Applicability [N/A= 0, Applicable = 1]	Weight Factor [1-5]	Applicability * Weight Factor	Input [1- 5]	Value [Weight Factor * Input]	Input [1- 5]	Value [Weight Factor * Input]
Cost	1	5	5	2	10	3	15
Energy expediture	1	3	3	2	6	3	9
Social acceptance	0	5	0		0		0
Carbon footprint	1	5	5	2	10	3	15
Mass / Area / Volume	1	5	5	2	10	3	15
Design Complexity	1	3	3	2	6	3	9
Deployment complexity	1	3	3	2	6	3	9
Operational complexity	1	3	3	2	6	3	9
Failure Tolerance	1	2	2	3	6	3	6
Capacity factor	0	4	0		0		0
Modularity	1	4	4	3	12	3	12
Scalability	1	4	4	3	12	3	12
TRL / Heritage	1	1	1	3	3	2	2
Lifetime	1	4	4	3	12	3	12
Industrial capability/scalability	1	3	3	3	9	3	9
TOTAL SCORE					**2.40**		**2.98**

Table 3-32 AOCS station keeping thruster trade-off

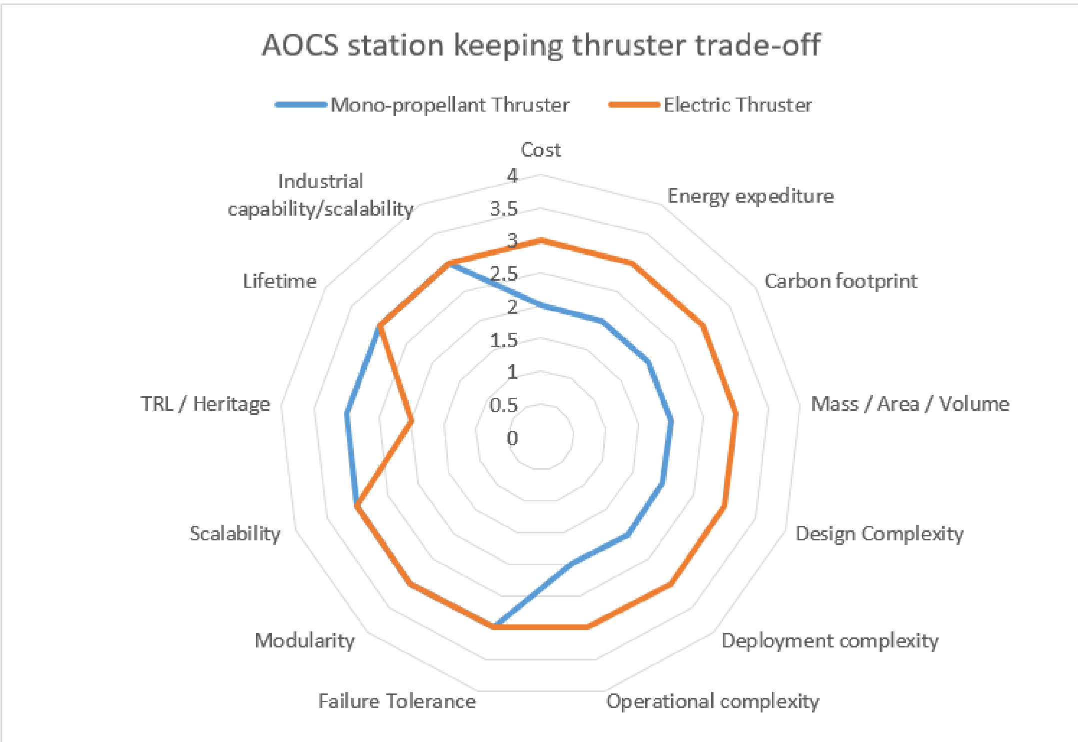


Figure 3-43 AOCS station keeping thruster trade-off summary graph

The above tradeoff allows to define the reference architecture for attitude control and station keeping function.

This reference architecture is composed by a

- star trackers
- sun sensors
- accelerometer gyroscopes
- ground station tracking
- control momentum gyros (CMGs)
- monopropellant RCS thrusters
- electric thrusters

Particularly for electric thruster , the hall effect thrusters are considered as the reference technology.

Nowadays these thruster are able to generate mN-magnitude thrust, but are under developing thruster able to generate N-magnitude that have to be considered as reference to compensate a solar wind perturbation of 40-60 N .

The class of magnitude for CMGs and RCS thruster for attitude control could be preliminary evaluated once a reference geometrical (including mass properties) architecture would be defined.

3.4.2.9 Structures & Materials trade-off

This trade-off is focused on the SKR identified 3 options concerning structures with the relevant materials for the solar array modules concurring to the SBSP assembly as here after summarized:

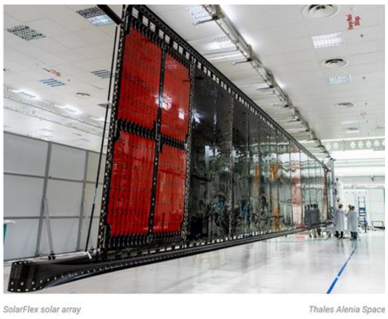
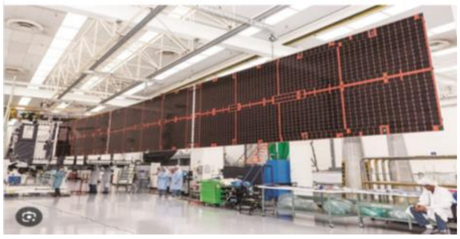
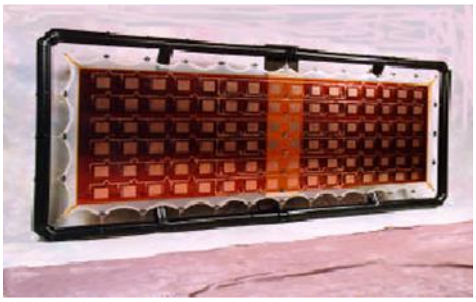
OPTION 1	OPTION 2	OPTION 3
Flexible Roll-out Structures	**Rigid Structures**	**Inflatable Structures**
		

Figure 3-44 Options for Structures for Trade-off

Here below are reported for both the general and technical criteria the notes which have supported the final scoring evaluation table

General Criteria Notes for Structures & Materials

General Criteria		OPTION 1	OPTION 2	OPTION 3
Criteria	**Description**	**Flexible Roll-out Structures**	**Rigid Structures**	**Inflatable Structures**
Cost	Relative cost of the proposed solution, VALCOE, LCOE	Mimimun in relation to simple manufacturing and launch costs	High in relation to more complex manufacturing and launch costs	Medium in relation to manufacturing and launch costs
Energy expediture	Energy Returned on Energy Invested across the system lifetime	Minimum energy expenditure expected due to simple manufacturing, number of launches and simple deployment	High energy expenditure expected due to simple manufacturing, high number of launches and more complex deployment	Medium energy expenditure expected due to medium complexity in manufacturing, number of launches and inflation/ deployment/rigidization
Social acceptance	People acceptance of the proposed solutions	Very good due to simple but highly functional solution	Good as current baseline in all satellites	Medium due to the risks connected to the successful inflation/rigidization of the inflatable supporting structure
Environmental impact	Carbon footprint of the proposed solutions	Minimum carbon footprint expected due to simple manufacturing and completion of SBSP with a minimum number of launches	High carbon footprint expected due to more complex manufacturing and completion of SBSP with a high number of launches	Medium due to the inflation/rigidization system and number of launches

Table 3-33 General Criteria Notes for Structures & Materials

Technical Criteria Notes

Technical Criteria		OPTION 1	OPTION 2	OPTION 3
Criteria	Description	Flexible Roll-out Structures	Rigid Structures	Inflatable Structures
Mass / Area / Volume	Physical dimensions of the analysed solutions will be assessed and quoted	By swapping rigid panels for thin, flexible sheets, the upgraded design achieves reduced weight and compact stowage. The adoption of flexible polymer material is just 0.002 inches thick, so showing a significant mass & volume reduction (source Lockheed Martin). In accordance with data the gain in mass wrt rigid solar arrays is in the 20% range, the gain in volume is of 75%, the reference area of about 90-100 m2. Mass of one Roll-Out solar array of 350 kg.	Traditional solar panels used to power satellites are bulky, with sandwich panels folded together using mechanical hinges and considering the gap to be left between adjacent folded panels for dynamic. Typical rigid solar panels range from 0.75 to 1.5 inches thick based on CFRP skins with Al alloy H/C core, leading to higher mass and volume wrt flexible solutions.	The inflatable structures can save less in terms of mass and volume wrt the roll-out structures based on the need for and inflation system and require, depending on the rigidization technique, an additional mass expense has to be considered (e.g. for hardening foam or heaters & harness/power system to provide curing of the inflated booms/frame).
Design Complexity	Streamline of proposed design	The design complexity is related to composite booms which have to be designed to provide the necessary strain energy release in order to successfully operate the deployment. The entire system including substrate flexible membrane with the attached flexible solar cells are assumed as an available design to be upscaled from potential suppliers (Redwire Corporation or Thales Alenia Space France) of roll out solar arrays. The design has to take into account of a 15 years lifetime duration in the exposed environment (debris, radiation, etc.).	They exploit standard consolidated design based on sandwich panels (CFRP skins with Al alloy honeycomb) to support rigid solar cells which yield to solar panels that are large in dimensions and rigid. Since a higher number of components and mechanisms (HDRMs and hinges) affect the design complexity and reliability although widely used in past and current satellites. The design has to take into account of a 15 years lifetime duration in the exposed environment (debris, radiation, etc.).	The design complexity is mainly relevant to the inflatable booms and/or frames and their rigidization system to deploy and keep in shape the flexible membranes supporting the flexible solar cells. The inflation and rigidization system are then adding further complexity in terms of the fluidic control for inflation by gas or directly operated by a rigidizable foam or power system to provide uniform curing of the inflatable parts if not relying on curing by UV exposure. The attached flexible solar cells are assumed as an available design to be upscaled from potential suppliers (Redwire Corporation or Thales Alenia Space France) as per the roll out solar arrays. The design has to take into account of a 15 years lifetime duration in the exposed environment (debris, radiation, etc.).

Technical Criteria		OPTION 1	OPTION 2	OPTION 3
Deployment complexity	How difficult would it be to launch and assemble the SBSP system	The deployment complexity of the each module is very low as it is based on the composite booms strain energy release for the membrane with the attached solar cells rolling out, instead of complex deployment mechanisms, so drastically reducing the likelihood of jamming or motors failure during this operation. Launch has been already perfomed in dedicated canisters and assembly to the SBSP in unrolled configuration can be thought as robotically perfomed on a truss with dedicated attachment points.	The deployment complexity of each module obtained by the joining of several panels is low due to the wide experience in past and current satellites with the relevant HDRMs and deployment mechanisms. One or more modules could be launched in stacked configuration, each one composed of several panels and then assembled to the SBSP in folded configuration for example robotically performed on a truss with dedicated attachment points.	The deployment complexity of each module is high in relation to the inflation and rigidization which has to occur slowly such as to avoid jamming of the parts, puncturing or damaging of the inflatable elements but this slow deployment process could lead to premature and not uniform rigidization with consequent deviations in shape. Launch of modules could be performed in dedicated support platforms (e.g. sandwich panels) including on the backside the relevant inflation system and assembly to the SBSP before inflation can be thought as robotically perfomed on a truss with dedicated attachment points.
Operational complexity	How difficult would it be to operate, maintain and decommission the SBSP system	The operational complexity is very low with the support of a robotic arm (as demonstrated on the ISS using the Robotic Arm) for installation, the deployment is activated and commanded via local controllers and possibly assisted by video. The unrolling operation performed by booms strain energy release.	The operational complexity is well known and very low due to hundreds of rigid solar arrays release and deployment with different dimensions of the panels and in different orbits.	The operational complexity is high (as mentioned above for the deployment complexity) in relation to the risks connected to the deployment/inflation and subsequent rigidization. High risk is related to the debris impacts which may occur before final inflation and rigidization of the inflatable structure so compromising the entire module.

Technical Criteria		OPTION 1	OPTION 2	OPTION 3
Failure Tolerance	Capability of the solution to withstand to failure and performance degradation	The risk of failure during the deployment phase is very low due to simplicity of the system. The risk of local damaging by in-orbit particles impacts is only locally affecting the panels performances and the connections redundancy is normally adopted to avoid affecting an entire string of solar cells. The risk of damages is increased for long mission duration and increased exposed surfaces like for the SBSP. Maintenance and repair of other parts of the module or its full replacement has to be performed by robotics. Performance degradation expected due to solar cells efficiency degradation between BOL & EOL.	The risk of failure of hinge mechanisms between adjacent panels or HDRMs misfunctioning could lead to lack or partial deployment of a single module composed of several panels but is considered low due to wide heritage and redundancies. Also in this case the local impacts of particles is not affecting the failure of an entire string of solar cells due to redundant contacts. The risk of damages is increased for long mission duration and increased exposed surfaces like for the SBSP. Maintenance and repair of other parts of the module or its full replacement has to be performed by robotics. Performance degradation expected due to solar cells efficiency degradation between BOL & EOL.	The risk of puncturing/damaging during packaging and deployment is high, in addition to the risk of being impacted during the very same inflation/rigidization process and redundancy of the inflatable parts is not practicable. Jamming during deployment or non uniform rigidization can lead to abnormal final shape with a performances degradation. As per the solar cells also in this case the local impacts of particles is not affecting the failure of an entire string of solar cells due to redundant contacts. The risk of damages is increased for long mission duration and increased exposed surfaces like for the SBSP. Maintenance and repair of other parts of the module or its full replacement has to be performed by robotics. Performance degradation expected due to solar cells efficiency degradation between BOL & EOL.
Capacity factor	How much power can be provided by the solution	The Roll-out Solar Arrays span in terms of specific power (w/kg) from 120 to 200 w/kg depending on the solar cells efficiency (29 to 33 %).	The Rigid Solar Arrays in terms of specific power (w/kg) are in the 50 w/kg depending on the solar cells efficiency (29 %) to be compared with the more than double 120 w/kg specific power of the Roll-out Solar Arrays.	This option can roughly be placed in between the Roll-out Solar Arrays and the Rigid Solar Arrays due the less favourable specifc power caused by the inflation/rigidization system
Modularity	Capability of the analyzed solution to be realized with separate parts that, when combined, form a complete whole	The modularity is high for Roll-out Solar Arrays as demonstrated for the ISS application and for the SBSP each module can directly concur to the final assembly.	The modularity is practicable and each module is composed by submodules (single solar arrays panels) concurring to the final SBSP assembly. The rigid solution however imposes more	As for the Roll-out Solar Panels the modularity is high and based on single modules concurring to the final SBSP assembly.

Technical Criteria		OPTION 1	OPTION 2	OPTION 3
			limitations in terms of final dimensions of the module.	
Scalability	Capability of the analyzed solution to be scalable in performance	Scalability with respect to the current Roll-out Solar Arrays size and power production on the ISS has been already done passing from a scaled-down on-orbit flight testing to the actual ISS full size and can further be pursued for very high power levels with a modular photovoltaic blanket assembly and scaled deployable booms.	Less scalable for higher power purposes due to the rigid nature of these solar arrays which requires more volume due to lower compaction with respect to Roll-Out Solar Arrays.	Scalability is more limited with respect to the Roll-out Solar Arrays as this option requires also a scaling up of the entire active system for inflation and rigidization to provide deployment and shaping. Also the time and difficulty for inflation and optimal rigization of the inflatable structure is not in favour of size increase. The solar cells parts would be on the other hand as scalable as per the Roll-out Solar Arrays option.
TRL / Heritage	Technology maturity of the proposed solution	TRL9 based on Roll-Out Solar Arrays (IROSA) for the International Space Station.	TRL9 based on past and current satellites deployable Solar Arrays	TRL4-5 for the technologies relevant to the deployment and rigidization of inflatable booms and frames
Lifetime	Capability of the analyzed solution to comply with the specified functionalities for the entire lifetime minimizing the maintainability	Lifetime and EOL performances are mainly relevant to the solar cells efficiency degradation due to the prolonged radiation exposure and space enviroment considering a lifetime of 15 years. A higher BOL efficiency e.g. 34% is not enough to guarantee higher EOL efficiency. A degradation in the 20-30% has to be considered.	As per Roll-out Solar Arrays	As per Roll-out Solar Arrays
Industrial capability/scalability	In terms of logistic (technological reasons vs. geopolitical location) and industrial supply	Capability and scalability in US and France (TASF)	Capability & scalability in France (TASF) and worldwide	Capability & scalability in US & France (TASF) for the flexible solar arrays, capability in US for the inflatable truss or frame structures

Table 3-34 Technical Criteria Notes for Structures & Materials

The relevant scoring table based on the above criteria notes has led to the following results:

Structures and materials						
Criteria				OPTION 1	OPTION 2	OPTION 3

	Applicability [N/A= 0, Applicable = 1]	Weight Factor [1-5]	Applicability * Weight Factor	Flexible Roll-out Structures		Rigid Structures		Inflatable Structures	
				Input [1-5]	Value [Weight Factor * Input]	Input [1-5]	Value [Weight Factor * Input]	Input [1-5]	Value [Weight Factor * Input]
Cost	1	5	5	4	20	2	10	3	15
Energy expediture	1	3	3	4	12	2	6	3	9
Social acceptance	1	5	5	5	25	4	20	3	15
Carbon footprint	1	5	5	5	25	2	10	3	15
Mass / Area / Volume	1	5	5	5	25	2	10	3	15
Design Complexity	1	3	3	4	12	3	9	2	6
Deployment complexity	1	3	3	5	15	4	12	2	6
Operational complexity	1	3	3	5	15	4	12	2	6
Failure Tolerance	1	2	2	4	8	4	8	2	4
Capacity factor	1	4	4	5	20	3	12	4	16
Modularity	1	4	4	4	16	3	12	4	16
Scalability	1	4	4	4	16	2	8	3	12
TRL / Heritage	1	1	1	5	5	5	5	2	2
Lifetime	1	4	4	3	12	3	12	3	12
Industrial capability/scalability	1	3	3	4	12	5	15	2	6
TOTAL SCORE					**4.41**		**2.98**		**2.87**

Table 3-35 Final Scoring Table for Structures & Materials

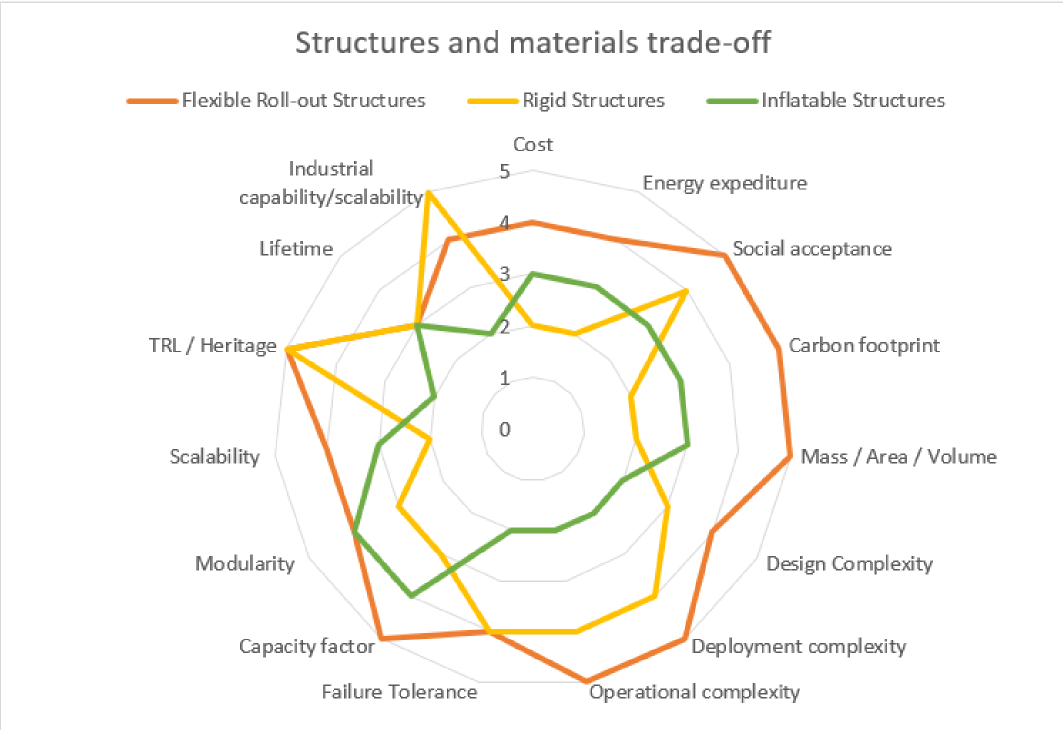


Figure 3-45 Structures and material trade-off summary graph

The Option 1 based on Flexible Roll-out Structures for the SBSP solar arrays results the most suitable for this application.

3.4.2.10 In-space transportation and infrastructure trade-off

As the proposed orbits are GEO and EO and due to the size and inertia of the SPS, the satellite shall be built directly in the operational orbit to prevent the structure to be subjected to excess forces during transportation. Then two routes appear feasible for the transportation and assembly in space orbit-wise: take advantage of a parking LEO orbit (or Geostationary transfer orbit for the GEO case) for transporting the modules via an Orbiter Tug and then transfer it to the target orbit, or an insertion directly in the final orbit. The trade-off has been conducted with the help of the trade-off table interpreting the criteria as follows:

Criteria		OPTION 1	OPTION 2	OPTION 3
Criteria	Description	Injection in LEO	Injection in GTO	Injection in GEO/EO
Cost	Amount of launches required to put all the modules in orbit	Transporting in LEO will allow to exploit the maximum payload capability of the laucher	Lower transportable mass than LEO but higher than directly GEO	Lowest amount of transportable mass
Energy expenditure	Delta V to bring the satellite from transfer orbit to desired orbit	The Delta V required is higher the smallest the semi-major axis of the transfer orbit is	Relatively small as the majority of the Delta V required to increase the apogee has been already applied by the launcher	The satellite is injected directly into the desired orbit, thus no additional insertion maneuvers needed
Carbon footprint	Travel performed via high efficiency thruster	If the Orbital Tug uses an high impulse propulsion system (e.g. electrical propulsion) the transfer from LEO to EO/GEO will consume less propellant than a direct insertion	Same as LEO evaluation with less travel performed using high efficiency thruster	Full chemical propulsion as the only engines utilized are the launcher's ones
Deployment complexity	Ease of inserting modules in target orbit	Orbiter Tug required to capture the payload form the launcher's cargo bay and bring the modules in the operational orbit	Orbiter Tug required to capture the payload form the launcher's cargo bay and bring the modules in the operational orbit	No additional Orbiter Tug required

Criteria		OPTION 1	OPTION 2	OPTION 3
Criteria	Description	Injection in LEO	Injection in GTO	Injection in GEO/EO
Operational complexity	Difficulty for In-Orbit operations	Due to high atmospheric drag and difference in drag area between Orbital Tug and launcher/modules, the rendezvous and retrieval operations will be difficult in LEO	In GTO, it will be easy to perform In-Orbit operations near the apogee, where no air drag is present	The modules will be placed directly in the operational orbit
Scalability	Capability to bring modules for bigger SPS	A LEO injection will allow the full exploit of the launcher's cargo bay, which will in turn allow bigger sized modules	Injection in GTO will allow ≈1/5 of the transportable mass w.r.t. LEO insertion	Injection in GEO will allow ≈1/10 of the transportable mass w.r.t. LEO insertion

Table 3-36 Trade-off criteria for in-orbit transportation and infrastructure

In-space transportation and infrastructure									
				OPTION 1		OPTION 2		OPTION 3	
				Injection in LEO/MEO		Injection in GTO		Injection in GEO/EO	
Criteria	Applicability [N/A= 0, Applicable = 1]	Weight Factor [1-5]	Applicability * Weight Factor	Input [1-5]	Value [Weight Factor * Input]	Input [1-5]	Value [Weight Factor * Input]	Input [1-5]	Value [Weight Factor * Input]
Cost	1	5	5	5	25	3	15	1	5
Energy expediture	1	3	3	2	6	3	9	5	15
Social acceptance	0	5	0		0		0		0
Carbon footprint	1	5	5	5	25	3	15	1	5
Mass / Area / Volume	0	5	0		0		0		0
Design Complexity	0	3	0		0		0		0
Deployment complexity	1	3	3	2	6	2	6	5	15
Operational complexity	1	3	3	2	6	4	12	5	15
Failure Tolerance	0	2	0		0		0		0
Capacity factor	0	4	0		0		0		0
Modularity	0	4	0		0		0		0
Scalability	1	4	4	5	20	3	12	1	4
TRL / Heritage	0	1	0		0		0		0
Lifetime	0	4	0		0		0		0
Industrial capability/scalability	0	3	0		0		0		0

TOTAL SCORE	3.83		3.00		2.57

Table 3-37 In-space transportation and infrastructure trade-off

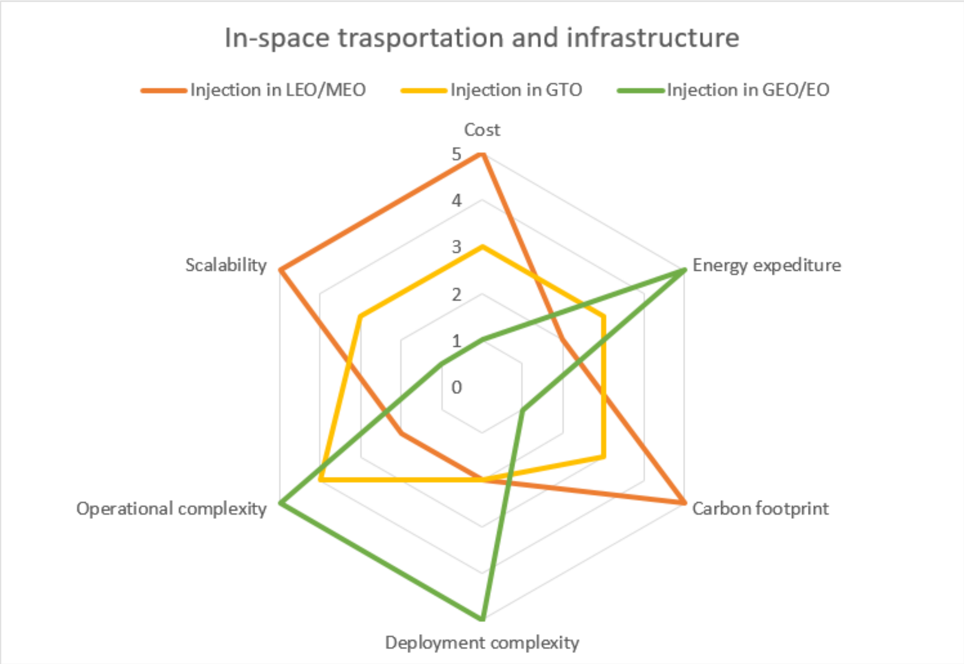


Figure 3-46 In-space transportation and infrastructure trade-off summary graph

The trade-offs shows using a LEO as injection orbit brings the most advantages compared to other configurations, especially considering the propellant required.

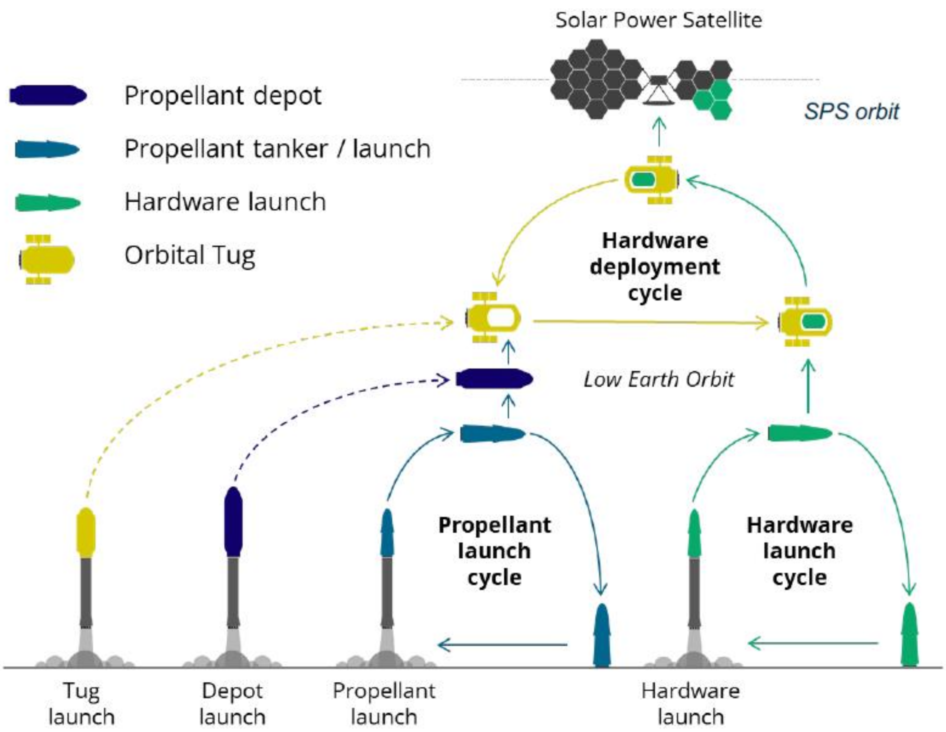


Figure 3-47 Reusable deployment logistics for scenarios using Orbital Tugs

Considering an injection orbit at 500 [km] altitude it is possible to have a rough idea of the amount of launches required to bring all the modules in orbit as well as all the propellant required for the transfer to the operational orbit. It is supposed to have a launcher capable to bring 100 tons in the injection orbit (no volume constraints have been considered as well as no phasing/mating manoeuvers by the Tug). Considering a Tug mass of 60000 [kg] and an SPS mass of 10000 [tons] the results based on the propulsion system specific impulse of the Tug is the following:

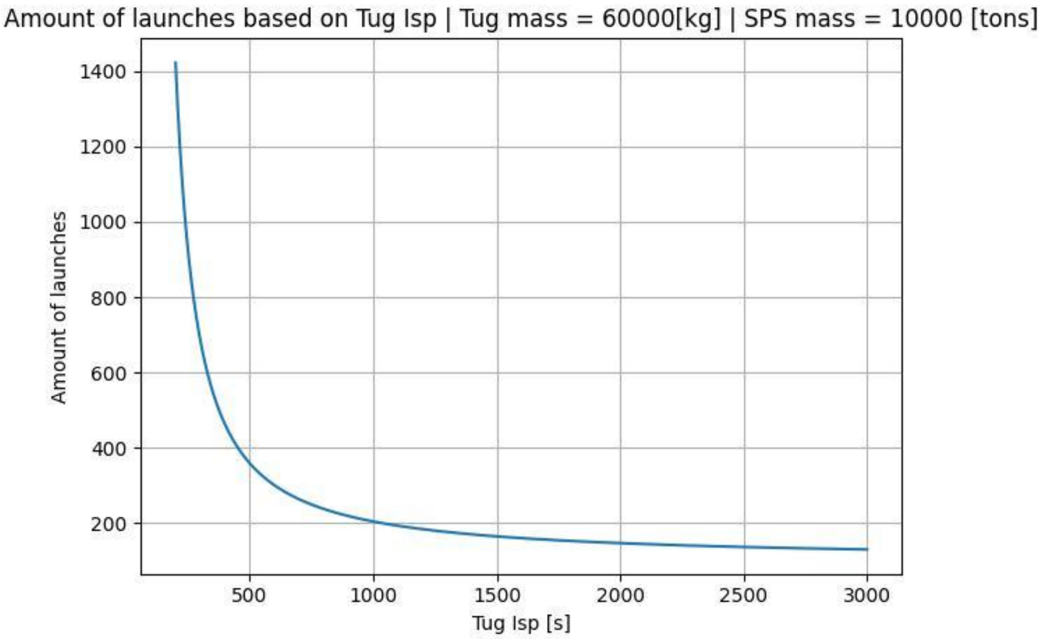


Figure 3-48 launches required based on Tug propulsion system Isp

Another evaluation can be done in terms of Tug and SPS masses, which are reported below:

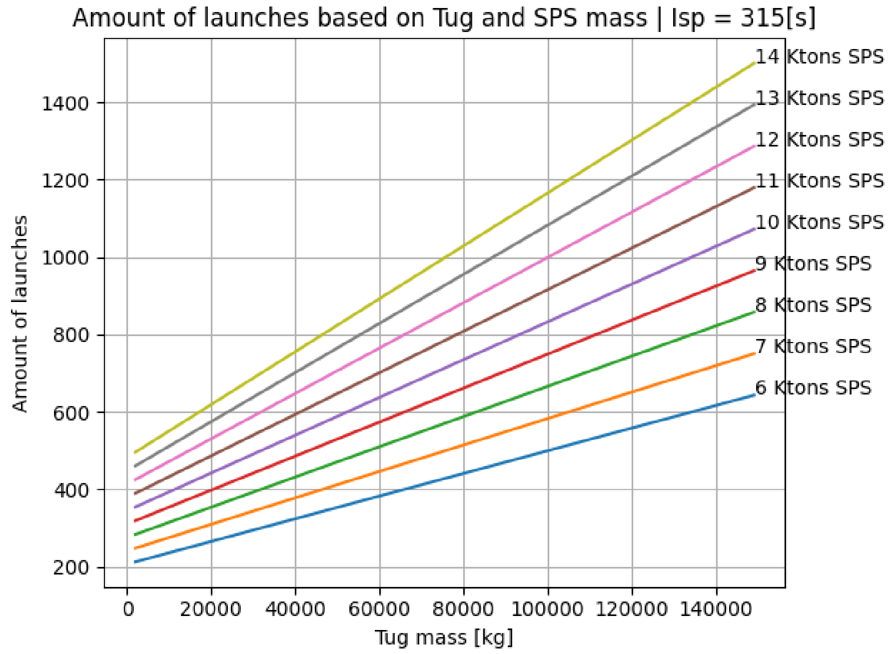


Figure 3-49 Launches required using chemical propulsion

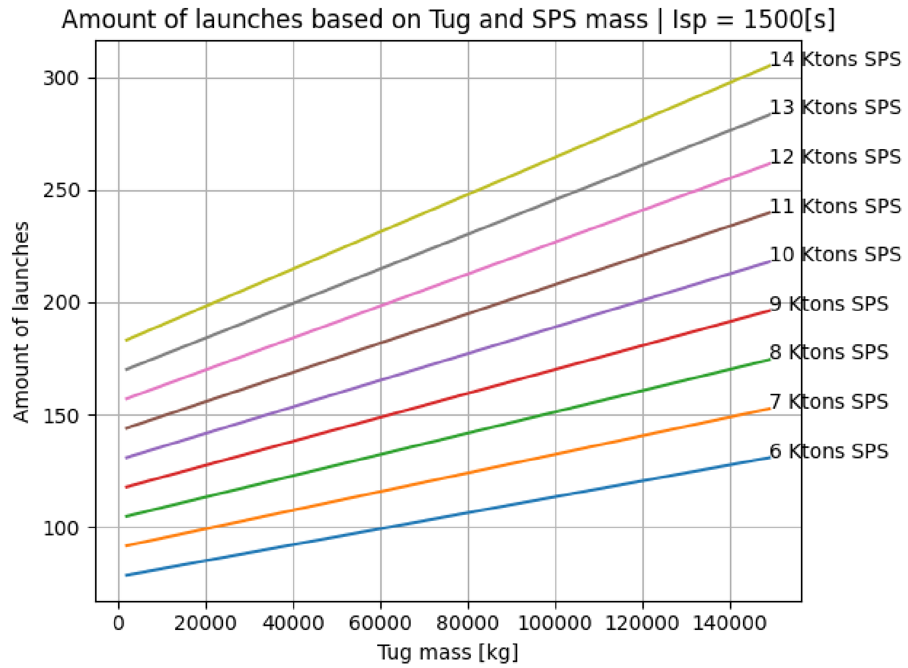


Figure 3-50 Launches required using electrical propulsion

It is no surprise how increasing the Isp bring a great benefit in terms of propellant required, thus of total launches. The downside of having high Isp, thus using electric propulsion w.r.t. chemical is the increase in travel time from injection orbit to operational orbit due to the lower thrust of electric propulsion system. Thus a trade-off shall be performed in later stages based on mission requirements and time constraints.

3.4.3 Ground Segment trade-offs

3.4.3.1 GPS location trade-offs

Taking into account the parameters reported below the difference between on-shore and off-shore is marked. The on-shore installation, considering the high level of power that the station must handle is the best compromise among all the parameters. This installation, especially as a first big plant of this kind, will probably require a continuous control and continuous improvement approach to be optimized. The added complexity due to an off-shore installation will probably introduce several other potential failure modes and difficulties in O&M operation that cannot be considered in principle as the first plant of its kind. In a second phase, once the plant will be optimized and all the technical issue solved, we can think to move on an off-shore installation.

GPS location							
				OPTION 1		OPTION 2	
				On-shore		Off-shore	
Criteria	Applicability [N/A= 0, Applicable = 1]	Weight Factor [1-5]	Applicability * Weight Factor	Input [1- 5]	Value [Weight Factor * Input]	Input [1- 5]	Value [Weight Factor * Input]
Cost	1	5	5	5	25	3	15
Energy expediture	1	3	3	5	15	3	9
Social acceptance	1	5	5	3	15	4	20
Carbon footprint	1	5	5	4	20	3	15
Mass / Area / Volume	1	5	5	5	25	2	10
Design Complexity	1	3	3	5	15	2	6
Deployment complexity	1	3	3	5	15	2	6
Operational complexity	1	3	3	5	15	2	6
Failure Tolerance	1	2	2	4	8	2	4
Capacity factor	1	4	4	5	20	3	12
Modularity	1	4	4	5	20	3	12
Scalability	1	4	4	4	16	3	12
TRL / Heritage	1	1	1	5	5	2	2
Lifetime	1	4	4	5	20	3	12
Industrial capability/scalability	1	3	3	5	15	2	6
TOTAL SCORE					4.61		2.72

Table 3-38 GPS location trade-off

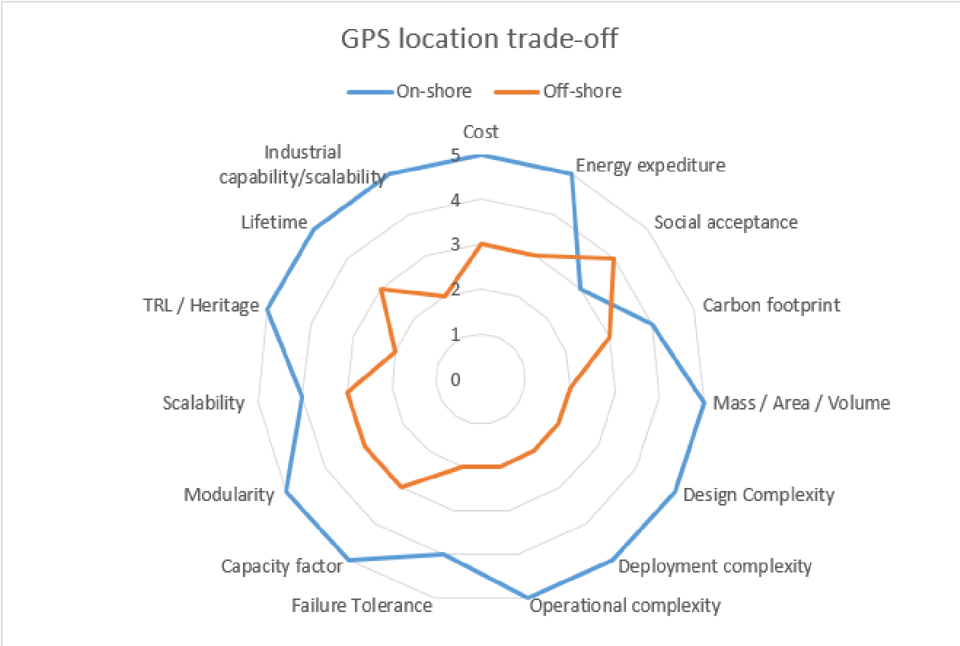


Figure 3-51 GPS location trade-off summary graph

Considering the location among all the parameters the main driving input is related to cost and to the connection to European energy distribution network. We need also to take into account the social acceptance of the receiving antenna and, since the trade-off between on-shore and off-shore is in favor of an on-shore installation, the human factor can be quite important. All the 3 countries considered are actually quite open to installing this kind of technological platforms especially if related to renewable energy. The labor cost can do the difference among these 3 countries. With the actual inputs Spain seems to be among all the countries the best solution.

GPS location (country)				OPTION 1		OPTION 2		OPTION 3	
				Germany		Spain		Sweden	
Criteria	Applicability [N/A= 0, Applicable = 1]	Weight Factor [1-5]	Applicability * Weight Factor	Input [1- 5]	Value [Weight Factor * Input]	Input [1- 5]	Value [Weight Factor * Input]	Input [1- 5]	Value [Weight Factor * Input]
Cost	1	5	5	4	20	5	25	4	20
Energy expediture	1	3	3	5	15	5	15	3	9
Social acceptance	1	5	5	4	20	4	20	5	25
Carbon footprint	0	5	0		0		0		0
Mass / Area / Volume	0	5	0		0		0		0
Design Complexity	0	3	0		0		0		0
Deployment complexity	0	3	0		0		0		0
Operational complexity	0	3	0		0		0		0
Failure Tolerance	0	2	0		0		0		0
Capacity factor	0	4	0		0		0		0
Modularity	0	4	0		0		0		0

Scalability	0	4	0		0		0		0
TRL / Heritage	0	1	0		0		0		0
Lifetime	0	4	0		0		0		0
Industrial capability/scalability	0	3	0		0		0		0
TOTAL SCORE					4.23		4.62		4.15

Table 3-39 GPS location (country) trade-off

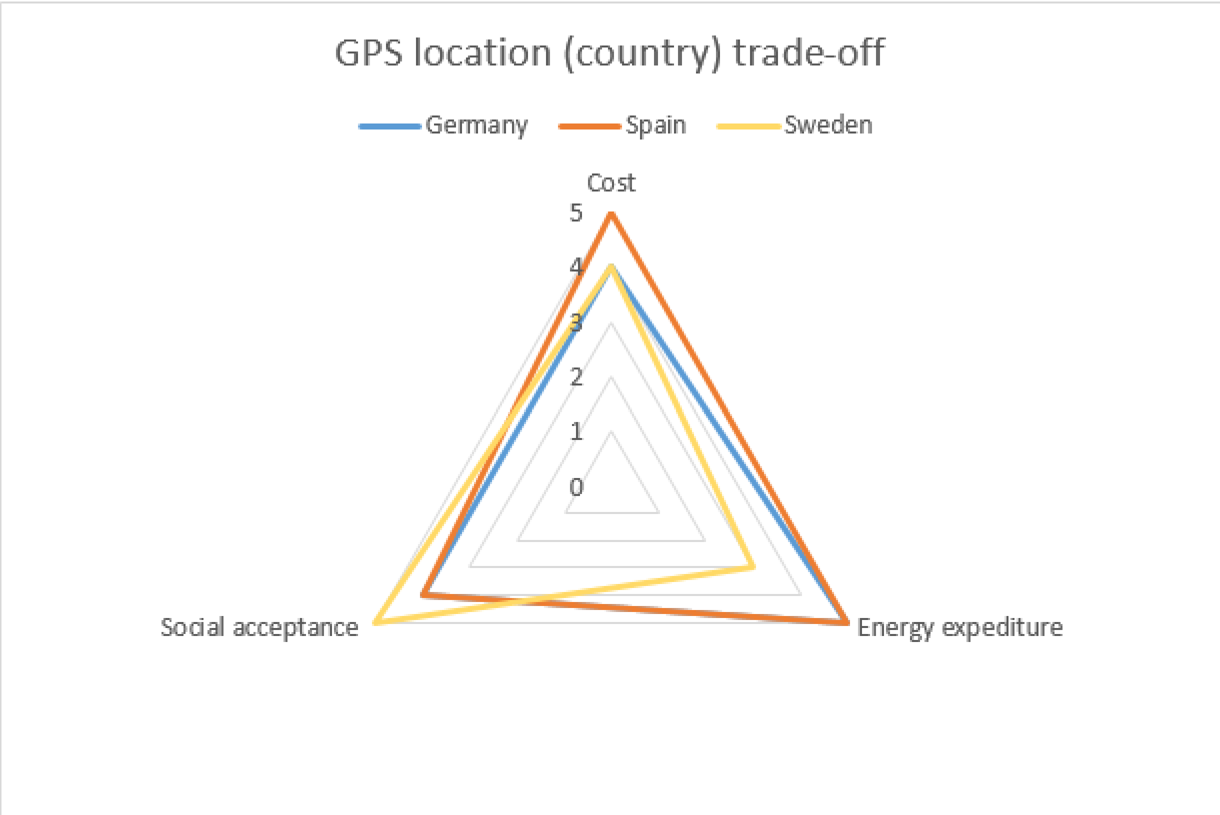


Figure 3-52 GPS location (country) trade-off summary graph

3.4.3.2 Energy storage system trade-off

Electrochemical double-layer supercapacitors (SuperCap) have considerable short term applications (< 60 s discharge duration), due to their high specific power density and long cycle life, with dozens of kW/kg power density and up to 1M cycles there is no competition with Li-ion and battery in general in term of cost per kW and performances.

Anyway, the major drawback of SuperCap is their low energy density, which lies in the range of 3-5 Wh/kg, two orders of magnitude lower than that of the commercial lithium-ion batteries, therefore, also very high cost per kWh.

In the last years, SuperCap have emerged as a promising alternative for Li-ion as they exhibit high power densities, excellent and fast cycling stability and longevity. New materials for SuperCap are now providing ultra-high theoretical energy density (300 Wh/kg), elemental abundance in the earth's crust, and environmental friendliness. Without sacrificing power density and reliability the cost per kWh is getting close to Li-ion.

Energy storage system				OPTION 1		OPTION 2	
				Lithium batteries		Supercapacitors	
Criteria	Applicability [N/A= 0, Applicable = 1]	Weight Factor [1-5]	Applicability * Weight Factor	Input [1- 5]	Value [Weight Factor * Input]	Input [1- 5]	Value [Weight Factor * Input]
Cost	1	5	5	4	20	2	10
Energy expediture	1	3	3	4	12	4	12
Social acceptance	1	5	5	4	20	4	20
Carbon footprint	1	5	5	3	15	4	20
Mass / Area / Volume	1	5	5	4	20	2	10
Design Complexity	1	3	3	4	12	4	12
Deployment complexity	1	3	3	4	12	4	12
Operational complexity	1	3	3	3	9	5	15
Failure Tolerance	1	2	2	3	6	4	8
Capacity factor	1	4	4	4	16	4	16
Modularity	1	4	4	4	16	4	16
Scalability	1	4	4	5	20	5	20
TRL / Heritage	1	1	1	5	5	4	4
Lifetime	1	4	4	2	8	5	20
Industrial capability/scalability	1	3	3	4	12	3	9
TOTAL SCORE					**3.76**		**3.78**

Table 3-40 Energy storage system trade-off

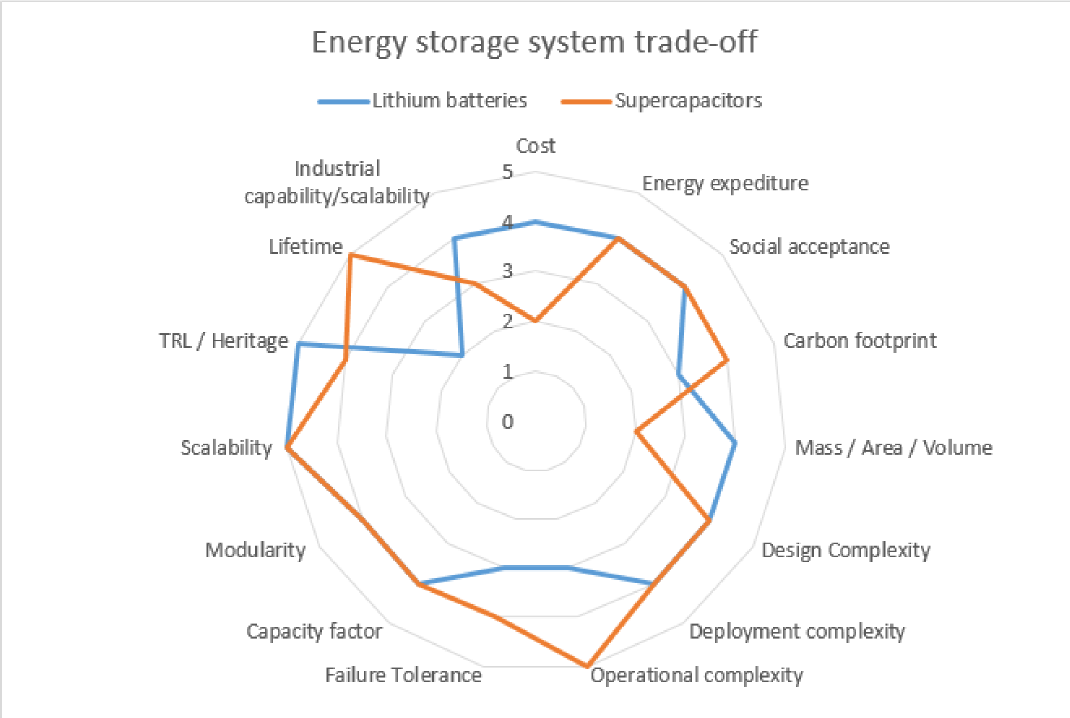


Figure 3-53 Energy storage system trade-off summary graph

3.5 SBSP architecture selection

The SBSP overall architecture, including both the Flight segment and the Ground segment, is reported in Figure 3-54.

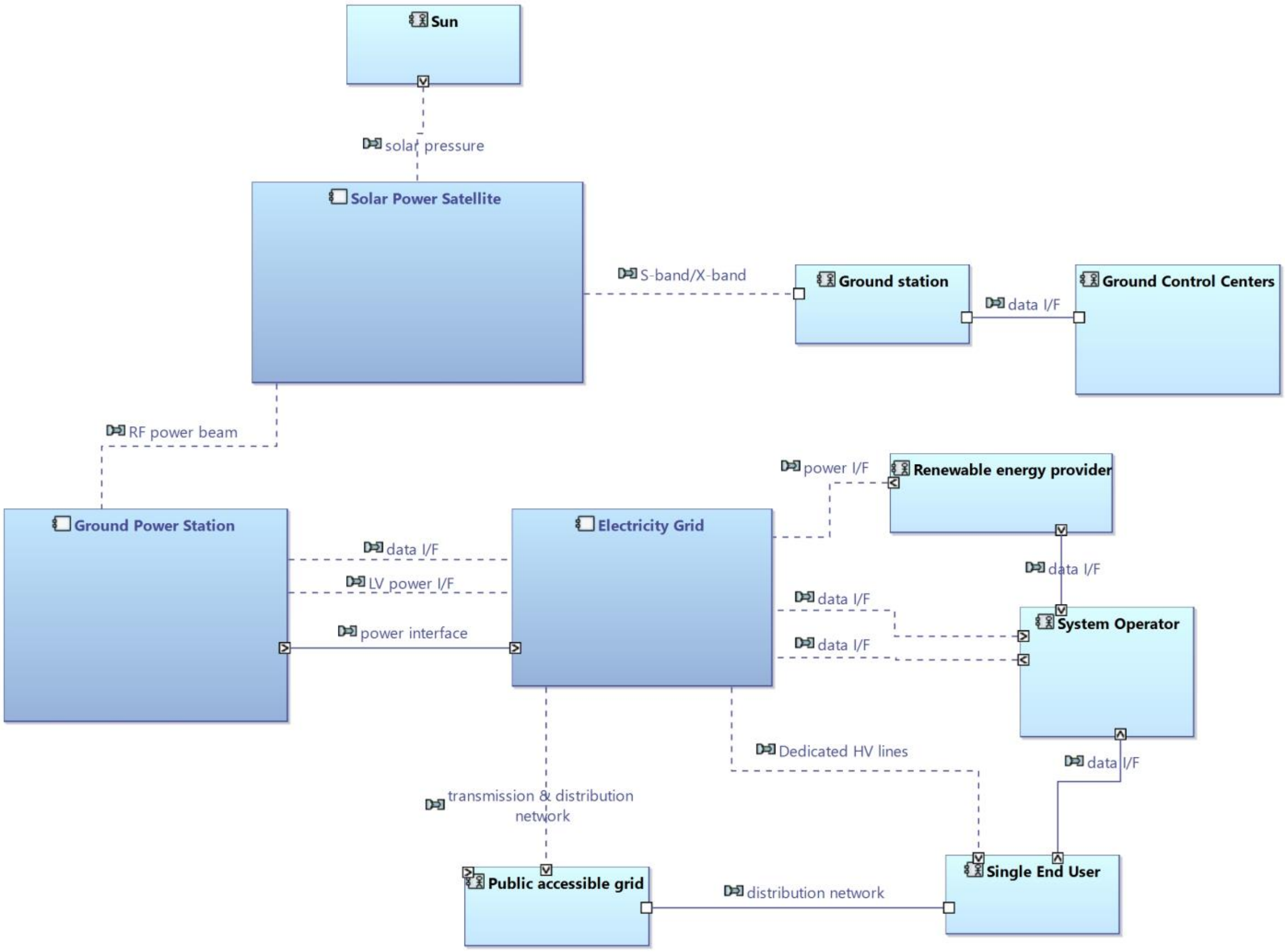


Figure 3-54 SBSP overall architecture

Based on the performed trade-offs, summarized in Table 3-41, the following architecure has been selected for the SPS:

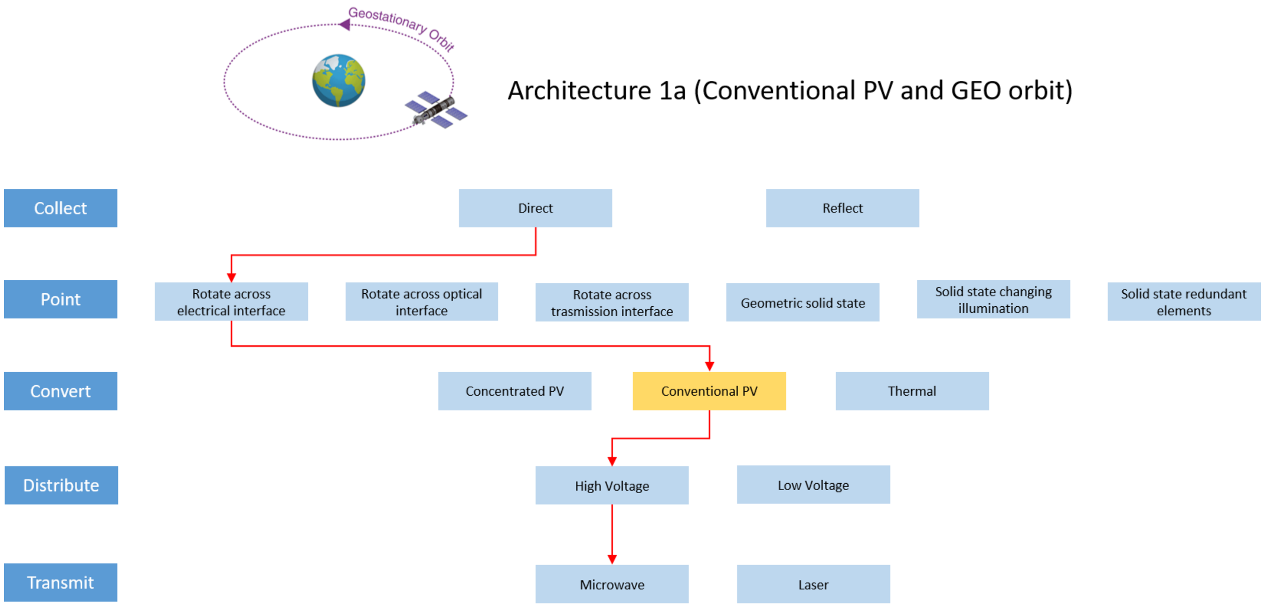


Figure 3-55 SPS Architecture 1a (Conventional PV and GEO orbit)

	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
	AOCS trade-offs	- star trackers - sun sensors - accelerometer gyroscopes - ground station tracking - control momentum gyros (CMGs) - monopropellant RCS thrusters - electric thrusters (hall effect thrusters)
	Structures and materials for solar array modules trade-off	Flexible Roll-out Structures
	In-space transportation and infrastructure trade-off	Injection in LEO/MEO
	GPS location trade-off	On-shore

Ground Segment	GPS location (country) trade-off	Spain
	Energy storage system trade-off	Supercapacitors

Table 3-41 Trade-offs summary

The proposed architecture answers to the questions included in the Annex C of ESA's SOW and reported in Table 3-42.

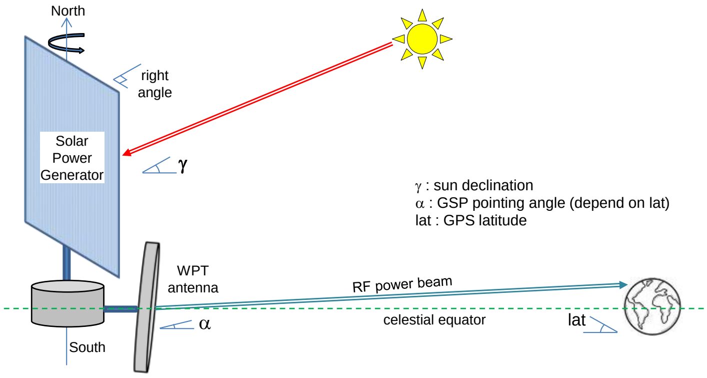
Example Architectural Trades	Example Questions	Answer
SBSP Service Use-Case	What is the expected service use-case of the SBSP system?	On-grid baseload power provision to Europe
Type of Power Plant	If operating as a power plant, what type of power shall be provided to the grid (e.g., baseload, load-following, peaking etc.)?	Baseload
	What are the required characteristics of power provided by the SBSP system and how does this impact the architecture?	The baseload power provision requires constant SPS/GPS coverage
SPS per Ground Power Station	How many SPSs should provide power to each Ground Power Station?	Considering the GEO 1 SPS can fully supply one ore SPS in Europe.
Ground Power Stations served per SPS	How many Ground Power Stations should each SPS be able to serve?	One as no configuration with multiple GPS has been considered
	Should each SPS be able to provide power to multiple Ground Power Stations?	The architecture selected by our Consortium does not require this feature
SPS Service Delivery	If each SPS provides power to multiple Ground Power Stations, how should this power be delivered (i.e., sequentially, simultaneously)?	N/A
	Which locations can be served by the SPS if serving multiple Ground Power Stations?	Europe
Energy Storage on Ground	Should the SBSP system utilise energy storage at Ground Power Stations to meet power service needs?	Energy storage option shall be consideredto cover loss of grid power due to eclipses or S/C maintenance activities
Orbit Selection	Which orbits should SPS operate in?	GEO
	Which orbits are most attractive for the envisioned type of power service delivery (use-case)?	GEO

Example Architectural Trades	**Example Questions**	**Answer**
	Should multiple orbit planes or constellations be exploited?	The result of the trade-off clearly shows that using a GEO orbit with a single SPS has more advantage than a constellation of satellites in a EO orbit.
	What are the implications of different candidate orbits on the SBSP system design?	If considering the GEO, one satellite is required for full coverage and the station-keeping to be applied is North-South and East-West station-keeping commonly used in GEO. On the other hand, EO 2:1 synchronicity orbit require a constellation of 3 satellite for full coverge, as well as a heavier station-keeping due to Earth's oblateness. The GPS antenna size is proportional to the slant range, but heavily affected by the elevation angle between GPS and SPS, that for GEO remains constant while for the EO vary during the orbit. The energy transmission beam will stay fixed if considering a GEO orbit, while it will move in case of EO so, in case a no-flight zone would be required, the EO will be more problematic. Regarding the GPS location, in case the GEO is chosen, the best GPS to use in terms of elevation angle is the one located in Spain as it is the one with the lowest latitude. In case of the EO, the best is the one in Germany, as it will have better coverage during the SPS apoapsis.
Number and Size of Satellites	Should the SBSP architecture consider fewer, larger satellites or large constellations of smaller satellites?	Fewer larger satellites
	What is the overall size and mass of the SPS system, and how does this impact the architecture selection?	This info will be available during the architecture elaboration
SBSP System Capacity	How much power should be delivered into the grid from a single SPS or from a constellation of SPSs (i.e., 100s Megawatts or less, 1-2 Gigawatts, >2 Gigawatts)?	1-1.5 Gigawatts (refer to TN1)
Wireless Power Transfer	How should power be delivered to the ground from space?	Two types of electromagnetic waves that can cross the atmosphere can deliver the power: the light either in the visible window (380 - 750 nm) or in several IR windows (in particular 800nm and 1.5µm) and the low bands of the radiofrequency spectrum (30 MHz - 30 GHz). In case of visible light, the SPS is simply a mirror redirecting the sunlight toward the ground. In the two other cases (IR & RF), the sunlight shall be first converted into electricity, and then the electricity is converted in electromagnetic waves to be beamed to a Ground power station.

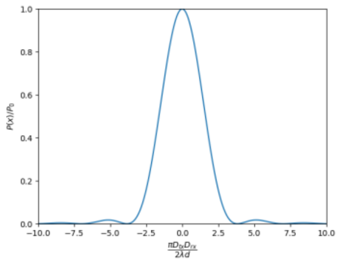
Example Architectural Trades	Example Questions	Answer
	Should this assume RF (e.g., microwave or alternative) or optical transmission?	Among the possible options listed above (radiofrequencies, infrared and light in visible window) RF band microwaves are selected in order to assure the 24/7 baseload power requirement (infra-red power beaming is not compliant with this because of the high atmospheric losses)
	Which frequencies should be used for power transfer considering system impacts, interferences, and regulation?	Frequency choice is one of the critical points of SBSP system concept. As mentioned in TN2 and in the case study analysis it is plausible to consider a range of operative frequencies between 1 and 24 GHz (in particular considering the ISM frequencies available). However, frequencies above 10 GHz are strongly affected by the atmosphere. Consequently the availability of the power link and its power capacity (losses) will depend on weather conditions (rain, snow, fog, etc.) above the GPS so this is not compliant with the 24/7 baseload use case considered. For this reason, and considering the available ranges of ISM band, the best options are 2.45 GHz and 5.8 GHz. After a detailed trade-off 5.8 GHz has been selected as baseline
	Are there other alternative methods to transmit power to ground (e.g., focused or reflected sunlight)?	As explained previously the atmosphere has few transparent windows. One of them is the visible light (380 - 750 nm) window. The simplest way to use this window is to send sunlight from orbit to ground. We call this technique, passive SBSP. In a passive system, the sunlight is collected in orbit then retransmitted to Earth. The GPS collects the retransmitted sunlight in addition to the direct natural sunlight, converts it to DC by photovoltaic panels and conditions DC for distribution to the ground power Grid. The electricity production is performed only on ground within the GPS. The SPS aims only at increasing the illumining sunlight flux at the GPS. This increase can be a strengthening of the natural sun illumination or a time extension of the illumination, for example lighting during the night. A passive SBSP plants consists of a set of SPS which are essentially heliostats in orbit and of one or several GPS which are simply solar farms. There will be different architectures depending on the altitude of the orbit and on the technology of the mirrors (focusing or not). Such solution will be not studied further in this study.
Power Collection by SPS	How should the SPS capture solar energy in space?	According to TN2, there are four methods to capture solar energy in space:

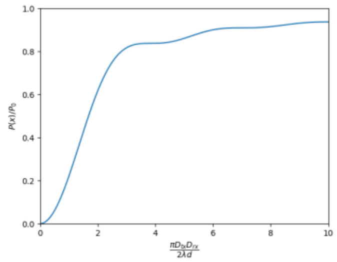
Example Architectural Trades	Example Questions	Answer
		✓ Photovoltaic (PV) with semiconductor solar cells. It has good efficiency around 25-30% with prospects of reaching 35%-40% (depending on the cell technology considered). The theoretical thermodynamic maximum efficiency is 43%. ✓ Thermoelectric: the heat flux between the face in the sun and the face in the shade is directly into electricity (effect Seebeck/Peltier). Except some breakthrough technologies, at the moment this solution presents low efficiencies of around 10%. ✓ Thermodynamic: a thermodynamic cycle machine (Stirling, Brayton, and Rankine) requiring boilers, turbines, generators and radiators produce electricity. The hot reservoir is the sun while the cold reservoir is the shade. This technology is discarded for the very high weights and unreliability of the solution for large-scale concepts. PV has been selected by our Consortium as baseline technology to capture solar energy.
Power Collection Photovoltaics	If Photovoltaics are used for power collection, which type of cells should be used?	Among the selected options, thin film InGaP/GaAs/Ge cells (e.g., 3G30-C) and Perovskite cells stand out as the two most promising choices, each offering distinct advantages. The first technology excels in terms of efficiency and Technology Readiness Level (TRL), while the second one demonstrates cost-effectiveness and high specific power density (the best among all the cell technologies at the moment). Considering the provided expected module efficiencies and the results from our analysis, it becomes evident that Perovskite cells require larger solar panel areas compared to thin film InGaP/GaAs/Ge cells. However, when factoring in specific power density, the advantages of choosing Perovskite cells become relevant, despite their current low TRL (500 tons of overall PV cells with respect to 10000 tons for InGaP/GaAs/Ge cells) From the above considerations, it becomes clear that the implementation of Perovskite cells for the SPS is more advantageous.

Example Architectural Trades	Example Questions	Answer
		In conclusion, while thin film InGaP/GaAs/Ge cells hold their own in terms of efficiency and TRL, Perovskite cells prove to be a compelling option due to their cost-effectiveness and impressive specific power density, even considering their current lower TRL status (which is an attribute with low value in the project decisional logic). Moreover, as showed in Table 3-25, this technology shows an incredible rise in efficiencies in the last 10 years, from 14% in 2013 to 26% in 2023 (lab tested). For this reason (with adequate funding needed for further research to increase lifetime, crystal stability and overall TRL) Perovskite cells could result as the most promising option for future SPS applications. Therefore, Perovskite PV cells are selected as baseline
	What efficiency vs cost vs low-mass concepts for power collection could be available for SBSP systems if sufficient funding was available?	It is difficult to anticipate technical and financial developments in the field of photovoltaic cells in the next 20 to 30 years. For example the Swanson's law predicts that the price of photovoltaic panels tends to drop 20 percent for every doubling of cumulative shipped volume. According to this, costs could go down 75% about every 10 years. Another clear example of future progress is the perovskite solar cell (PSC). Advertised efficiencies have increased from 3.8% in 2009 to 26% in 2023 for single-junction. Perovskite solar cells have therefore been the fastest-advancing solar technology and, if sufficient funding is available for further researches to increase lifetime, crystal stability and overall TRL (now 3-4), Perovskite cells could result as the most promising option for future SPS applications.
Use of Concentrators	Should the SPS use concentrators for the collection of solar power?	The implementation of CPV for collecting solar power has some pros and cons with respect to conventional PV cells (as reported in section 3.4.2.6). In line with the study objective to minimize overall system complexity and considering the Direct solution adopted, the implementation of CPV does not result in any significant advantage in mass/area/volume system. CPV implementation adds operational and design complexity factors such as the need of 3 DoF sun pointing system for the solar arrays and very high thermal loads to be dissipated with respect to Conventional PV. For these reasons, conventional PV cells are selected as baseline.
	If so, what type of concentrator should be used?	N/A

Example Architectural Trades	**Example Questions**	**Answer**
SPS Power Management and Distribution	How should the SPS manage and distribute power (between collection and transmission)?	The huge amount of power involved in Space Based Solar Power applications makes necessary managing very high voltage ranges. Thus, highly performant power conversion technologies will be needed. Details about EPS architecture will be provided in the relevant Architecture Definition Document (TN4).
Simultaneous Power Collection and Transmission Approach by SPS	What approach should be employed to simultaneously collect solar energy (requiring sun pointing) and beam power to the ground power station (requiring Earth pointing)?	Depending on the type of orbit and the season, the direction of the Earth and that of the Sun are different and vary in time and according to the movement along the orbit. For GEO, the direction of the Earth is constant and is in direction of the centre of the Earth (axe X) and perpendicular to the velocity vector (axe Y) of the orbiting object. GEO being a circular equatorial orbit, the sun seems to revolve around the object in orbit, at the rate of one rotation per day. The rotation axe is North-South (axe Z) The solar declination varies by +/- 23.4deg per year (seasons).  Consequently, the WPT antenna will point the GPS in a fixed way (in relation to X-axis); the solar panels will be animated by a rotational movement around the north south axis (Z axis) to face the sun. The direction of the sun relative to the normal of the solar panels will vary +/- 23 deg. per year (declination).
SPS Orbit Control	What are the expected perturbations on the SPS and what approaches should be employed for station-keeping and orbit control?	In GEO the expected perturbation induced by solar radiation pressure is between $4.4*10^{-6} – 4.75*10^{-6}$ N/m^2 which lead to impress on the S/C a total force of 57N . For station keeping needs, this total perturbation force shall be compensated and the elettric thruster, in particular Halle Effect thrusters, seems the most suitable solution to cover this aspect.

Example Architectural Trades	Example Questions	Answer
SPS Attitude Control	What approaches are needed to ensure stability of the SPS considering the expected eigenfrequencies of the system (e.g., are active control methods needed and what should these be)?	The SPS shall guarantee pointing stability by means of Control Moment Gysro's and Thrusters, the first one are used for fine pointing maneuvers, while the second are used for large attitude maneuver and un-load the CMGs.
SPS Thermal Control	What approaches are needed to perform thermal control on the SPS?	Active and passive thermal system are the two possible approaches to achieve thermal control. Given the large size of the SPS and the complexity of the architecture, the passive thermal control approach is preferable to reduce the mass and the single points of failure. A modular approach is recommended, considering to equip each module with an integrated thermal control system has to be considered, tailored on the configuration of the specific module.
Launch and Deployment	What strategies can be considered to deploy all SPS hardware to its operational orbit?	The most feasible option is to assembly the SPS directly in orbit with In-Orbit satellite servicers.
	What vehicles and capabilities need to be developed to deploy SPS systems to orbit?	Due to the size of an SPS and considering the commercial implication of the mission, heavy lift reusable launcher shall be the way to go as they would make the mission economically feasible. Moreover advanced In-Orbit satellite servicers are required to perform assembly, maintenance and refueling of SPS
	What type of propulsion should be used?	Due to the nature of the mission, the electric propulsion seems the most reasonable choice. If no time constraints applies the low thrust capability of electric thrusters should not negatively affect the whole mission
	How much propellant is needed for each SPS deployment?	For the moment it is impossible to estimate the SPS mass since the assembly orbit has not been finalized. This info will be available during the architecture elaboration
SPS Assembly Concept	Should the SPS hardware be assembled and aggregated in one orbit before transfer to the power beaming orbit, or assembled directly in the power beaming orbit?	Two options could be considered: transferring and building the satellite directly inside the final orbit or take advantage of an injection orbit nearer to Earth and then bring and assembly the modules in the target orbit. As the trade-off shows, the exploitation of a LEO injection orbit seems the best option in terms of required launches. The option to build the satellite in a transfer orbit and then bring it to the power beaming orbit has been discarded due to structural challenges derived by the high inertia of the whole system.
	Once all SPS hardware is in the assembly location, how will it be assembled in orbit (and what systems are needed for assembly)?	The preferred approach to bound the system complexity is to fly the system folded and unfold it on-orbit with 'simple' HDRM/spring approach'. As alternative, or for further construction/extension, it is conceivable to have a moveable robotic system capable to pick objects and mount/deploy them on the 'edges' of the satellite. The robotic system can be an high TRL arm (heritage Canadarm or ERA operational on the ISS) or a moveable robotic system (low/medium TRL, under techno boost with the ESA ISAAC study) capable to pick object, walk on standard I/F and mount objects on the 'edges' of the satellite.

Example Architectural Trades	**Example Questions**	**Answer**
Ground Power Station Location	Where should the Ground Power Stations be located?	Spain
	Should Ground Stations be located near to cities, offshore or in rural areas?	The on-shore installation, considering the high level of power that the station must handle, is considered the best option. The location near cities should be avoided considering social acceptance factors and GPS(s) dimensions.
Number and Size of Ground Power Stations	How many Ground Power Stations should there be considering the SPS conceptual architecture?	86 according to our reference use-case (see TN1)
	How does ground power station footprint scale with space segment architecture sizing?	The antenna of the Wireless Power Transfer generates and points a RF power beam toward the GPS. This is a critical sub-system since it defines the sizes and area of both the GPS land and the WPT antenna. The expected area of the WPT antenna is very wide and its design answers to the diffraction theory. It tells us that the beam undergoes diffraction, which generates secondary lobes or beams in the pattern. The footprint of the beam is therefore a diffraction pattern, i.e. a series of concentric circles. Its shape varies depending on the dimension of the Antenna, the frequency and the distance between the WPT antenna and the GPS according to the formula: $$I(D_{tx}, D_{rx}, \lambda, d) = \frac{P_0 \pi D_{tx}^2}{4\lambda^2 d^2}\left[\frac{2J_1\left(\frac{\pi D_{rx} D_{tx}}{2\lambda d}\right)}{\frac{\pi D_{rx} D_{tx}}{2\lambda d}}\right]^2$$  The power distribution varies according to the formula: $$P(x) = P_0\ [1 - J_0^2(x) - J_1^2(x)],$$ where $x = \frac{\pi D_{rx} D_{tx}}{2\lambda d}$. The main (first) beam includes the 83.8% of the total transmitted power and the second the 7.2%.

Example Architectural Trades	**Example Questions**	**Answer**
		 So the WPT antenna and the GPS are not strictly mutually constrained, but they can be varied depending on the amount of power we want to intercept on the ground.
Operational Maintenance and Logistics	What strategies could be employed to provided maintenance and logistics to the SPS over its operational lifetime?	'On-site' maintenance and logistic can be performed using a moveable robotic system (low/medium TRL, under techno boost with the ESA ISAAC study) capable to walk along the structure on standard I/F and inspect/replace objects.
	Should maintenance and refurbishment be performed in orbit on the SPS over its lifetime or should users accept a degradation of performance with time?	If the 1GW power provision need to be kept then in-orbit maintenance andrefurbishment will be needed
	How should the SPS be designed to operate with degradation?	The semi-conductor PV cell of the solar panels will undergo degradations, mainly: ✓ Variation in efficiency (voltage) as a function of cell temperature. The hotter, the lower efficiency. ✓ Reduced efficiency with space radiation cumulated doses, with an End of Life (EoL) reduced efficiency of a few percentage, ✓ Degradation of certain photovoltaic cell technologies by UV light, but also of the cover glass of the panels ✓ Degradation by micro-meteors, causing cell or string failure. For these reasons proper cover glasses could be needed and the implementation will be analysed in the architecture elaboration. The Solaris performance should therefore be estimated at beginning of life (BoL) and at end of life (EoL).
End-of-Life Strategies	What approach should be used for the end-of-life (i.e., decommissioning) of SBSP system elements?	At this stage, two options for SPS disposal have been proposed (for further details refer to Section **Error! Reference source not found.**): ✓ Option 1: Graveyard orbit: ✓ Option 2: Disassembly and lunar transfer
Contingency Approaches	In the event of failures, how much fault tolerance should be built into the system, and how should this be implemented?	This info will be available during the architecture elaboration

Example Architectural Trades	Example Questions	Answer
	How can operations be sustained in the event of failures?	Failures shall be managed with redundancies and implementingdistributed and hierarchical autonomy on-board
Security and Safety	What approaches can be implemented to address concerns related to safety of life?	Power beam shall be constantly monitored
	What approaches can be implemented to address concerns related to safety of assets and service loss?	The GPS shall be protected by fence and access strictly controlled
	How could the SPS be designed so that it is not susceptible to attack from bad actors?	Cybersecurity and cryptography shall be implemented. QKD is a promising technology which could be implemented if properly demonstrated (in LEO firstly and in higher orbits subsequently)
	Are ancillary systems needed to protect the SPS from attack?	This option will be investigated during the architecture elaboration
	What strategies exist to mitigate risks and concerns associated with space debris and space weather?	This option will be investigated during the architecture elaboration
	How can safety concerns related to power beaming to the ground be addressed by the SPS design?	Retroreflecting beaming technique shall be used to track & correct antenna pointing

Table 3-42 Architecture trade-space solutions

3.5.1 Preliminary sizing of the selected architecture

A preliminary sizing of the selected architecture has been performed and is summarized in Table 3-43.

Item	Mass [tons]	Remarks
PV	2000	This mass has been computed considering a PV area of 6 km2. We are considering Perovskite cells as the baseline solution with a weight of 0.08 kg/m2. Additionally, we are hypothesizing that the cell weight is only 25% of the full PV Assembly weight, which amounts to 0.3 kg/m2.
Phased Array Antenna	250	Considering Caltech ultra-lightweight phased array antenna technology [RD2]. The idea is to develop a lightweight RF IC (integrated circuit) glued on a foil of about 0,5 kg/m^2 of density (considering also SSPA and all the integrated circuit)
Structure	3300	This mass has been computed considering a truss-like structure. This value is likely to fall considering the evolution of materials used

Table 3-43 Architecture preliminary sizing

The power link budget, considering an operating frequency of 5.8GHz and the Perovskite solar cells, is about 11.5% in line with the topical literature (see [RD26]). All the efficiencies listed in Table 3-44 are described in Section 3.4.2.2. These values could be subject to changes during the next study phases.

Efficiency	Value	System efficiency	Power [MW]
Solar Power Generator (0.232)			8593
Photovoltaic cell efficiency	0.29	0.29	2492
Solar panel surface efficiency	0.86	0.249	2143
Illumination efficiency	0.96	0.239	2057
Power line efficiency	0.99	0.237	2036
Power conditioning efficiency	0.98	0.232	1996
Wireless Power Transfer (0.6)			
Power distribution network	0.98	0.227	1956
Power conditioning efficiency	0.95	0.215	1858
RF power generator	0.83	0.178	1542
Antenna efficiency	0.99	0.176	1526
Atmospheric attenuation	0.98	0.172	1495
Beam collection efficiency	0.81	0.139	1211
Ground Power Station (0.83)			
Rectenna panel surface efficiency	0.98	0.136	1187
Rectenna efficiency	0.9	0.124	1069
Power line efficiency	0.99	0.123	1058
Power conditioning efficiency	0.95	0.117	1005

Table 3-44 Power link budget

A.1 Annex 1: Concept Elaboration & Trade

Attached file: *Annex1_Concept Elaboration & Trade.xlsx*

END OF DOCUMENT