Space-Based Solar Power

Delivers solar energy from space to Earth

Stakeholder Interchange Workshop

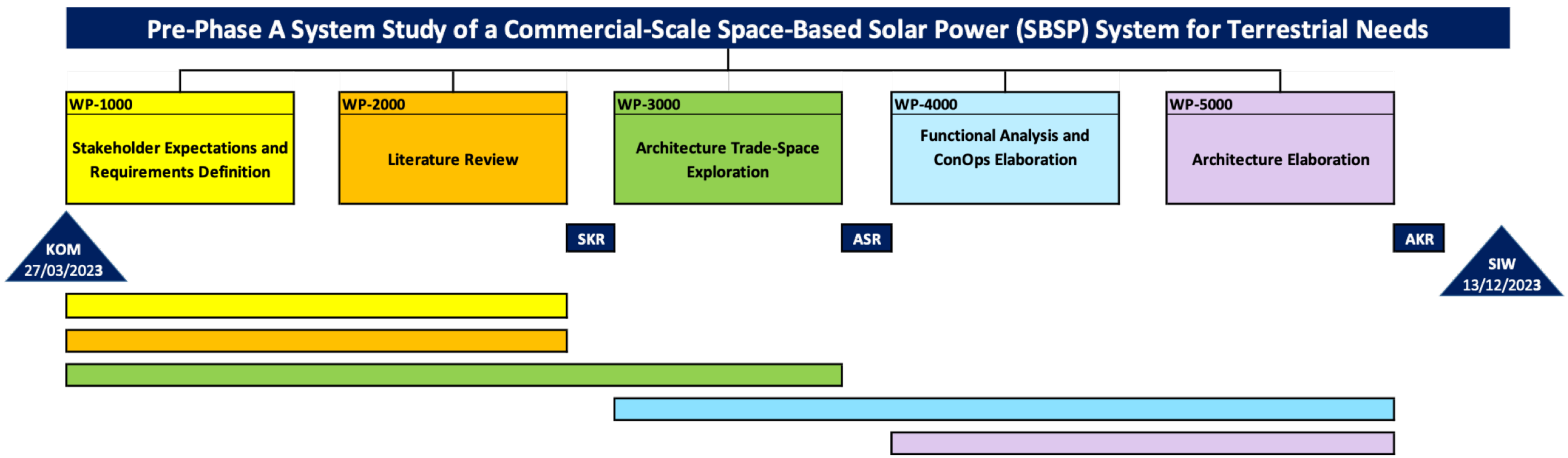
December 13, 2023 @ ESA-ESTEC

TABLE OF CONTENTS

1. INTRODUCTION

1. STUDY TEAM

/// Pre-Phase A System Study of a Commercial-Scale Space-Based Solar Power (SBSP) System for Terrestrial Needs



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2. USE CASE & CONCEPT OF OPERATIONS

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2.1 REFERENCE USE-CASE

/// Between 17 and 20 April 2023 ESA has organized **consultation meetings** with the **relevant energy sector players** to establish a consistent set of stakeholder needs and expectations for a prospective future SBSP service.

SCHELLHAS THE CLIMATE INNOVATOR equinor Microsoft eDF TRANSNET BW EirGrid GROUP

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

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

with one **S**olar **P**ower **S**atellite in Geostationary Orbit

and the **G**round **P**ower **S**tation located in Spain

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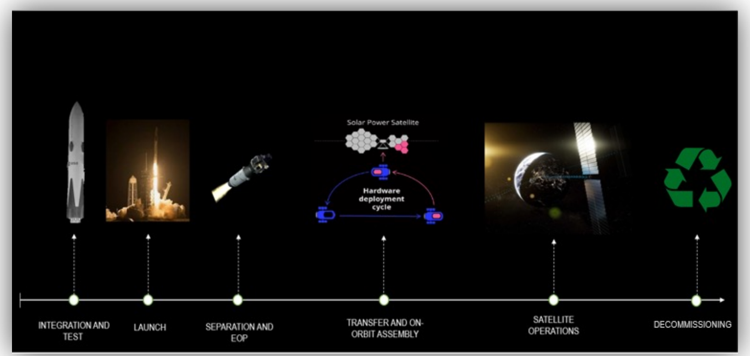
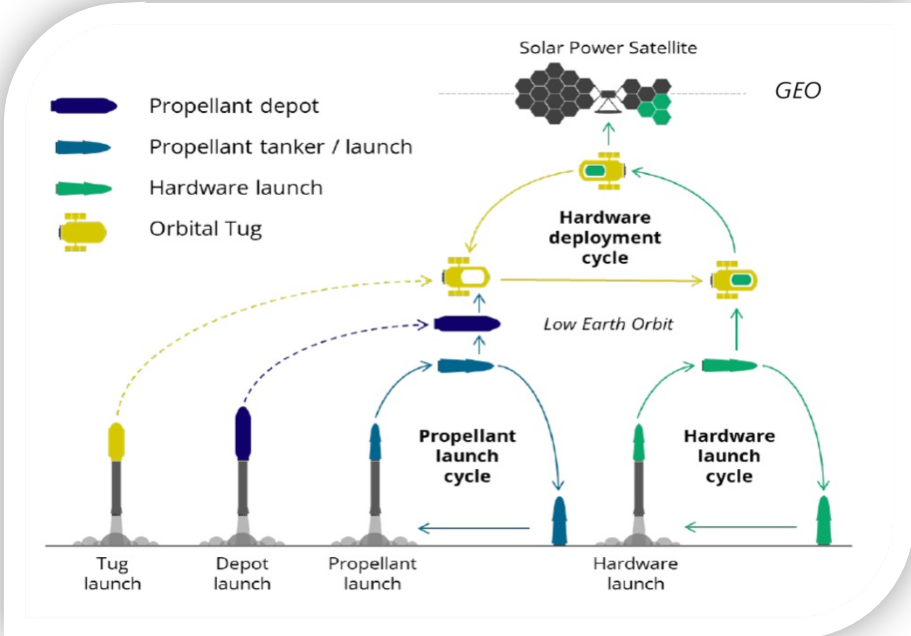
2.2 CONCEPT OF OPERATIONS (1/2)



- /// Cargo launched in LEO and **transferred in GEO via Orbital Tug**
- /// Hardware assembled in GEO **via robotic systems**
- /// The SPS can be operated in a **reduced power mode before the complete assembly**, allowing solar power beaming from early stage of the mission and in orbit tests
- /// During nominal operations **in-orbit maintenance** will be performed when necessary

LAUNCH, DEPLOYMENT & ASSEMBLY



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2.2 CONCEPT OF OPERATIONS (2/2)

/// Decommissioning will be performed with the same technologies required for the assembly, taking advantage of the robotic systems used to disassembly the SPS components.

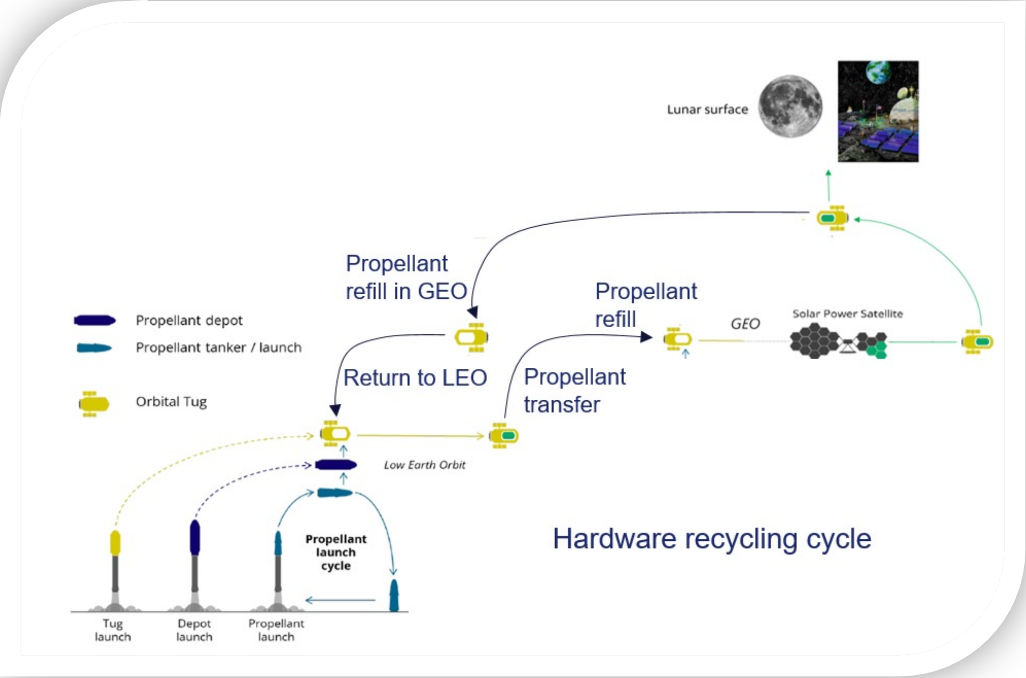
/// The Orbital Tug will perform GEO to Moon orbit and back trip to **bring the SPS components in a Moon orbit**.

/// From the **Moon orbit to Lunar surface** (where recycling take place) a lander will be required to bridge the gap.

/// The Orbital Tug will be able to perform a **LEO to GEO transfer bringing the propellant** required to perform the GEO to Moon transfer

/// Disassembly and in-situ recycling is also possible with the SPS elements disassembled and then **recycled in GEO** via in-orbit manufacturing.

DECOMMISSIONING STRATEGY



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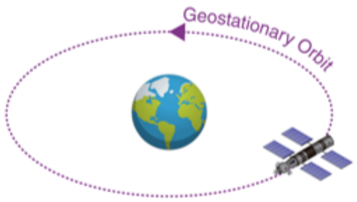
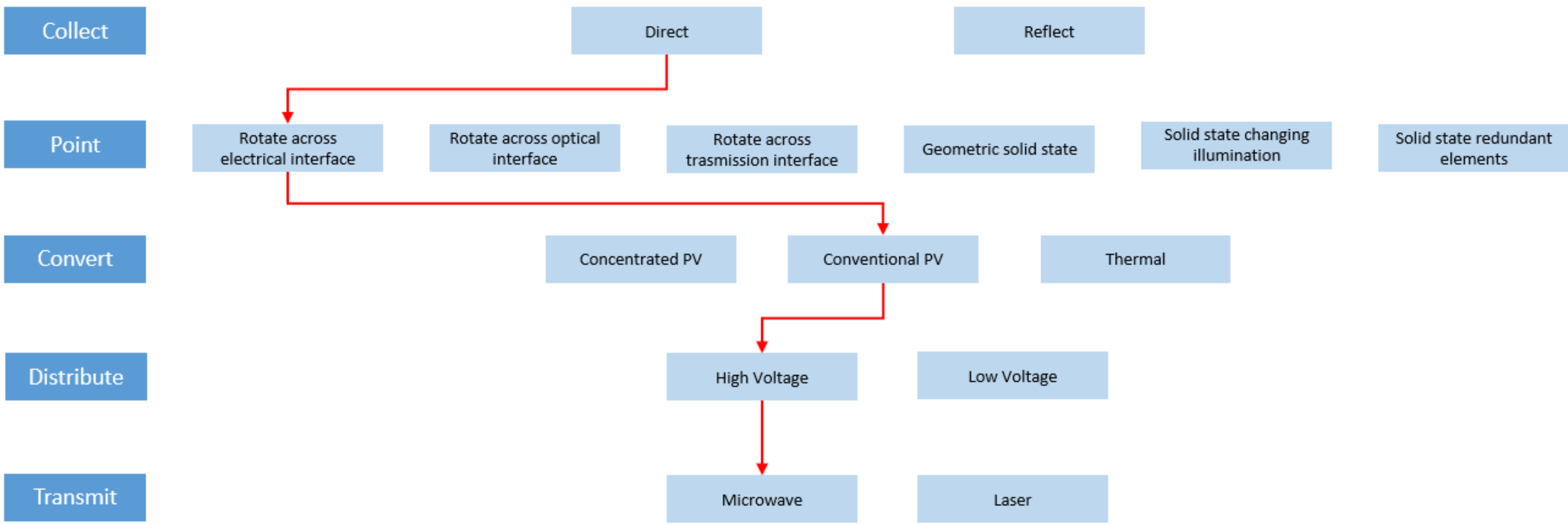
3. SYSTEM OVERVIEW

3.1 SPS SELECTED ARCHITECTURE



Architecture 1a (Conventional PV and GEO orbit)



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ThalesAlenia Space
a Thales / Leonardo company

3.2 TRADE-OFFS SUMMARY

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

3.3 SYSTEM SIZE OPTIMIZATION

System areas	Area value [km2]
Ground Power Station	34
Photovoltaic Assembly	6.20
On-board antenna	0.44

/// Baseline solution, optimized for:

- Transmission frequency : 5.8 GHz
- PV cell technology : Perovskite
- GPS location : Spain

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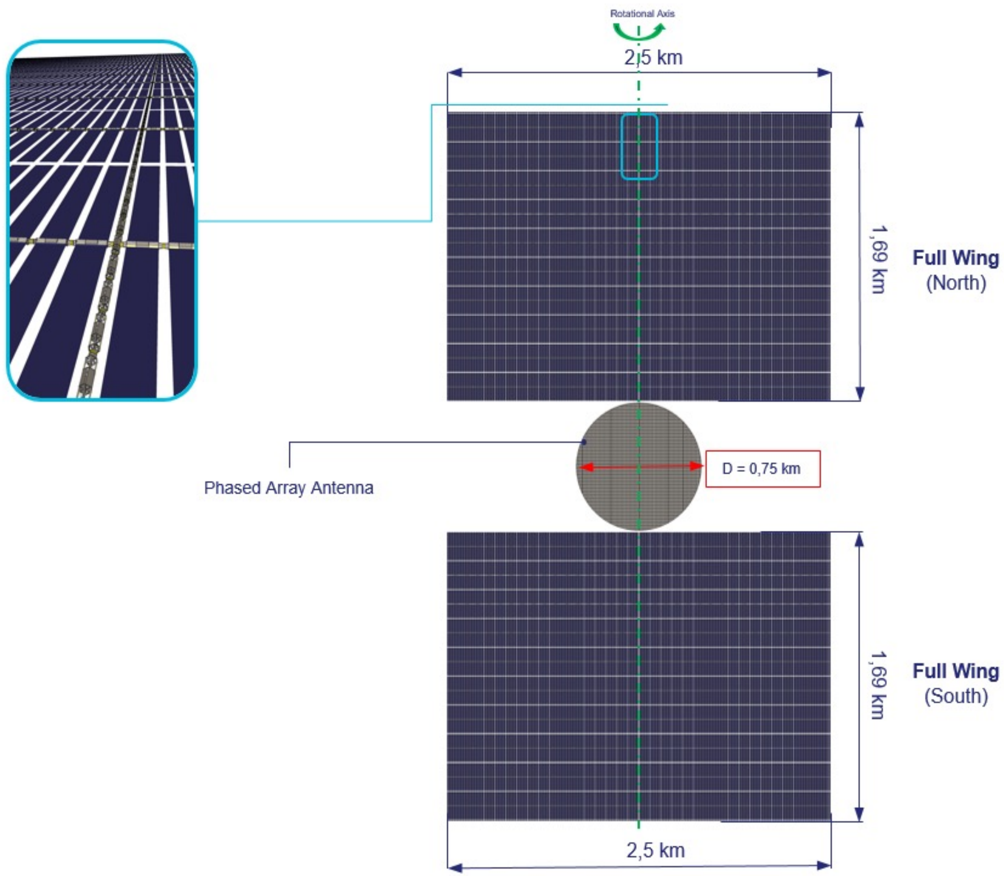
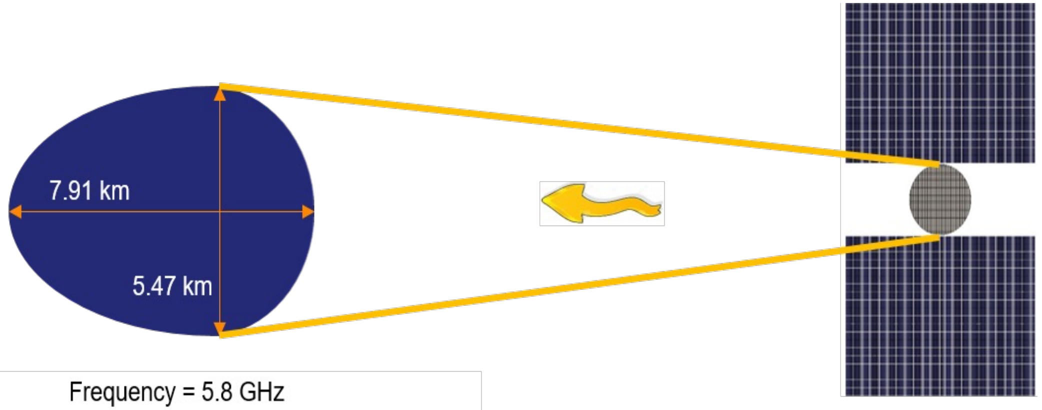
3.4 SOLAR POWER SATELLITE OVERVIEW



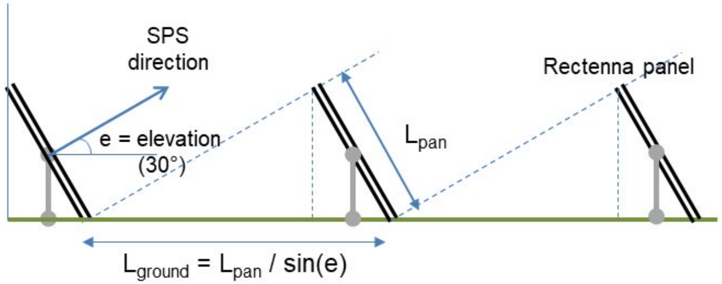
3.5 GROUND POWER STATION OVERVIEW

GPS FOOTPRINT



Frequency = 5.8 GHz
Latitude GPS = 40 deg
Area GPS = 34 km2

INCLINED MESH PANELS



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Ref: Not referenced
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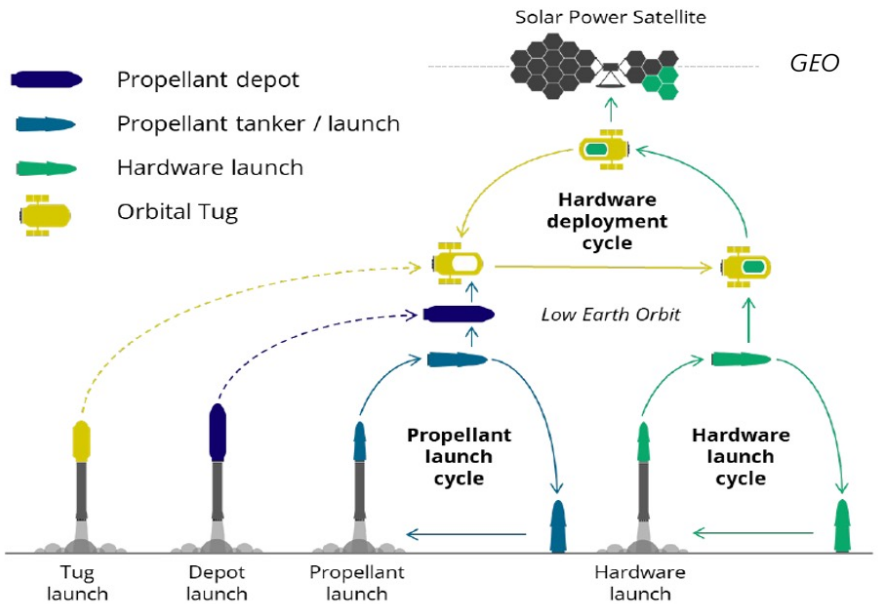
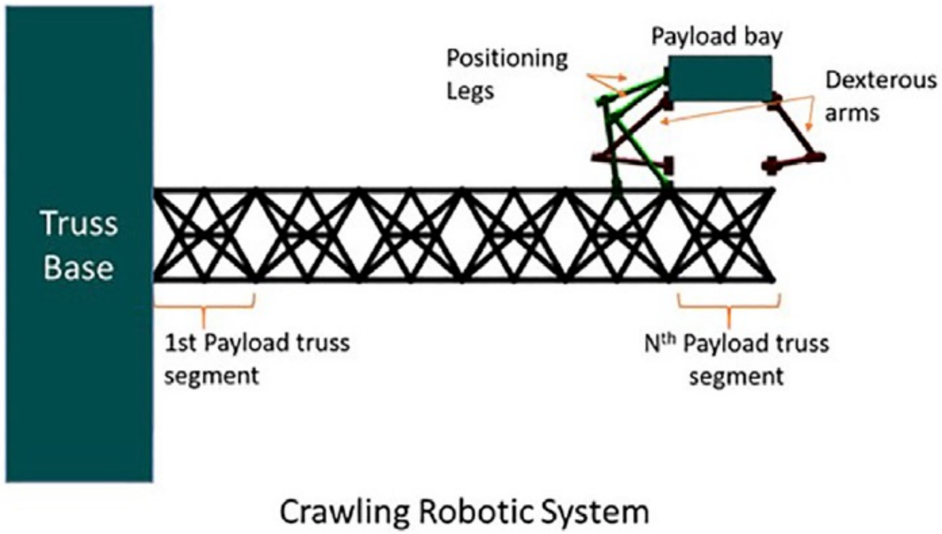
3.6 IN-ORBIT TRANSPORTATION AND ASSEMBLY OVERVIEW

6 orbital tugs for in-space transportation (LEO-GEO) to be compliant with 2 years of construction time



x 24 robotic systems for in-orbit assembly



(Credits: U.S. Naval Research Laboratory)

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3.7 MASS BUDGETS

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

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Ref: Not referenced
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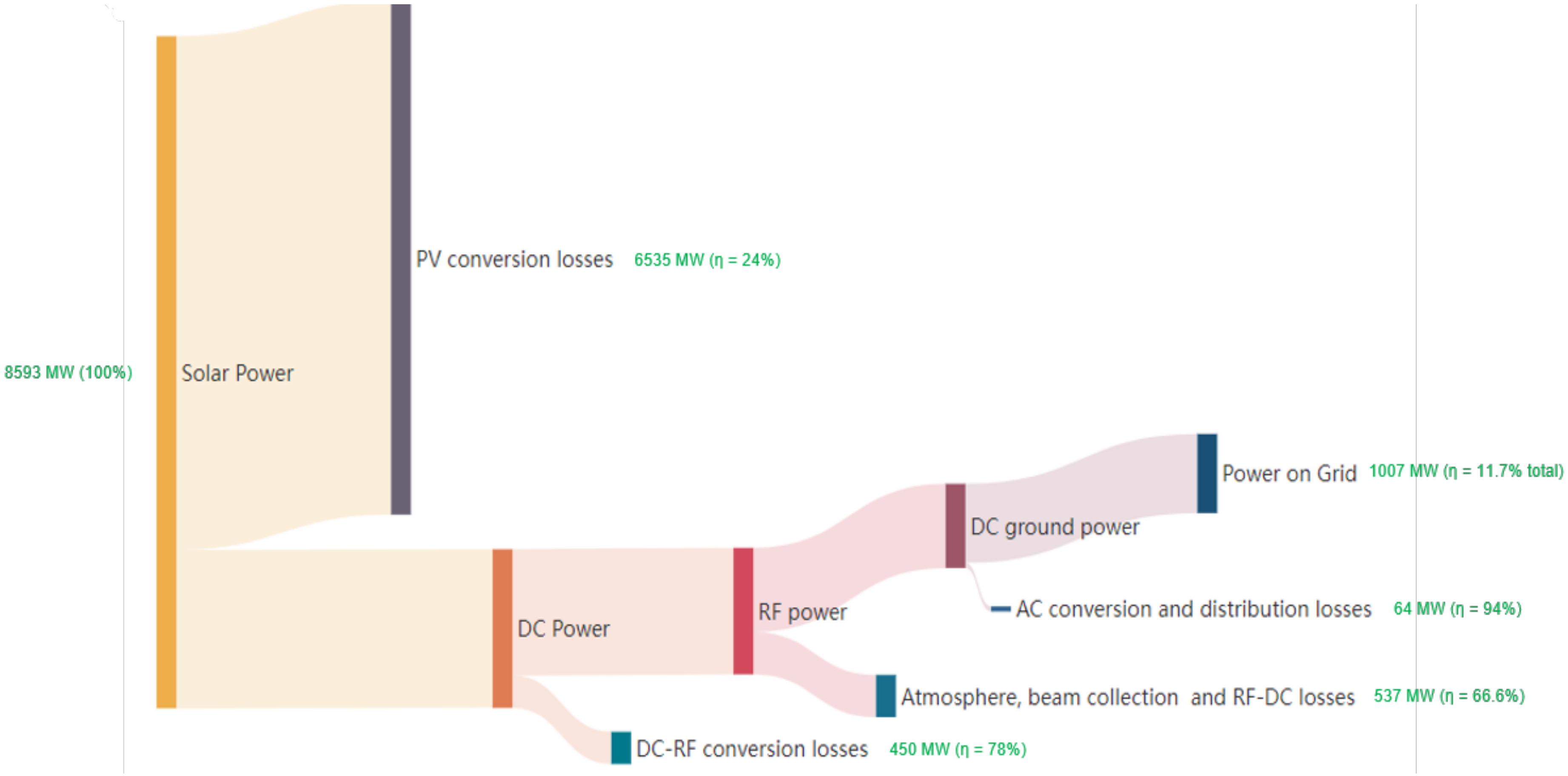
3.8 POWER LINK BUDGET (SANKEY DIAGRAM)



4. C_{O2}, COST & ENERGY ESTIMATIONS

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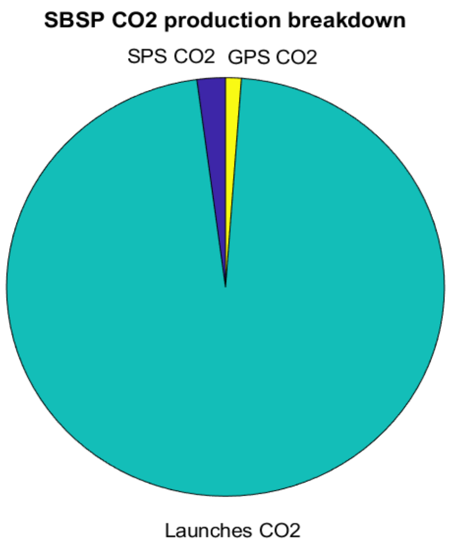
4.1 PRELIMINARY ASSESSMENT OF CO_2 PRODUCTION FOR THE MISSION

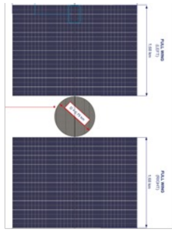
/// Taking into account preliminary evaluations, a first estimate of the **Greenhouse Gas (GHG) parameter** for CO_2 has been evaluated as the total amount of C_{O2} divided by the expected energy generated over the system lifetime.

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



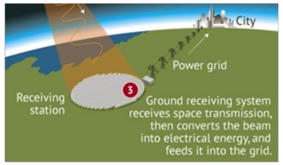
4.2 COST & ENERGY ESTIMATION (1/2)

/// The SBSP mission costs are divided in four areas:



SPS costs

Launches and in orbit transportation costs



Ground segment costs (Ground Power Station)

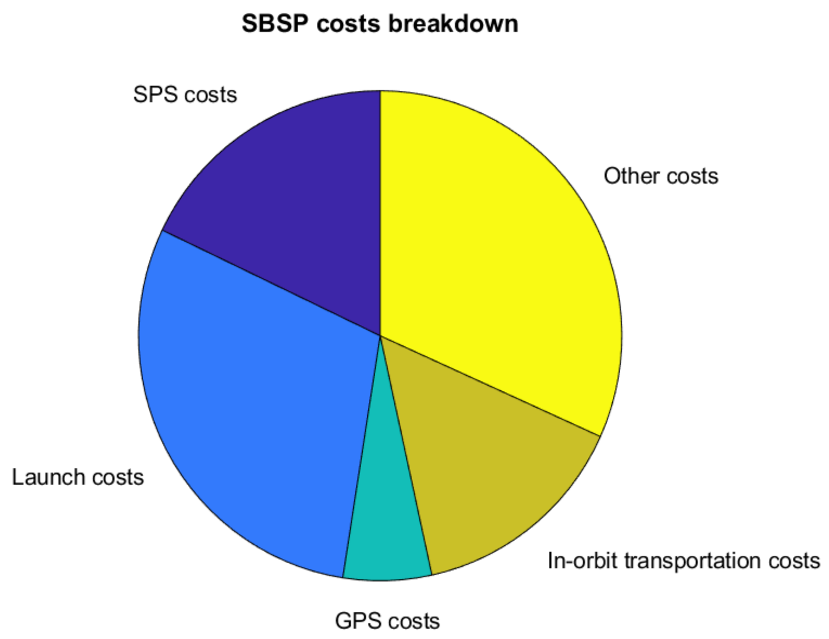
Other costs (development costs, insurance costs,etc.)

→ Overall mission costs and LCOE index

4.2 COST & ENERGY ESTIMATION (2/2)

/// An estimation of the total cost for a FOAK (First Of a Kind) SBSP system is evaluated

Parameter	Composition and value			
CAPEX	SPS costs	Truss module costs	0.01 B$	7.71 B$
		Roll-out modules (with PVA) costs	0.18 B$	
		Node modules costs	0.002 B$	
		WPT system costs	0.50 B$	
		AOCS costs	1.43 B$	
	Launch and in-orbit transportation/assembly costs	Launch costs	3.31 B$	
		In-orbit transportation costs	1.65 B$	
		Robotic hardware costs for assembly	0.004 B$	
	GPS costs	Land occupation costs	0.06 B$	
		Rectenna mesh costs	0.17 B$	
		GPS power control costs	0.36 B$	
OPEX	Insurance costs		1.7 B$	3.66 B$
	OM costs		1.6 B$	
	AOCS thrusters refueling costs		0.36 B$	
TOTAL SBSP MISSION COST	**11.4 B$**			



4.3 TOTAL ENERY DELIVERED & LCOE

/// The following Levelized Cost of Energy (LCOE) is obtained for a FOAK SBSP system

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

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

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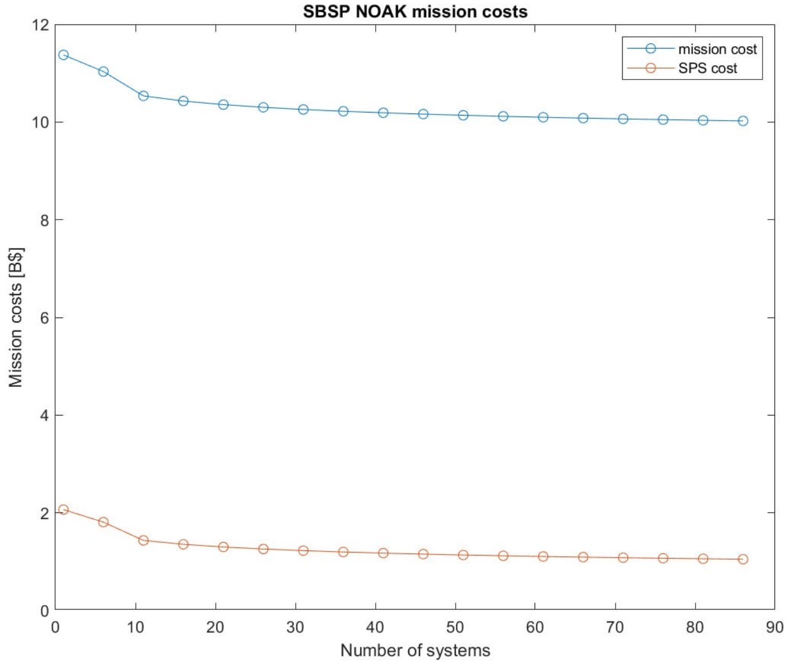
4.4 FOAK VS NOAK SYSTEM COSTS

/// The learning curve approach is applied to assess a preliminary estimation of what could be the cost for an n-of-a-kind (NOAK) system with respect to a first-of-a-kind (FOAK) system

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



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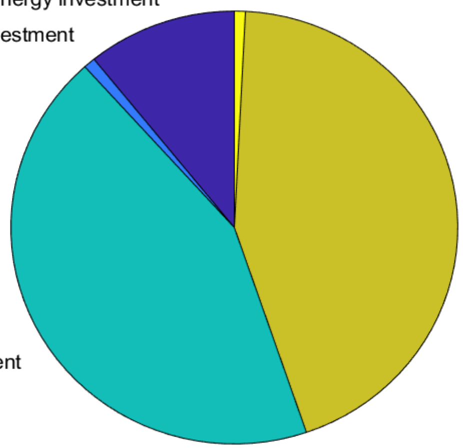
4.5 ENERGY INVESTMENT, EPBT & EROEI

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

/// W.r.t. other renewable technologies (e.g., PV farms) the **EPBT is minimal**, making clear the possible advantages of **SBSP** and its **economic potential**



Date: 20/12/2023
Ref: Not referenced
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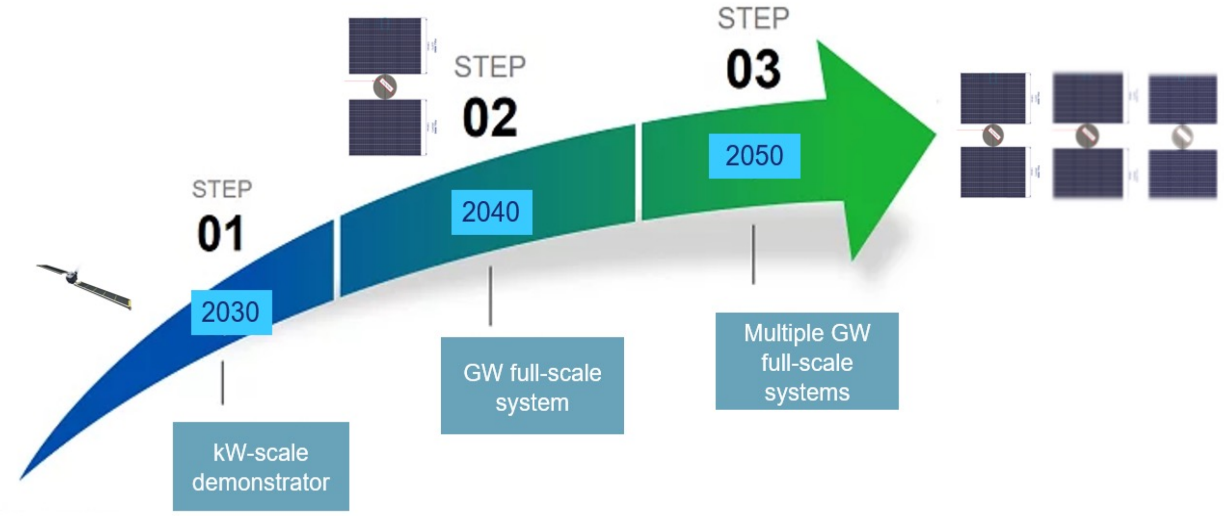
5. ROADMAP & DEMONSTRATOR MISSION

5.1 SBSP ROADMAP

/// The SBSP development roadmap towards a commercial scale SBSP system development, including a kW-scale demonstrator along the way, proposed by our Consortium:



Date: 20/12/2023
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5.2 FUNCTIONS & TECHNOLOGIES FOR THE DEMONSTRATOR (1/2)

/// When dealing with a SBSP demonstrator, it is necessary to **reconsider and adapt several key functions** and assumptions from the full-scale system to a sub-scale system.

/// The aim of the demonstrator is to **prove the feasibility of wireless power transmission** from orbit to Earth incorporating and **validating** as many of the **technologies of the full-scale system**.

/// The following three **primary functions** of the SBSP energy chain are still valid when addressing sub-scale systems:

- Converting **solar power to DC power**: accomplished through **PV panels**;
- Converting **DC power to RF power**: carried out by an **antenna** equipped with DC-RF converters;
- Converting **RF power to DC power**: fulfilled by a Ground Power Station equipped with **rectenna** (RF-DC converters) mesh.

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5.2 FUNCTIONS & TECHNOLOGIES FOR THE DEMONSTRATOR (2/2)

/// The **three main system areas** that define the SBSP sub-scale system, as for the full-scale system, are:

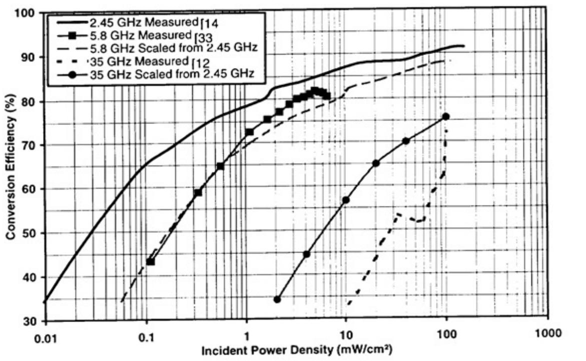
- PV area;
- On-board antenna area;
- GPS area.

/// The relationship between the on-board antenna area and the GPS area is influenced by three interrelated factors that **necessitate re-evaluation for the sub-scale system**:

- **Orbit altitude**
- **Transmission frequency**
- **Beam collection efficiency** (the proportion of the emitted power beam from the antenna that is intended to be captured on ground)

/// The beam collection efficiency, as well as other efficiencies like the RF-DC conversion efficiencies, will affect the total PV area needed.

/// The RF-DC efficiency significantly diminishes when dealing with lower power densities, a scenario encountered in a demonstrator where reduced power levels are validated



Date: 20/12/2023
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5.3 PRELIMINARY RECOMMENDATIONS FOR THE DEMONSTRATOR (1/3)

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

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

/// The proposed solutions arise from an **initial compromise involving the three primary SBSP domains**: the GPS area, the PV area, and the on-board antenna area

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5.3 PRELIMINARY RECOMMENDATIONS FOR THE DEMONSTRATOR (2/3)

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

- **emerging cell technologies**, such as Perovskite, in space environment
- the power **conversion performances**
- the effectiveness of **wireless power transmission**
- the **reliability of the SPS components**

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

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5.3 PRELIMINARY RECOMMENDATIONS FOR THE DEMONSTRATOR (3/3)

- /// Using as reference the values from the 0.01 kW on ground proposed satellite, **it would be possible to use deployable solar panels** and a **foldable/inflatable phased array antenna** to fit the satellite inside a **single launcher fairing**.
- /// The satellite's design **shall prioritize the maximization of both solar array and antenna areas** in order to **reduce the required GPS area**. Considerations on the beam collection efficiency will also help in reducing the GPS area, for example by collecting only the peak of the intensity profile, increasing the mean rectenna efficiency.
- /// A **demonstrator mission will play a pivotal role** in assessing the viability of a full-scale Space-Based Solar Power (SBSP) mission

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Ref: Not referenced
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6. CONCLUSIONS

6. CONCLUSIONS

/// **SBSP presents a promising avenue for addressing our growing energy needs.**

Technical Feasibility

- The technical analysis reveals that the concept of harnessing solar power in space is scientifically sound. **Advances in solar panel efficiency, wireless power transmission, and space-based construction techniques** contribute to the overall feasibility of the project.

Economic Viability

- While the initial investment for space-based solar power infrastructure is substantial, **our study indicates that the long-term economic benefits**, including consistent and abundant energy production, **outweigh the costs**. Continued technological advancements and economies of scale could further enhance the economic viability of SBSP.

Programmatic Feasibility

- Implementing a space-based solar power program would require international collaboration, regulatory frameworks, and strategic planning. Our study underscores the importance of robust **international partnerships and comprehensive policies** to navigate the complexities of space-based energy generation.

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

Date: 20/12/2023
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VIDEO