ESA ESTEC
Keplerlaan 1
2201 AZ Noordwijk
The Netherlands

STATEMENT OF WORK

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

Prepared by	TEB
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TABLE OF CONTENTS

1 Introduction

1.1 Scope of the Document

This document describes the activity to be executed and the deliverables required by the European Space Agency in relation to the "***Pre-Phase A System Study of a Commercial-Scale Space-Based solar Power (SBSP) System for Terrestrial Needs***".

This document will be part of the Contract and shall serve as an applicable document throughout the execution of the work.

1.2 Discovery, Preparation and Technology Development Basic Activities

ESA's Discovery and Preparation elements of the Discovery Preparation and Technology Development (DPTD) activities (esa.int/discovery) interfaces in different ways with all of ESA's programmes, carrying out preparatory analysis and laying the groundwork for the Agency's future activities.

The objectives are to:

- Study feasibility for selection of new mission concepts
- Prepare/demonstrate the case for approval and funding of new optional projects/programmes
- Implement interdisciplinary discovery project for paradigm shifts and game changers
- Perform early "blue sky" research on topics that are recognised as being potential breakthrough ideas but not implementable in the next ten years
- Support the evolution of ESA by analysing and testing new working methodologies

A diversity of topics is investigated via Discovery & Preparation undertakings, running across the entire spectrum of the Agency's activities. In average, each study lasts one to two years, sufficient time for in-depth exploration of each subject.

The studies undertaken by the Discovery & Preparation provide ESA and its Member States with the necessary information on which to base their decisions about the implementation of new programmes and the future direction of space activities.

1.3 Acronyms and Abbreviations

AB	Abstract
AD	Applicable Document
AKR	Architecture Key-Point Review
ASR	Architecture Selection Review
CAD	Computer-Aided Design
CASSIOPeiA	Constant Aperture, Solid-State, Integrated, Orbital Phased Array
CAST	China Academy of Space Technology
CCD	Contract Closure Documentation
CM22	ESA Council at Ministerial level (2022)
CM25	ESA Council at Ministerial level (2025)
CO	Contracts Officer
ConOps	Concept of Operations
DMS	Data Management System
DPTD	Discovery Preparation and Technology Development
ECSS	European Cooperation for Space Standardization
ERoEI	Energy Return on Energy Invested
ESR	Executive Summary Report
ESTEC	European Space Research and Technology Centre
ETD	Early Technology Development
FLPP	Future Launchers Preparatory Programme
FOR	Forced Outage Rate
FP	Final Presentation
FR	Final Report
GEO	Geostationary Orbit
GSO	Geosynchronous Orbit
GSTP	General Support Technology Programme
ISDC	International Space Development Conference
ISO	International Organization for Standardization
ITT	Invitation To Tender
KO	Kick Off
KOM	Kick Off Meeting
LCA	Life Cycle Assessment
LCOE	Levelized Cost of Energy
LEO	Low Earth Orbit
MBSE	Model Based Systems Engineering
MEO	Medium Earth Orbit
MR-SPS	Multi-Rotary joints SPS
NIAC	NASA Institute for Advanced Concepts
NSS	National Space Society
OSIP	Open Space Innovation Platform
PDF	Portable Document Format
PV	Photovoltaics
PVID	Promotional Video
PVIS	Promotional Visuals
RD	Reference Document
RF	Radio Frequency
RFP	Request for Proposals
ROM	Rough Order of Magnitude
SBSP	Space Based Solar Power
SKR	Stakeholder Key-Point Review
SOW	Statement of Work
SPS	Solar Power Satellite
SPS-ALPHA	SPS by means of Arbitrarily Large Phased Array
TBC	To Be Confirmed
TBD	To De Determined
TBR	To Be Resolved
TBW	To Be Written
TO	Technical Officer
TRL	Technology Readiness Level
VALCOE	Value Adjusted Levelized Cost of Electricity
WP	Work Package
WPT	Wireless Power Transmission

1.4 Applicable and Reference Documents

The Contractor should be aware that the Applicable and Reference documents are subject to further evolution. New issues of documents may be provided by ESA to the Contractor during the study.

1.4.1 Applicable Documents

The following documents shall be applicable to the study Contract. These Applicable Documents (ADs) contain requirements related to the work of this activity. The Contractor shall consult the ADs as needed to complete the work of this activity.

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)

AD1 will be produced by ESOC and will contain analyses and considerations for different candidate orbits for Space-Based Solar Power systems. A first issue of AD1 will be provided by ESA at the activity Kick Off Meeting (KOM). ESOC may perform additional analyses related to candidate orbits in response to outputs from the study. Subsequent issues of AD1 may be provided by ESA at the Stakeholder Key-Point Review (SKR) and the Architecture Selection Review (ASR) (see section 3.1).

AD3 will be provided at the activity KOM.

AD5 will be provided as soon as available for distribution. ESA expects this may be available to provide by SKR (TBC).

1.4.2 Reference Documents

The following documents include relevant reference information to this activity. They are provided to the Contractor for information only. The Contractor may consult these Reference Documents (RDs) as needed to complete the work of this activity.

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”

RD2 Final Deliverables from Roland Berger for ESA-funded study titled “Cost-Benefit Analysis of Space-Based Solar Power Generation for Terrestrial Energy Needs”

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. 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

2 Background and Objectives

2.1 Background

2.1.1 SOLARIS Initiative

This activity is a part of ESA's SOLARIS initiative on Space-based Solar Power for terrestrial needs. This initiative has the intention to assess the technical feasibility, economic practicality, and social and environmental acceptability of SBSP to provide clean energy to Europe in the future.

SOLARIS responds directly to ESA's Agenda 2025 which recognises that "*Space-based services to support the energy transition, and potential space-based solar power generation deserve to be further investigated*". It aims to prepare by 2025 the basis for further decision-making on a potential new clean energy source for Europe, Space Based Solar Power. This will be achieved through the advancement of system concepts and by using SBSP as a driving application for technology developments which are far reaching in their potential applications.

The objectives of the SOLARIS initiative in the 2023 – 2025 timeframe are to:

1) Evaluate the technical feasibility, costs, benefits, and risks of Space-Based Solar Power.
2) Develop key technologies required for SBSP realisation.
3) Raise awareness of SBSP amongst key stakeholders.
4) Establish opportunities for international cooperation.
5) Potentially prepare a proposal for a decision by end 2025 on a SBSP development programme, including a first in-orbit demonstrator project.
6) Position Europe as a key player in SBSP.

2.1.2 SOLARIS System Study Activities

SBSP has been studied by several different actors over the past decades. These efforts have produced several different architectures and concepts. While these past activities have developed novel and interesting solutions, ESA does not consider that these have sufficiently addressed the developmental, technological, and environmental challenges of SBSP. ESA itself has not performed any significant SBSP technical studies at **system-level** in the last 20 years. Therefore, an activity to define an up-to-date European reference architecture for future commercial SBSP systems (including both the space and ground segments) is now needed to inform further investigation of the technical, economic, and programmatic feasibility of SBSP for supporting Europe's Net Zero goals.

SOLARIS currently foresees a multi-step approach towards the commercial realisation of SBSP services after a potential decision in 2025. Firstly, launching a *sub-scale space-based demonstrator mission* by 2030 is considered an important step to demonstrate the viability of space-based solar power to institutional and commercial stakeholders. Incremental developments would follow the demonstrator mission in the 2030s to deploy systems with increasing capacity; this anticipates a first

SBSP commercially-viable *pilot solar power station* before the deployment of the first *commercial-scale SBSP system*.
“Commercial-scale” is currently anticipated to consider single SBSP systems that are sized and capable to deliver 100’s of Megawatts or Gigawatts of baseload power to the European energy market.

Consequently, two System Study activities are envisioned in the SOLARIS activity plan between 2023 and 2025 (as shown in Figure 2-1):

1) Pre-Phase A System Study of a Commercial-Scale Space-Based Solar Power System for Terrestrial Needs (this activity).

2) Phase 0/A/B1 System Study of a Sub-Scale Space Based Demonstrator Mission (pending approval).

The SOLARIS initiative proposes a system study on the commercial-scale SBSP system first to provide inputs to subsequent system studies concerning the definition of the demonstrator mission, as well as to identify additional technology and research requirements specific to the new reference architecture to be developed.

The timeline for other intermediate steps and system studies towards realising a commercial-scale SBSP (i.e., including the pilot plant system) are similarly expected to be defined by ESA later using the outputs of this system study activity.

2.1.3 Other SOLARIS Activities

The SOLARIS initiative anticipates additional activities to the system studies. These include:

- *Technology Development Activities*: these activities are intended to mature key technologies needed for realisation of SBSP systems. Technology activities will be initiated from the start of the SOLARIS initiative (based on current understanding of technology needs from previous ESA and international studies) but also at later points in response to outputs from the system studies.

- *Stakeholder Engagement Activities*: these activities are intended to bring together ESA and European Industry with key stakeholders for future SBSP systems (including traditional energy suppliers and actors along the energy value chain). The purpose of these activities will be to generate inputs for the definition of SBSP architectures and system studies, but also to raise awareness of SBSP with these stakeholders. Task 1 of this activity has a direct link with the Stakeholder Engagement activities (see task descriptions in Section 3).

- *Environmental and Socioeconomic Activities*: these research activities are intended to explore the wider socioeconomic and environmental impacts of space-based solar power. These studies may interface with the system studies.

- *Launcher Studies*: ESA’s Future Launchers Preparatory Programme (FLPP) is planning to run studies on the definition of re-useable and heavy-lift launch capabilities for Europe. These activities are being conducted in support of the SOLARIS initiative due to the anticipated demanding launch requirements of SBSP systems. There will be close interfacing between the FLPP studies and the SOLARIS System Studies to ensure the two are well coordinated. *Information regarding launcher studies will be included in a future version of this document.*

Figure 2-1 provides a high-level overview of the SOLARIS initiative activities in relation to this activity.

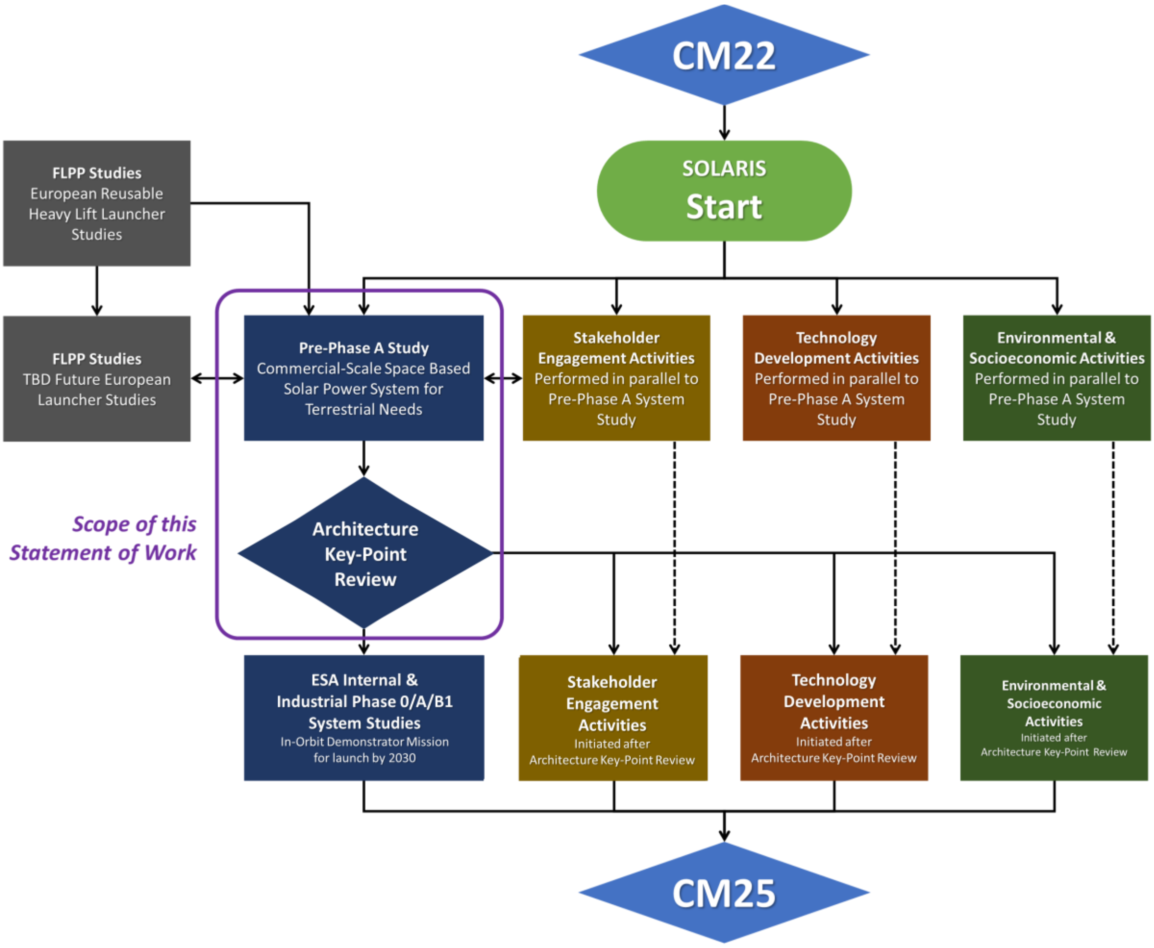

Figure 2-1. Simplified Work methodology for the SOLARIS initiative activities between 2023 and 2025. This activity concerns the Pre-Phase A System Study of a Commercial-Scale SBSP System. The Architecture Key-Point Review will generate inputs to support immediate follow-up activities in the SOLARIS workplan. ESA may initiate other SOLARIS activities not specified in the figure above.

For more details on SOLARIS refer to www.esa.int/solaris.

2.1.4 SBSP System Overview

Figure 2-2 provides an overview of the currently anticipated main elements of a future SBSP System.

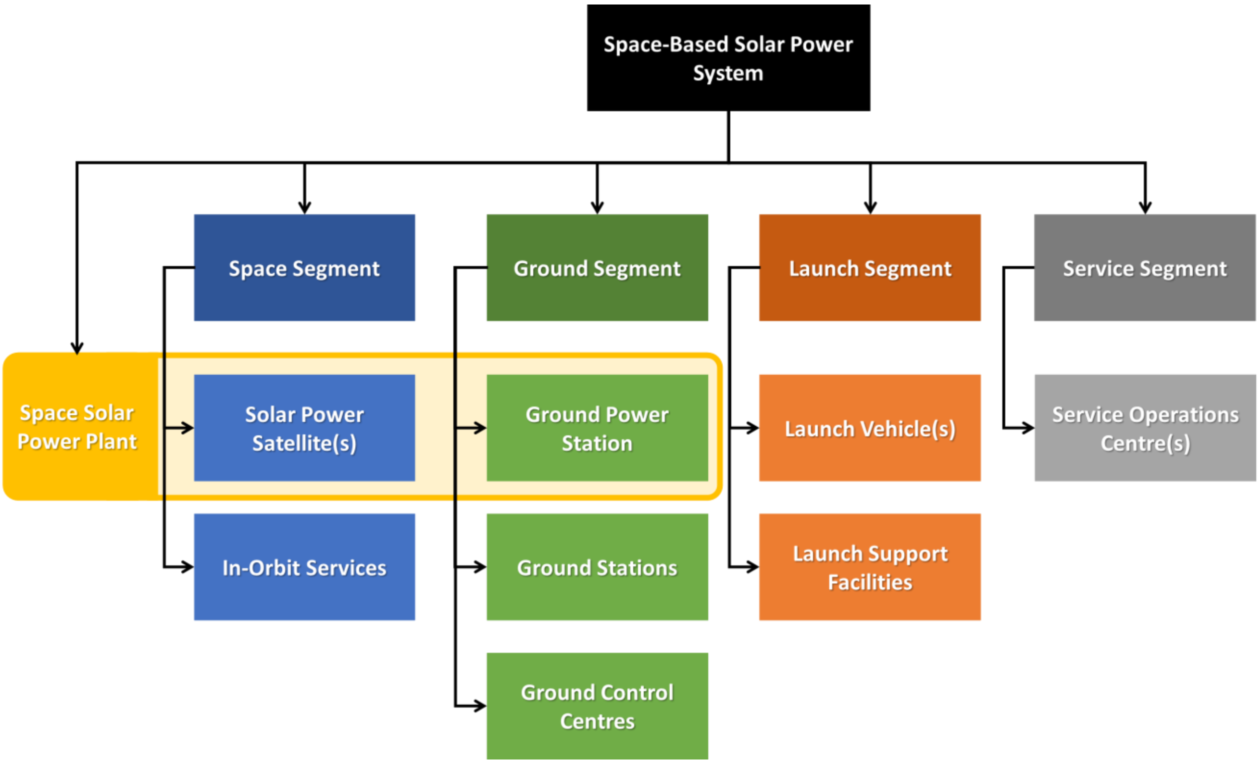

Figure 2-2. Notional elements of the Space-Based Solar Power System

Definitions of the terms within Figure 2-2 is provided below:

SBSP System This refers to the complete system including all elements including Space, Ground, Launch, and Service Segments. The SBSP System may also be referred to as the "SBSP Service".

Solar Power Satellite (SPS) The system responsible for collecting solar power in space and transmitting power down to the ground.

In-Orbit Services Refers to the multitude of systems and capabilities which may be required to facilitate operations of the Solar Power Satellite(s) throughout their lifetime. This may include functions related to transfer and assembly in-orbit, support of routine operations, maintenance and resupply, and end-of life. Possible example systems may include orbit transfer vehicles, logistics vehicles, robotic assembly systems, propellant storage depots etc.

Launch Vehicle(s) The system(s) responsible for the launch of Space Segment systems into orbit.

Launch Support Facilities Refers to the facilities responsible for supporting launch vehicle operations and managing Launch Segment operations.

Ground Power Stations The system responsible for receiving power transmitted from Space Segment systems and delivering power to the energy grid (or alternative output depending on selected use-case).

Ground Stations Refers to the elements responsible for performing uplink and downlink of communications between the Space and Ground Segments.

Ground Control Centres Refers to the facilities responsible for managing Space Segment operations.

Service Operations Centre(s) Refers to the element(s) of the service segment responsible for the managing operations of the SBSP energy service delivery.

Space Solar Power Plant Collectively refers to space and ground systems responsible for the generation of power and provision into the grid (or alternative output depending on selected use-case). Each Space Solar Power Plant is currently anticipated to include one Ground Power Station but may include one or multiple Solar Power Satellite(s) for power provision.

2.2 Purpose of the Activity

The purpose of this Pre-Phase A Systems Study is ***to define a reference SBSP architecture*** to evaluate its technical feasibility and to provide requisite information for SOLARIS environmental and socioeconomic assessments of SBSP and stakeholder engagement activities.

2.3 Study Objectives

The objectives of this Pre-Phase A system study will be to:

I. Identify and define stakeholder expectations and requirements for a future Space-Based Solar Power System which can serve European energy needs.

II. Develop an original SBSP System architecture for a reference commercial use-case considering cost, risks, technology maturity, environmental impact, industrial capability, safety, and operational constraints.

III. Identify technology and capability development needs required to mature a technically feasible, economically, and commercially attractive SBSP System architecture which offers a demonstrable net-positive environmental impact.

IV. Provide details and results of a reference system design to inform parallel environmental and socioeconomic studies and stakeholder engagement activities performed within the framework of the SOLARIS initiative.

V. Provide technical and programmatic inputs (including cost drivers, schedule, and risks) to inform subsequent SOLARIS system studies (including follow-up studies into a sub-scale in-orbit SBSP demonstrator mission).

VI. Provide information to inform management decisions about the direction of the SOLARIS initiative.

2.4 Scope of the Activity

The scope of the activity is on the ***full definition of the SBSP System*** (see Figure 2-2). However, special attention shall be given to the definition of the Solar Power Satellites (SPSs) and the Ground Power Stations. Definition of the launcher system is limited (see section 2.4.1). Definition of in-space transportation elements is included (these are assumed within "*In Orbit Services*" in section 2.1.4).

2.4.1 Scope of Launch Systems Definition

The definition of future launcher systems relevant for the SOLARIS initiative will be explored by ESA through FLPP activities. Relevant results from these activities will be fed into the SOLARIS System Studies as appropriate.

The Contractor shall be responsible for incorporating the provided FLPP results into their analyses and work in this activity.

Note: At the time of publication of this SoW ESA anticipates that intermediate results from the European Reusable Heavy Lift Launcher Studies activities[1] (see Figure 2-1) will be available to share with the Contractor by the KOM of this activity. Similarly, final results from this FLPP activity will be available to the contractor at PM1[2].

In parallel the Contractor shall also collect and exploit other data on launcher capabilities outside of Europe expected in the timeframe of the SBSP system deployment.

2.4.2 Scope of Environmental Impact Assessments

It is extremely important to consider the environmental impact of future energy systems early in the design and planning phases. This is especially true for SBSP systems given their anticipated scale and potential application. The expected environmental impacts of SBSP systems will therefore need to be well understood before pursuing implementation.

The Life Cycle Assessment (LCA) methodology is an ISO standardised methodology used to quantify the environmental impacts of products or services on the earth eco-sphere. The impacts in space environment (i.e., space debris) shall be addressed by the Contractor separately.

In this activity the Contractor shall perform a *preliminary* Life Cycle Assessment (LCA) to generate inputs for comparing the environmental impacts of proposed *commercial-scale* SBSP architecture(s).

The Contractor shall propose a methodology for assessing environmental impacts in the proposal based on AD2. The proposed methodology shall be used to support the selection of a reference architecture in Task 3 and to support the environmental impact analyses in Task 5 (see section 3.3 for details).

The Contractor's proposed methodology shall be agreed with ESA by the KOM (see special conditions of tender for details).

The methodology proposed by the Contractor shall clearly specify the following:

- Definition of the system boundaries of the studies systems.
- Definition of the "functional unit" of the studied systems (see AD2).
- Definition of the environmental impact indicators to be considered in this activity (see AD2).
- Distinction between contributions from launchers and SBSP systems.

The methodology proposed by the Contractor shall cover the following as a minimum:

- Identification of the CO2 generation "hot spots" of studied SBPS architecture(s).
- Assessment of the expected carbon footprint of candidate SBSP architecture(s).
- Assessment of the carbon payback time of candidate SBSP architecture(s).
- Evaluation of launches required over the lifetime for SBSP architecture(s).
- High-level bill of materials (BoM) for SBSP architecture(s).
- Environmental impact of BoM for SBSP architecture(s).

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[1] The title of this activity is "euroPean Reusable and cOsT Effective heavy lIft transport investigatioN" or PROTEIN

[2] See

Figure 3-1 and Section 4.4 of this document for details on key study meetings.

2.4.3 Scope of Cost Assessments

ESA expects the costs associated with the deployment of commercial-scale Space-Based Solar Power Systems are not commensurate with the costs of conventional space projects. As a result, conventional cost approaches used within the space industry may have significant uncertainties associated with the results.

The Contractor shall propose a methodology for assessing the costs of SBSP architectures studied in this activity in the proposal. The proposed methodology shall be used to support the selection of a reference architecture in Task 3 and to support the cost analyses in Task 5 (see section 3.3 for details).

The Contractor's proposed methodology for costing activities shall be agreed with ESA by the KOM (see special conditions of tender for details).

The methodology proposed by the Contractor shall clearly specify the following:

- How costs will be considered for quantitative comparisons between SBSP architectures (relevant for Task 3).
- How cost drivers will be identified and evaluated.
- How a cost assessment will be performed in Task 5.
- Scope and expected accuracy of comparative cost assessments.
- Assumptions to be taken in cost analyses.
- Technology readiness levels (TRL) considered at the time of the estimate.
- Formulas and boundaries used for the evaluation of LCOE and VALCOE (see recent ESA cost-benefit studies [AD6, AD7] for reference).

The proposed methodology shall be used to support the selection of a reference architecture in Task 3 and to support the environmental impact analyses in Task 5 (see section 3.3 for details).

3 Work To Be Performed

3.1 Work Logic

The work for this activity is organised into four tasks:

Task 1 Stakeholder Expectations and Requirements Definition

Task 2 Literature Review

Task 3 Architecture Trade-Space Exploration

Task 4 Functional Analysis and ConOps Elaboration

Task 5 Architecture Elaboration

The proposed Work Logic of these tasks is shown

Figure 3-1. The Contractor may propose alternative work logics to be implemented from the study KO.

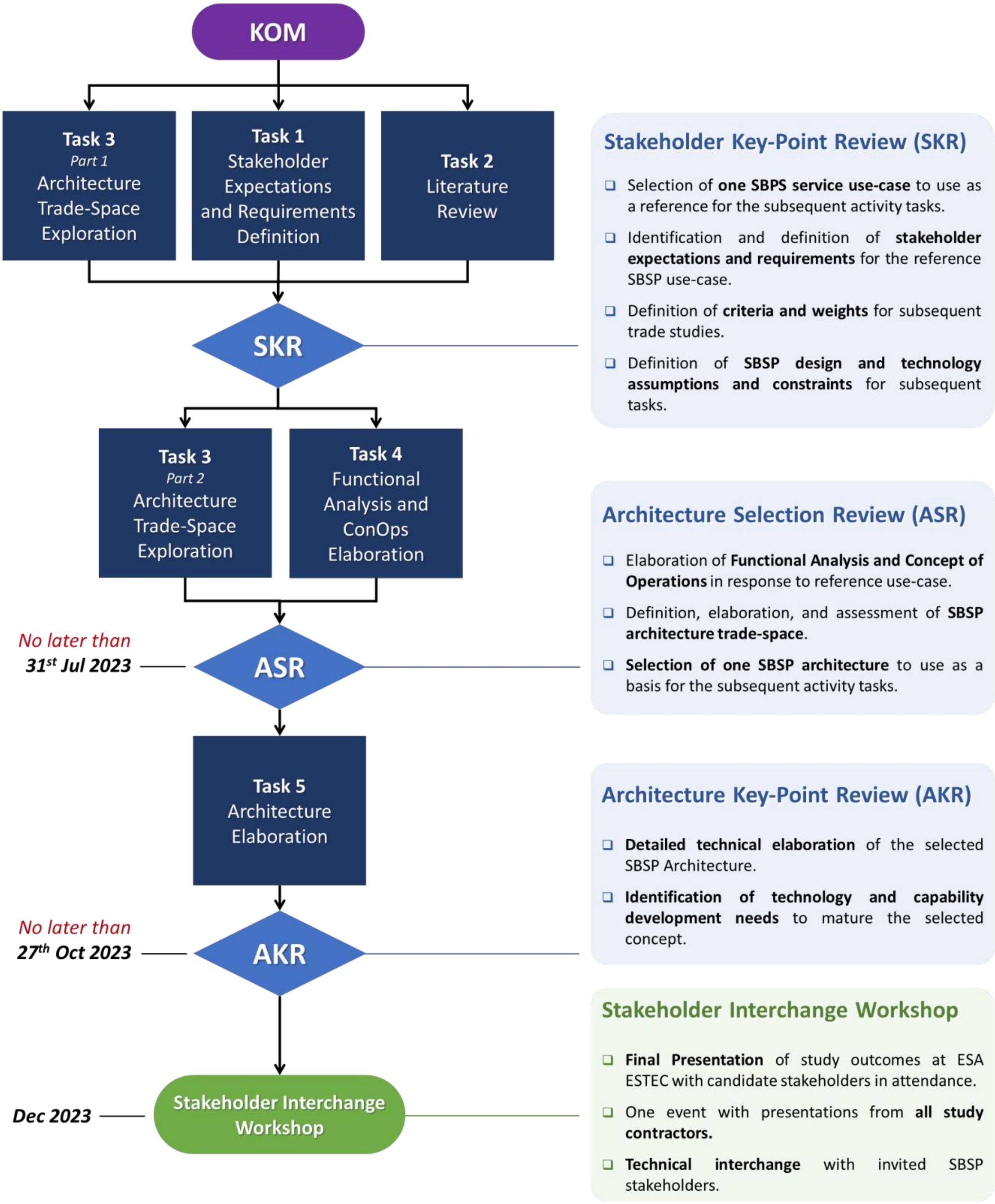

Figure 3-1 Proposed Work Logic

3.2 MBSE Objectives for this Activity

ESA recognises the use of Model Based Systems Engineering (MBSE) as beneficial for projects. The identified benefits include the provision of digital continuity within projects, establishment of a "single point of truth", improved communications with stakeholders, and easier model navigation and access to information.

MBSE allows users to have direct digital access to project data by organizing them in models instead of documents. Engineering Data Modelling permits the design team to have constant access to most design data, not only of their domain area, but also of all other disciplines. A design team can use Engineering Data Modelling to maintain a consistent single-source-of-truth for all relevant engineering data.

Early MBSE adoption can allow for the digitalisation of study data to propagate from pre-Phase A towards later phases, reaching several different stakeholders.

The MBSE objectives to be achieved in this activity are:

I. Requirements Engineering in a digital requirement management/modelling tool**:**

1. Elicit the requirements in a digital requirement management/modelling tool.
2. Allocate requirement ownership to requirements.
3. Provide a rationale and justification to derived requirements.
4. Implement flow-down traceability among requirements, from higher-level requirements to lower-level requirements, where necessary.
5. Implement traceability between requirements and the functional and physical architecture with or within a system model.

II. Functional, Logical and Physical Architectures defined in digital models**:**

6. Establish a mission Concept of Operations for each phase of the mission using operational activities flow diagram.
7. Elaborate a functional architecture model for each space element, derived from the operational activities flow diagram.
8. Assign functions to a physical architecture model encompassing all equipment and its physical properties (e.g., mass, dimension, power, etc.) to a level of granularity and detail to be agreed with the Agency and as appropriate for a Pre-Phase A assessment.

III. System Budgets elaboration in digital tools**:**

9. Use MBSE tools to collect the necessary data to
   i) deliver technical budgets and
   ii) capture mission performance parameters (as required).

IV. Regular model and data exchange with ESA:

10. Facilitate the exchange and reporting of the functional architecture by linking the model with the planned deliverable documents and exchange of data with the ESA study team on a regular basis.
11. Facilitate the exchange and reporting of the physical architecture by linking the model with the planned deliverable documents and exchange of data with the ESA study team on a regular basis.

Important: ESA anticipates multiple industrial pre-phase A system studies on a commercial-scale Space-Based Solar Power Systems to be performed in the coming years. ESA consequently sees especially strong value in implementing MBSE methods within all SOLARIS system studies to facilitate effective information exchange between consecutive study activities.

3.3 Tasks

3.3.1 Task 1: Stakeholder Expectations and Requirements Definition

Task Description:

The purpose of this task is to establish a consistent set of stakeholder needs and expectations for a prospective future SBSP service. This shall include the selection of a reference commercial use-case for the SBSP service and system. This information will then be used to inform the identification and definition of stakeholder requirements and SBSP System architectures in subsequent study tasks.

ESA does not anticipate being the primary owner and operator of future commercial SBSP systems. ESA assumes that this role will be held by other private and public actors. Capturing the expectations and needs of these prospective external stakeholders is therefore necessary to inform the selection and elaboration of a reference architecture for a commercial-scale system.

ESA will organise up to three (TBC) consultation meetings between the Contractor and prospective SBSP stakeholders. These meetings will be held between the KOM and the Stakeholder Key-Point Review (SKR). The stakeholders are currently anticipated to be the future commercial operators along the value chain of future SBSP services. Representatives from public institutions and regulatory bodies as well as private investors may also be engaged.

ESA anticipates that there are several possible use-cases of a commercial SBSP System. Possible use-cases include energy delivery to the European electricity grid but also international export of energy outside of Europe. Industrial non-electrical use-cases are also a possibility such as hydrogen production, synthetic fuel production, and carbon capture.

The Contractor shall use the consultation meetings to:

- Elicit the stakeholder needs and expectations of prospective commercial SBSP systems
- Identify and define different use-cases for a commercial SBSP system
- Discuss the systems-level implications of different use-cases with the stakeholders
- Collect inputs to support the selection of a reference use-case for subsequent study tasks
- Identify and define assumptions, constraints, and risks to consider in subsequent study tasks
- Identify and define trade-criteria and weights to support trade studies in subsequent tasks

The Contractor shall begin to define in parallel candidate Operational Scenarios of the SBSP System during this task. The Operational Scenarios shall describe how the system may be used to satisfy the stakeholder expectations for the various use-cases. This shall describe the system from an operational perspective to help facilitate an understanding of the system goals between the Contractor, ESA, and the Candidate Stakeholders. This may lead to further refinement of the initial set of stakeholder expectations by the Contractor if gaps or ambiguous statements are discovered. The Contractor shall ensure that the scenarios and concepts described in the Operational Scenarios provide an implementation-free description of what the system needs to do to satisfy the stakeholder requirements (instead of addressing how the system should satisfy the need).

This first iteration of the Operational Scenarios shall include:

- Identification of the key stages across the complete lifecycle of the SBSP system.
- Description of how the SBSP system may be operated for different service use-cases.
- Indication of the timeline for different SBSP service availability.
- Identification of unique operational needs of different candidate service use-cases.

The Contractor shall also define the user and service requirements and system-level implications for the SBSP system in parallel to the definition of the reference use-case and stakeholder expectations.

The Contractor will be expected to review the Applicable Documents prior to the stakeholder consultation meetings.

Note: ESA currently anticipates that the stakeholder consultation meetings will be held with all Contractors and identified stakeholders simultaneously present. This is intended to make effective use of the stakeholder's available time and to provide similar inputs to all contractors.

Outputs:

The Contractor shall provide the following outputs of this task as a minimum:

- Definition of a set of use-cases which are envisioned to be valuable to prospective SBSP stakeholders.
- Identification and elaboration of the systems-level implications of different candidate use cases.
- Definition of a reference use-case to serve as a reference for the remaining study tasks. This shall also include a target number of SBSP systems to be deployed for the reference use-case by 2050.
- Definition of a list of expectation statements from stakeholders of a prospective future SBSP energy service.
- Definition of a set of stakeholder Needs, Goals, and Objectives (NGOs) for a future SBSP system for terrestrial energy provision.
- Definition of the Operational Scenarios of the commercial SBSP system.
- Definition of a set of SBSP key performance indicators which are used to measure the accomplishment of SBSP NGOs.
- Definition of a set of SBSP user and service requirements to use as input for the subsequent study tasks.
- Definition of study assumptions and constraints derived from stakeholder exchanges.
- Definition of study assumptions regarding governance and funding model to be used for the realisation of the Commercial-scale SBSP system.
- Identification of trade criteria and their associated weightings to support the assessments and architecture selection in later study tasks.

Task Specific Deliverables:

ID	Title	Type	SKR	ASR	AKR
Task 1:	Stakeholder Expectations and Requirements Definition				
TN1	Stakeholder Expectations Report	Report	Issue.1		
DM1	Requirements Model	Digital Model	Issue.1	Issue.2	Issue.3
RP1	Task 1 Review Presentation for SKR	Presentation	Issue.1		

Task Completion:

The **Stakeholder Key-Point Review (SKR)** is the task completion milestone for Task 1. The Contractor shall deliver all Task 1 key outputs (specified above) in the SKR deliverables.

The Contractor shall also deliver updated issues of DM1 for the Architecture Selection Review (ASR) and for the Architecture Key-Point Review (AKR) in response to the outcomes from other study tasks.

Approval Condition:

- ESA review and acceptance of the deliverables of this task.

3.3.2 Task 2: Literature Review

Task Description:

The purpose of this task is for the contractor to perform a critical review of SBSP technologies and to establish assumptions and constraints. The outputs from this review will then be used by the Contractor to support other study tasks in this activity.

The Contractor shall perform a literature review of key technologies required by SBSP systems. The review shall focus on the definition of assumptions and constraints related to the expected performances of these technologies available for SBSP deployment. This is expected to include identification and definition of quantifiable performances and technical parameters for the different technologies. This shall include the expected evolution of performances over the timeframe of the development of commercial-scale SBSP systems. The Contractor shall also provide an evaluation of the expected Technology Readiness Levels (TRL) for the stated technologies.

The key SBSP technologies to be covered include as a minimum:

- Solar power generation
- On-orbit power management and distribution
- Wireless power transmission
- Ground power reception, management, and distribution
- Space assembly, maintenance, and servicing
- Structures, materials, and controls
- Thermal materials and management
- In-Space transportation and infrastructure
- Platform systems

The Contractor shall also perform a literature review to identify other design assumptions and constraints related to environmental, health, safety, and security factors.

Outputs:

The Contractor shall provide the following outputs of this task as a minimum:

- For the critical review of SBSP technologies:
  - Definition of assumptions and constraints for the key SBSP technologies.
  - Identification of key performance metrics for key technologies to serve as input to SBSP architecture design efforts.
  - Identification of TRLs for key SBSP technologies.

- Identification of design assumptions and constraints (including identification and assessment of environmental, health, safety, and security factors)

Task Specific Deliverables:

ID	Title	Type	SKR	ASR	AKR
Task 2:	**Literature Review**				
TN2	SBSP Design Assumptions and Constraints Report	Report	Issue.1	Issue.2	Issue.3
RP2	Task 2 Review Presentation for SKR	Presentation	Issue.1		

Task Completion:

The **Stakeholder Key-Point Review (SKR)** is the task completion milestone for Task 2. The Contractor shall deliver all Task 2 key outputs (specified above) in the SKR deliverables.

The Contractor shall also deliver updated issues of TN2 for the Architecture Selection Review (ASR) and for the Architecture Key-Point Review (AKR) in response to the outcomes from other study tasks.

Approval Condition:

- ESA review and acceptance of the deliverables of this task.

3.3.3 Task 3: Architecture Trade-Space Exploration

Task Description:

Exploring the trade-space of candidate architectures is a key activity within early phase studies. This is required to support the identification of preferred design architecture(s) before focusing on a narrower subset of the trade-space in later phases. In essence, this task is concerned with identifying the different ways "how" the SBSP system could be designed to achieve "what" the system must do.

The trade-space for SBSP architectures is large and numerous alternative architectures have been studied in the past decades. One purpose of this task is therefore for the Contractor to "***define the trade-space***" for SBSP architectures. Importantly the Contractor shall **propose their own design alternatives and novel ideas in addition to existing concepts** to arrive at a "complete" view of the SBSP architecture trade-space.

In this task the Contractor shall also perform **initial pruning and trade-offs of options** in the defined trade-space to identify promising and self-consistent SBSP architectures. The Contractor shall conclude this task with the selection of one reference architecture. This selected architecture will be carried through to Task 5 for detailed elaboration and analysis.

Note: The proposed work logic in section 3.1 anticipates that this task will be divided into two parts. These separate parts constitute separate iterations of the same subtasks with the following distinction:

- *Part 1*: This iteration is performed prior to SKR i.e., before the selection of a reference use-case for the commercial SBSP system. During Part 1 of this task the Contractor shall therefore perform the trade-space exploration work with the reference use-case still open.

- *Part 2*: After SKR the Contractor shall complete the trade-space exploration focused on the architectural options relevant to the selected reference use-case

The Contractor shall therefore perform both the *Trade-Space Definition* and *Trade-Space Pruning* work (described below) in both part 1 and part 2.

3.3.3.1 Trade-Space Definition

The Contractor shall define and elaborate the trade-space of design alternatives for SBSP architectures.

The Contractor shall define options within the SBSP architecture in a "architecture trades matrix", specifying candidate design options for each architecture trade domain.

The Contractor shall identify and define design options and alternatives at the subsystem and module level for each element of the SBSP system.

As a generic example, identified architecture alternatives may consider:
- Alternative functional allocations,
- Alternative technology basis,
- Alternative operational scenarios.

More specifically the trade-space generated by the Contractor shall include options identified for the following design decisions and topics presented in 0as a minimum.

Note: The Contractor shall also consider additional inputs on architectural trade-options that may be provided by ESA. These additional inputs by ESA may be provided at KOM and SKR.

3.3.3.2 Trade-Space Pruning

The purpose of this subtask is for the Contractor to perform analysis and trade-studies on the SBSP architecture options defined in the architecture trades matrix. The outcome of this task shall be the eventual selection of one self-consistent SBSP system architecture to carry forward to Task 5.

The Contractor shall identify, evaluate, and justify the design trades within the key trades-matrix which will have a driving impact on the complete SBSP system, including the following drivers:

- Cost (i.e., relative cost of options, Value Adjusted Levelized Cost of Energy (VALCOE), Levelized Cost of Electricity, LCOE).
- Environmental impact (i.e., expected outputs from a preliminary Life Cycle Assessment).
- Energy expenditure (i.e., Energy Returned on Energy Invested, ERoEI, across the system lifetime).
- Scalability and industrial capability (i.e., supply chains, material scarcity, industrial throughput etc.).
- Technology maturity (targeting TRL 5 by 2030) and development investments needed.
- System capacity and capacity factor (i.e., how much power can be provided, what is the expected output over a given period compared to the theoretical maximum in that period and is this a meaningful amount in the context of energy transition for net-zero).
- Risk (i.e., risk of failure, total/partial outage of the system, impact of specific failures).

Note: The architecture elaboration within Task 5 shall focus primarily on a single SBSP system (i.e., a single "Space Solar Power Plant" as per section 2.1.4). However, the Contractor shall consider the implications of a multi-decade roll-out of several SBSP systems in the selection of a reference architecture here in Task 3.

Outputs:

The Contractor shall provide the following outputs of this task as a minimum:

- For the trade-space definition:
  - Definition of complete SBSP system trade-space within a key-trades matrix which includes consideration of all elements of the SBSP system.
  - Identification of major design decisions and associated options for each decision.

- For the trade-space pruning:
  - Identification of the design decisions anticipated to be driving for the SBSP architecture with respect to the criteria outlined in the task description.
  - Identification of design options and trades which will require detailed assessment.
  - Quantitative analyses and trade-offs to assess driving options within the trade-space to facilitate architecture down-selection.
  - Definition and sizing of candidate SBSP architectures (including technical budgets).
  - Trade-offs between candidate SBSP architectures to facilitate selection.
  - Identification of one self-consistent SBSP system architecture to carry forward to the following task based on the above.

The Contractor shall present to ESA intermediate results of this task at SKR (prior to use-case selection for the commercial SBSP system).

Following SKR, the Contractor shall perform analyses and trade-offs to support the identification of one candidate SBSP architecture. The trade studies shall use the criteria identified in Task 1.

The Contractor shall present to ESA the results of this task at ASR.

Task Specific Deliverables:

ID	Title	Type	SKR	ASR	AKR
Task 3:	Architecture Trade-Space Exploration				
TN3	Architecture Selection Report	Report	Issue.1	Issue.2	
DM4	Architecture Trade-Space Model	Digital Model	Issue.1	Issue.2	Issue.3
DM5	Physical Architecture Model	Digital Model	Issue.1	Issue.2	Issue.3
RP3.1	Task 3 Review Presentation for SKR	Presentation	Issue.1		
RP3.2	Task 3 Review Presentation for ASR	Presentation		Issue.1	

Task Completion Milestone:

The **Architecture Selection Review (ASR)** is the task completion milestone for Task 3. The Contractor shall deliver all Task 3 key outputs (specified above) in the ASR deliverables.

The Contractor shall provide a first issue of TN3, DM4, and DM5 at the Stakeholder Key-Point Review (SKR). The Contractor shall also deliver updated issues of DM4 and DM5 for the for the Architecture Key-Point Review (AKR) in response to the outcomes from other study tasks.

Approval condition:

- ESA review and acceptance of the deliverables of this task.

3.3.4 Task 4: Functional Analysis and ConOps Elaboration

Task Description:

The purpose of this task is for the Contractor to perform a functional analysis of the SBSP System to clearly define "what" the SBSP System needs to do to deliver on the stakeholder expectations and requirements defined within Task 1. Similarly, the Concept of Operations (ConOps) of the SBSP system will be elaborated in greater detail by the Contractor to better understand how the system will satisfy the stakeholder expectations.

The Contractor shall perform a **Functional Analysis** to identify the key functions required by the SBSP system to address the selected reference use-case defined in Task 1. This shall include identification of required constituent systems and subsystems, identification of interfaces within the SBSP system, and definition of functional and interface requirements.

The Contractor shall also use the outputs of the Functional Analysis to further support the identification of trade-space options (in parallel with Task 3).

The Contractor shall also elaborate the **Concept of Operations (ConOps)** of the SBSP System for the reference service use-case defined in Task 1.

The ConOps shall detail how the commercial SBSP system will be operated and include identification and definition of the roles and responsibilities of the various stakeholders.

The ConOps shall cover the entire lifetime of the commercial SBSP system. In particular, the Contractor shall detail the following:

- Launch and deployment options for SBSP
- Commercial operations
- Maintenance options for SBSP
- End-of-life options for SBSP
- Identification of safety critical aspects (including safety of life and asset safety).
- Identification of security critical aspects

The Contractor shall use the Functional Analysis and Concept of Operations to further identify and define requirements for the SBSP system.

Note: ESA expects that the outputs of this task do not presume the selection of a SBSP architecture as this is the intended output of Task 3. The functional analysis and concept of operations should be elaborated in parallel to Task 3 and therefore be implementation neutral. Further elaboration and consolidation of the Functional Analysis and ConOps is expected in Task 5 (see section 3.3.5).

Outputs:

The Contractor shall provide the following outputs of this task as a minimum:

- Functional analysis of the SBSP system including:
  - Functional Tree
  - Functions/Products Matrix
  - Functional Flow Block Diagram
  - Functional interfaces and identification of interface requirements
  - Identification and characterisation of external system interfaces.

- Elaboration of the SBSP architecture Concept of Operations including
  - Major mission/architecture phases.
  - Operational timelines.
  - Communications strategy.
  - Command and data architecture.
  - Fault management strategies.
  - Operational facilities.
  - Critical events.
  - Space safety measures.
  - Ground safety measures.
  - Security measures.
  - Identification of options and concepts for:
    - Launch and deployment of SPS
    - Commercial operations
    - Maintenance of SPS
    - Disposal of SPS
    - Safety critical aspects
    - Security critical aspects

Task Specific Deliverables:

ID	Title	Type	SKR	ASR	AKR
Task 4:	Functional Analysis and ConOps Elaboration				
DM2	Functional Analysis	Digital Model		Issue.1	Issue.2
DM3	Concept of Operations	Digital Model		Issue.1	Issue.2
RP4	Task 4 Review Presentation for ASR	Presentation		Issue.1	

Task Completion Milestones:

The **Architecture Selection Review (ASR)** is the task completion milestone for Task 4. The Contractor shall deliver <u>all</u> Task 4 key outputs (specified above) in the ASR deliverables.

The Contractor shall also deliver updated issues of DM2 and DM3 for the for the Architecture Key-Point Review (AKR) in response to the outcomes from other study tasks.

Approval Condition:

- ESA review and acceptance of the deliverables of this task.

3.3.5 Task 5: Architecture Elaboration

Task Description:

The purpose of this task is for the Contractor to elaborate the selected SBSP system architecture from the Architecture Selection Review. This shall include detailed analyses and design elaboration to mature the selected architecture, assessments of the technical and economic feasibility, and analysis to understand its potential environmental impact. Outputs of this task are also required by ESA to provide information for parallel technology development activities and environmental and socioeconomic assessment of SBSP and further stakeholder engagement activities.

The Contractor shall complete the analysis activities specified in the outputs below to elaborate the reference architecture selected at ASR. This shall cover the following topics:

- Definition of the complete SBSP system
- Assessment of system performances
- Analysis of SPS critical areas
- Modelling of the wireless power transfer (or equivalent)
- Confirmation of the business case
- Energy balance analyses
- Environmental impact analyses
- Prospective system costs analyses
- System sensitivity analyses and modelling
- Assessments of scalability and industrial capability
- Technology development requirements
- Programmatics analyses
- Recommendations for a sub-scale space-based demonstrator

Outputs:

The Contractor shall provide the following outputs from this task:

- The technical elaboration of the **complete SBSP system** including:
  - The complete space segment, including the SPS systems, in-space transportation systems, systems required for the assembly, maintenance, and end-of-life SPS operations.
  - The requirements for the launch segment and an assessment of developments needed to deliver the SBSP system as per the requirements and stakeholder inputs.
  - The complete ground segment, including ground power stations, ground stations, and control centres.
  - Definition and technical elaboration of the complete system lifetime including transportation logistics for launch and deployment of SBSP systems to orbit, in-orbit assembly of SBSP systems, operational maintenance of SBSP systems in orbit and on the ground, end-of-life operations of the SPS.

- Quantitative technical assessments of the candidate **SBSP system performances** including the following:
  - System budgets
  - Mission analyses and orbit analyses
  - Power link budget
  - Power delivered by Ground Power Station
  - Capacity factor
  - Total SPS mass
  - SPS lifetime
  - SPS mass per unit power delivered by Ground Power Station
  - Ground Power Station(s) size and area
  - Ground Power Station(s) location
  - Assessment of SPS configuration and layout (including CAD models)
  - Assessment of Ground Power Station configuration and layout (including CAD models)

- Detailed assessment of the following **SPS critical areas** identified by ESA (additional critical areas may be provided at KOM and throughout the study):
  - SPS station keeping
  - SPS stability and pointing accuracy
  - SPS structural rigidity, eigenfrequencies and control
  - SPS attitude control approaches
  - Impact of radiation on SPS lifetime and performance
  - Impact of space weather events
  - Thermal analysis of SPS
  - Wireless Power Transmission efficiency chain from Space to Ground
  - Solar cell technology selection
  - Systems required for launch and deployment
  - Launch requirements
  - Operational maintenance
  - End-of-life approach
  - Space debris mitigation
  - Safety goals and measures
  - Security risks and needs

- Technical **modelling of wireless power transfer** from Space to Ground including:
  - Identification and evaluation of the efficiency of each step in the end-to-end chain for the selected architecture.
  - Evaluation of the characteristics of the power transfer at the space segment, across the link, and on the ground. This shall include footprint of the beam on ground and intensity profile.
  - Provision of a user-configurable parametric digital model containing formulae.

- Elaboration and confirmation of the **demand and business case** for the prospective SBSP service. This should build on the outputs of the stakeholder interactions from Task 1.

- Quantitative technical assessments of the candidate **SBSP system energy analyses** including the following:

  - Expected energy generated over the system lifetime considering capacity level, possible degradation, outages, capacity factor etc.
  - Expected lifetime energy investment required to deploy the SBSP system including contributions from ground transportation, launch and in-space transportation, SPS hardware, ground power station, in-space assembly, in-space operations and maintenance, and end-of-life.
  - An evaluation of the expected Energy Return on Energy Invested (ERoEI) based on the above.

- Assessments of the candidate **SBSP system environmental impact** including the following:
  - A preliminary Life Cycle Assessment (LCA) based on the methodology agreed between ESA and the Contractor by the KOM.
  - Identification of potential knowledge gaps which should be addressed with future environmental impact assessments.

- Assessments of the candidate **SBSP system costs** including the following:
  - A preliminary cost assessment based on the methodology agreed between ESA and the Contractor at the KOM.
  - An evaluation of the candidate architecture delivered Value Adjusted Levelized Cost of Energy (VALCOE) for a 1st-of-a-kind (FOAK) and nth-of-a-kind (NOAK) Space Solar Power Plant.

- Quantitative technical **sensitivity analyses** including:
  - Definition of a methodology to approach sensitivity analyses.
  - Identification of driving parameters to assess with sensitivity analyses
  - Identification of the magnitude of uncertainties of key design parameters.
  - Parametric analyses investigating the influence of driving design parameters on SBSP concept solution.
  - Provision of a user-configurable parametric digital model containing formulae.

- Quantitative technical assessments of the **scalability and industrial capability** required to deliver the candidate SBSP systems including:
  - Identification of critical materials and potential supply chain bottlenecks.
  - Industrial manufacturing and deployment throughput.
  -
  - Identification of possible dependencies on states outside of Europe.
  - Ability to achieve the target total capacity values specified by stakeholder needs.
  - Identification of required capacity developments requiring investment.

- Detailed technical assessments of the **technology developments needed** to deliver the candidate SBSP systems in time as per the requirements and stakeholder expectations. This shall include:
  - an assessment of technology needs against current and planned technology readiness levels.
  - provision of a preliminary technology development plan for technologies to reach TRL 5 for the commercial-scale system.

- Definition and assessment of the **programmatic aspects** of the SBSP architecture including:
  - Development roadmap towards a commercial scale SBSP system development, including major demonstrators along the way.
  - Preliminary risk analysis and risk management plan.
  - Identification of cost-driving elements for SBPS systems.

- **Elaboration and consolidation** of the study task outputs including:
  - Requirements Model
  - SBSP Design Assumptions and Constraints
  - Architecture Trade-Space Model
  - Physical Architecture Model
  - Functional Analysis
  - ConOps

- Identification of recommendations and requirements for a **Sub-Scale Space-Based SBSP demonstrator mission**. This shall include:
  - Identification and proposal of functions and technologies to be addressed by the demonstrator mission.
  - Identification of the expected scale and size of elements for the demonstrator mission.
  - Preliminary technical requirements for the demonstrator mission.

Task Specific Deliverables:

ID	Title	Type	SKR	ASR	AKR	Workshop / FP
Task 5:	**Architecture Elaboration**					
TN4	Architecture Definition Document	Report			Issue.1	
DM6	Space-to-Ground Power Delivery Model	Digital Model			Issue.1	
DM7	Parametric Architecture Model for Sensitivity Analyses	Digital Model			Issue.1	
DM8	CAD models	Digital Model			Issue.1	
TN5	Recommendations for Sub-Scale Demonstrator Mission	Report			Issue.1	
RP5	Architecture Key-Point Review Presentation	Presentation			Issue.1	

Task Completion Milestones:

The **Architecture Key-Point Review (AKR)** is the task completion milestone for Task 5. The Contractor shall deliver all Task 5 key outputs (specified above) in the AKR deliverables.

Approval Condition:

- ESA review and acceptance of the deliverables of this task.

4 Management, Reporting, Meetings and Deliverables

The Standard Requirements for Management, Reporting, Meetings and Deliverables (Appendix 3 to the Contract) shall apply, taking account of the following specific requirements for the present activity, which shall prevail in case of conflict.

4.1 Management

Section 1 of the Standard Requirements for Management, Reporting, Meetings and Deliverables shall apply.

4.2 Reporting

Section 2 of the Standard Requirements for Management, Reporting, Meetings and Deliverables shall apply with the following change:

Electronic versions of the Minutes of Meeting shall be issued and distributed to all participants, to the Agency's Technical Officer and to the Agency’s Contracts Officer, **not later than two (2) working days** after the meeting concerned.

4.3 Meetings

Section 3 of the Standard Requirements for Management, Reporting, Meetings and Deliverables shall apply.

4.4 Deliverables

No markings indicating restrictions to ESA’s free dissemination of the deliverables shall be applied. Any information the Contractor deems to be sensitive may be provided as a separate restricted annex. This shall be agreed with the ESA TO on a case-by-case basis.

Appendix 1 to
ESA AO/1-11606/22/NL/MGu

Table 1. Summary of Study Deliverables

ID	Title	Type	SKR	ASR	AKR	Workshop / FP
Task 1:	Stakeholder Expectations and Requirements Definition					
TN1	Stakeholder Expectation Report	Report	Issue.1			
DM1	Requirements Model	Digital Model	Issue.1	Issue.2	Issue.3	
RP1	Task 1 Review Presentation for SKR	Presentation	Issue.1			
Task 2:	Literature Review					
TN2	SBSP Design Assumptions and Constraints Report	Report	Issue.1	Issue.2	Issue.3	
RP2	Task 2 Review Presentation for SKR	Presentation	Issue.1			
Task 3:	Architecture Trade-Space Exploration					
TN3	Architecture Selection Report	Report	Issue.1	Issue.2		
DM4	Architecture Trade-Space Model	Digital Model	Issue.1	Issue.2	Issue.3	
DM5	Physical Architecture Model	Digital Model	Issue.1	Issue.2	Issue.3	
RP3.1	Task 3 Review Presentation for SKR	Presentation	Issue.1			
RP3.2	Task 3 Review Presentation for ASR	Presentation		Issue.1		
Task 4:	Functional Analysis and ConOps Elaboration					
DM2	Functional Analysis	Digital Model		Issue.1	Issue.2	
DM3	Concept of Operations	Digital Model		Issue.1	Issue.2	
RP4	Task 4 Review Presentation for ASR	Presentation		Issue.1		
Task 5:	Architecture Elaboration					
TN4	Architecture Definition Document	Report			Issue.1	
DM6	Space-to-Ground Power Delivery Model	Digital Model			Issue.1	
DM7	Parametric Architecture Model for Sensitivity Analyses	Digital Model			Issue.1	
DM8	CAD models	Digital Model			Issue.1	
TN5	Recommendations for Sub-Scale Demonstrator Mission	Report			Issue.1	
RP5	Architecture Key-Point Review Presentation	Presentation			Issue.1	
Other						
ESR	Executive Summary Report	Report				Issue.1
FR	Final Report	Report				Issue.1
FP	Final Presentation	Presentation				Issue.1
AB	Abstract	Abstract				Issue.1
PVIS	Promotional Visuals	Graphics File				Issue.1
PVID	Promotional Video	Video				Issue.1
CCD	Contract Closure Documentation	Other				Issue.1

4.4.1 Definitions of Deliverables Documentation

DMS (Data Management System) address: tecdms@esa.int . Please note that all finalised (i.e., reviewed and approved by ESA in their final version) documents resulting from a technology Contract shall be electronically sent by the Contractor to D/TEC's Data Management System (DMS) using the e-mail address tecdms@esa.int . This applies not only to the final documentation such as the Final Report or Summary Report but to all approved output documents (TNs, Progress Reports, etc.).

4.4.1.1 Documents

The Contractor shall provide the deliverable documents in the following formats:

- Native (WORD) file (for all issues)
- Electronically searchable, indexed, and non-encrypted PDF (for final issues)

The Contractor shall deliver the documents to the ESA Technical Officer.

The Table of Contents (TOC) for each document shall be submitted to the ESA TO for approval prior to document submission.

TN1 – STAKEHOLDER EXPECTATIONS REPORT

This document shall contain the outputs of Task 1.

The document filename shall begin with "TN1".

TN2 – SBSP DESIGN ASSUMPTIONS AND CONSTRAINTS

This document shall contain the outputs of the Task 2 activities concerning the Critical Review of SBSP Technologies. The document shall also contain the identified design assumptions and constraints related to environmental, health, and safety factors (or any other topics as identified).

The document filename shall begin with "TN2".

TN3 – ARCHITECTURE SELECTION REPORT

This document shall contain the outputs of Task 3.

This document shall also contain a summary of the complete architecture trade-space and supplementary information to DM4.

The document filename shall begin with "TN3".

TN4 – ARCHITECTURE DEFINITION DOCUMENT

This document shall contain the outputs of Task 5 excluding outputs concerning the Sub-Scale Space Based Demonstrator Mission.

The document also shall contain supplementary information to support the definition of:

- DM2 (Functional Analysis)

- DM3 (Concept of Operations)
- DM5 (Physical Architecture Model)
- DM6 (Space-to-Ground Power Delivery Model)
- DM7 (Parametric Architecture Model for Sensitivity Analyses)
- DM8 (CAD models)

The document filename shall begin with “TN4”.

TN5 – RECOMMENDATIONS FOR SUB-SCALE DEMONSTRATOR MISSION

This document shall contain the outputs of Task 5 concerning the Sub-Scale Space Based Demonstrator Mission.

The document filename shall begin with “TN5”.

4.4.1.2 Software/Digital Models

The draft version of the digital models shall be sent to the Agency’s Technical Officer in electronic format not later than two (2) weeks before the digital model is to be presented.

DM1 – REQUIREMENTS MODEL

This digital model shall include all requirements identified and defined throughout the study tasks. This includes stakeholder and use-case requirements defined in Task 1.

This digital model shall include the Preliminary technical requirements specification, the Requirement justification, and the Interface requirements (as per ECSS-E-ST-10-06 Annex A and ECSS-E-ST-10C Rev.1 Annex O).

All requirements shall include a unique identifier, justification, and proposed verification method. A link between requirements and the functional and physical architecture shall be made. The model shall include a Requirement Traceability Matrix (as per ECSS-E-ST-10C Rev.1, Annex N).

The Contractor shall specify by KOM the delivery media for this digital model (e.g., DOORS or alternative).

DM2 – FUNCTIONAL ANALYSIS

This digital model shall contain the outputs of the Task 4 activities concerning Functional Analysis.

This digital model shall include the Function Tree as per ECSS-E-ST-10C Rev.1, Annex H

The Contractor shall specify by KOM the delivery media for this digital model.

DM3 – CONCEPT OF OPERATIONS

This digital model shall contain the outputs of the Task 4 activities related to the Concept of Operations.

The Contractor shall specify by KOM the delivery media for this digital model.

DM4 – ARCHITECTURE TRADE-SPACE MODEL

This digital model shall contain the complete trade-space of options identified during Task 3.

The Contractor shall specify by KOM the delivery media for this digital model.

DM5 – PHYSICAL ARCHITECTURE MODEL

This digital model(s) shall be commensurate with ECSS-E-ST-10C Rev.1, Annex G, and include the Product tree (ECSS-M-ST-10C Rev. 1, Annex B), Technical budgets ECSS-E-ST-10C Rev.1, Annex I) and Technology Readiness Status List (ECSS-E-ST-10C Rev.1, Annex E).

The Contractor shall specify by KOM the delivery media for this digital model.

DM6 – SPACE-TO-GROUND POWER DELIVERY MODEL

This digital model shall contain the *technical modelling of wireless power transfer from Space to Ground* from Task 5.

This digital model shall be user-configurable and contain formulae used for the technical modelling of wireless power transfer.

The Contractor shall specify by KOM the delivery media for this digital model.

DM7 – PARAMETRIC ARCHITECTURE MODEL FOR SENSITIVITY ANALYSES

This digital model shall contain the *sensitivity analyses* from Task 5.

This digital model shall be user-configurable and contain formulae used for the technical modelling of wireless power transfer.

The Contractor shall specify by KOM the delivery media for this digital model.

DM8 – CAD MODELS

This digital model shall be an editable CAD file without access restrictions. The CAD file should be free of any commercial or confidential information.

The CAD models shall be provided as an output of Task 5.

The Contractor shall provide CAD models of the following final designs:

- Solar Power Satellite(s)
- Ground Power Station
- In-Orbit Services that are defined as part of this activity (see section 2.1.4 for a definition of In-Orbit Services).

The Contractor shall specify by KOM the delivery media for this digital model.

4.4.1.3 Review Presentations

This activity will aim to reduce the documentation requirements and number of deliverables required compared to conventional ESA studies.

This is intended to reduce the amount of time and effort required by the Contractor for preparing deliverables items so that more resources can be dedicated to the technical work described within the core study tasks.

ESA will therefore request greater emphasis and importance to be placed on presentations prepared for the study review meetings as well as extension of the duration of the co-location review meetings to allow for sufficient discussion between ESA and the industrial study teams. ESA's expectation is that the information typically presented inside study deliverables and reports would be contained within the review presentations. This will require the Contractor to deliver accessible, high quality and comprehensive presentation datapacks (strongly reflecting that "a picture, or plot, tells a thousand words") at the study reviews as these will constitute the primary inputs for the review.

4.4.1.4 Other Deliverables

The Contractor shall provide the following promotional materials by the final presentation.

These are requested to support the communication of the results of the study to the public and to support SOLARIS stakeholder engagement activities following the study conclusion.

PVIS - PROMOTIONAL VISUALS

The Contractor shall provide 3 (TBC) visuals to support communication of the results of the activity.

These may include:

- Single page infographic.
- Solar Power Satellite rendered image.
- Ground power station rendered image.

PVID - PROMOTIONAL VIDEO

The Contractor shall provide a 3-minute (TBC) promotional video to support communication of the results of the activity to prospective stakeholders.

4.4.2 Project Web Page

Section 4.4 of the Standard Requirements for Management, Reporting, Meetings and Deliverables shall not apply.

5 Schedule and Milestones

5.1 Study Deadlines

The Architecture Selection Review (ASR) shall take place ***no later than 31 July 2023***. Therefore, the deliverables for ASR shall be provided to ESA no later than 17 July 2023.

The Architecture Key-Point Review (AKR) shall take place ***no later than 27 October 2023***. Therefore, the deliverables for AKR shall be provided to ESA no later than 13 October 2023.

5.2 Technical Milestones

The following milestones shall apply:

- **Milestone 1**: Architecture Selection Review (ASR)
- **Milestone 2:** Architecture Key-Point Review (AKR)
- **Milestone 3**: Final Presentation / Stakeholder Interchange Workshop

5.3 Reviews

The following reviews shall be held during the activity:

5.3.1 Stakeholder Key-Point Review (SKR)

- **Date**: KOM + 2 months
- **Location**: Virtual
- **Input**: All deliverables (documents and models) shall be delivered 2 weeks before the review.
- **Description**: A formal review of the outputs of Task 1, Task 2, and Task 3 (part 1).
- **Output**: The selection of a reference SBSP service use-case for the activity and the defined stakeholder expectations and requirements for this use-case.

5.3.2 Architecture Selection Review (ASR)

- **Date**: ***no later than*** ***31 July 2023***
- **Location**: Virtual
- **Input**: All deliverables (documents and models) shall be delivered 2 weeks before the review.
- **Description**: A formal review of the outputs of Task 3 (part 2) and Task 4.
- **Output**: the selection of a reference architecture in response to the selected reference use-case.

5.3.3 Architecture Key-Point Review (AKR)

- **Date**: ***no later than*** ***27 October 2023***
- **Location**: ESA/ESTEC
- **Input**: All deliverables (documents and models) shall be delivered 2 weeks before the review.
- **Description**: A formal review of the outputs of Task 5.
- **Output**: consolidated and approved deliverable documentation and models.

5.3.4 Stakeholder Interchange Workshop

- **Date**: ***December 2023***
- **Location**: ESA/ESTEC
- **Input**: All deliverables shall be delivered 2 weeks before the workshop.
- **Description**: This workshop will be organised by ESA and shall serve as the final presentation of the activity. The purpose of this workshop is for all the Contractor(s) to present the results and conclusions of the activity to ESA and to relevant stakeholders.

5.4 Overview of the planning

The following meetings between ESA and the Contractor shall be scheduled for this activity:

Meeting	Date	Location
Kick-Off Meeting	T0	Virtual
Stakeholder Engagement Meetings	TBD	ESA, ESTEC
Stakeholder Key-Point Review	T0 + 2 months	Virtual
Architecture Selection Review	**No later than 31st Jul 2023**	Virtual
Architecture Key-Point Review	**No later than 27th Oct 2023**	ESA, ESTEC
Stakeholder Interchange Workshop (Final Presentation)	**Dec 2023**	ESA, ESTEC

5.4.1 Tag-up Meetings

Informal tag-up meetings (of duration ~ 30-60 mins) between the Contractor and the ESA Technical Officer shall be held weekly by video-conference. The purpose of these meetings will be for the Contractor to provide updates on the progress of study tasks, to ask questions to ESA related to the study, or to raise issues that will help the Contractor progress with study work in a timely manner.

6 ANNEXES

ANNEX A. TERMINOLOGY

The following table provides definitions of several terms used in power systems engineering:

Availability	The percentage of time that a power generating system is available to provide power.
Base load power plant	A power plant that is nominally operated to produce electricity at essentially a constant rate and which runs continuously. Nuclear power plants are an example of base load power plants.
Capability	The maximum electrical output a generating unit can provide for a specific period of time without exceeding its operational limits.
Capacity	The ability to produce a given amount of electrical power at an instant in time.
Capacity factor	The actual energy generated over a period of time by a generating unit divided by the maximum energy that could have been generated had the unit run at full capacity.
Cogeneration	The dual production of electricity and another form of useful thermal energy (such as heat or steam) for use in commercial/industrial heating or cooling processes.
Commercial operation	The point at which the owner of the generating unit that has been under construction declares it to be operational and capable of fulfilling its legal and regulatory obligations.
Delivery point	A point at which a power supplier delivers power to a participating municipality's distribution system.
Demand	A measure of the rate at which electrical energy is delivered to, or by, a system.
Forced Outage Rate (FOR)	The percentage of hours during a year in which a generating unit is unable to operate due to unplanned circumstances.
Grid	The system comprised of generators, transmission lines, and distribution components that provides for the production and delivery of electricity within a region.
Load	See demand.

Load curve A line on a graph used to show variations in electrical power demand in a given period of time.

Load factor The ratio of average demand to peak demand. Typically, this is used to show if electrical usage of a system is stable or has extreme peaks and valleys.

Load-following power plant A power plant that is nominally operated to provide adjusted power output as demand for electricity fluctuates throughout the day.

NIMBY An acronym for "not in my backyard". This term is often used to describe the attitude of people or entities who do not want industry power facilities build in the vicinity of their property or location.

Outage Any interruption to electrical supply.

Peak demand The maximum demand (load) of an electric system during a given period of time.

Peaking power plant A power plant that is nominally operated to run only at times when there is high demand (or peak demand) for electricity.

ANNEX B. PRELIMINARY TECHNICAL REQUIREMENTS

Important: These requirements are provided to give an initial indication of the expected needs of the SBSP system. **All the requirements below listed here are as placeholders and shall be considered as TBC as they are dependent on use-case selection. The requirements shall be revisited, redefined, and elaborated by the Contractor in consultation with the SBSP stakeholders as part of Task 1.**

SBSP-SYS-001	**Commercial Utilisation**
Requirement:	The SBSP System shall provide electrical power for commercial use in Europe.
Note:	*The system must be capable of delivering a reliable and stable source of electricity to customers with a focus on selling power to TBD customers in Europe. The system may also be used to sell power to consumers outside of Europe, depending on stakeholder needs, market conditions and business opportunities (TBC).*
Rationale:	*This requirement is included to specify that the eventual deployment and use of SBSP at scale is foreseen to be commercially driven.*

SBSP-SYS-002	**Space-Based Power Source**
Requirement:	The SBSP System shall collect solar power in space for transfer to Ground Power Stations on Earth.
Rationale:	*This requirement is included to specify that the primary power source for the SBSP System is intended to be space-based.*

SBSP-SYS-003	**Nameplate Capacity**
Requirement:	The nameplate capacity of each Ground Power Station in the SBSP System shall be at least TBD GWe.
Note:	*The nameplate capacity is defined as the intended full-load sustained output of the ground power station and is measured at the interface between the ground power station and the grid. The specific use-case and stakeholder needs of the SBSP system will determine the exact nameplate capacity requirements for the power stations.*
Rationale:	*The nameplate capacity is an important factor in determining the design and scale of SBSP systems.*

SBSP-SYS-004	**Capacity Factor**
Requirement:	The SBSP System shall have a capacity factor of at least TBD % including planned and unplanned outages and degradation due to failed elements.
Note:	*The required capacity factor is heavily dependent on the selected use-case of the SBSP system. The value of this requirement is anticipated to have an impact on potential SBSP system architectures and should be revisited during stakeholder interactions.*
Rationale:	*The nameplate capacity is an important factor in determining the design and scale of SBSP systems.*

SBSP-SYS-005	**Start of Commercial Operations**
Requirement:	The SBSP System shall start commercial operations by 2035 (TBC).
Rationale:	*This requirement is included to specify the need by date for the start of SBSP system power delivery. This is anticipated to drive the development schedule and technology selection for the first elements of the SBSP system.*

SBSP-SYS-006	**Target SBSP Capability**
Requirement:	The combined capability of all Space Solar Power Plants operating in Europe shall generate up to 750 TWh (TBC) per year of operation by 2050.
Note:	*This anticipates a roll-out of multiple SBSP Systems between the start of the commercial operations and 2050.*
Rationale:	*This requirement is included to capture the expected need for multiple SBSP Systems to be deployed. The design of the SBSP System will need to consider the need to scale up output through the deployment of multiple Space Solar Power Plants. This requirement is intended to prevent potential issues related to scalability and industrial capability from being neglected in the early design phase.*

SBSP-SYS-007	**System Lifetime**
Requirement:	The SBSP System shall have a nominal operational lifetime of 30 years (TBC).
Rationale:	*The system lifetime is an important factor in determining the design and scale of SBSP systems.*

SBSP-SYS-008	**Zero Space Debris**
Requirement:	The end-of-life operations for the solar power satellite(s) in the SBSP system shall result in zero space debris.
Note:	*ESA expects that this requirement can be fulfilled through recycling and reuse of components in space.*
Rationale:	*The system must be designed and constructed to ensure that the solar power satellite(s) can be safely and effectively decommissioned at the end of lifetime operations without generating any debris that could pose a risk to other spacecraft or space activities.*

ANNEX C. ARCHITECTURE TRADE-SPACE QUESTIONS

The table below provides questions expected to be addressed in the architecture trade-space exploration for the SBSP System.
The Contractor shall use this as an input to Task 3. The Contractor is also expected to identify additional questions and topics that will support the trade-space definition.

Example Architectural Trades	Example Questions
SBSP Service Use-Case	• What is the expected service use-case of the SBSP system?
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.)? • What are the required characteristics of power provided by the SBSP system and how does this impact the architecture?
SPS per Ground Power Station	• How many SPSs should provide power to each Ground Power Station?
Ground Power Stations served per SPS	• How many Ground Power Stations should each SPS be able to serve? • Should each SPS be able to provide power to multiple Ground Power Stations?
SPS Service Delivery	• If each SPS provides power to multiple Ground Power Stations, how should this power be delivered (i.e., sequentially, simultaneously)? • Which locations can be served by the SPS if serving multiple Ground Power Stations?
Energy Storage on Ground	• Should the SBSP system utilise energy storage at Ground Power Stations to meet power service needs?
Orbit Selection	• Which orbits should SPS operate in? • Which orbits are most attractive for the envisioned type of power service delivery (use-case)? • Should multiple orbit planes or constellations be exploited? • What are the implications of different candidate orbits on the SBSP system design?
Number and Size of Satellites	• Should the SBSP architecture consider fewer, larger satellites or large constellations of smaller satellites? • What is the overall size and mass of the SPS system, and how does this impact the architecture selection?
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)?
Wireless Power Transfer	• How should power be delivered to the ground from space? • Should this assume RF (e.g., microwave or alternative) or optical transmission? • Which frequencies should be used for power transfer considering system impacts, interferences, and regulation? • Are there other alternative methods to transmit power to ground (e.g., focused or reflected sunlight)?
Power Collection by SPS	• How should the SPS capture solar energy in space?
Power Collection Photovoltaics	• If Photovoltaics are used for power collection, which type of cells should be used? • What efficiency vs cost vs low-mass concepts for power collection could be available for SBSP systems if sufficient funding was available?
Use of Concentrators	• Should the SPS use concentrators for the collection of solar power? • If so, what type of concentrator should be used?

SPS Power Management and Distribution	• How should the SPS manage and distribute power (between collection and transmission)?
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)?
SPS Orbit Control	• What are the expected perturbations on the SPS and what approaches should be employed for station-keeping and orbit control?
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)?
SPS Thermal Control	• What approaches are needed to perform thermal control on the SPS?
Launch and Deployment	• What strategies can be considered to deploy all SPS hardware to its operational orbit? • What vehicles and capabilities need to be developed to deploy SPS systems to orbit? • What type of propulsion should be used? • How much propellant is needed for each SPS deployment?
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? • Once all SPS hardware is in the assembly location, how will it be assembled in orbit (and what systems are needed for assembly)?
Ground Power Station Location	• Where should the Ground Power Stations be located? • Should Ground Stations be located near to cities, offshore or in rural areas?
Number and Size of Ground Power Stations	• How many Ground Power Stations should there be considering the SPS conceptual architecture? • How does ground power station footprint scale with space segment architecture sizing?
Operational Maintenance and Logistics	• What strategies could be employed to provided maintenance and logistics to the SPS over its operational lifetime? • Should maintenance and refurbishment be performed in orbit on the SPS over its lifetime or should users accept a degradation of performance with time? • How should the SPS be designed to operate with degradation?
End-of-Life Strategies	• What approach should be used for the end-of-life (i.e., decommissioning) of SBSP system elements?
Contingency Approaches	• In the event of failures, how much fault tolerance should be built into the system, and how should this be implemented? • How can operations be sustained in the event of failures?
Security and Safety	• What approaches can be implemented to address concerns related to safety of life? • What approaches can be implemented to address concerns related to safety of assets and service loss? • How could the SPS be designed so that it is not susceptible to attack from bad actors? • Are ancillary systems needed to protect the SPS from attack? • What strategies exist to mitigate risks and concerns associated with space debris and space weather? • How can safety concerns related to power beaming to the ground be addressed by the SPS design?

ANNEX D. RELATED ESA TECHNOLOGY ACTIVITIES

ESA is currently running several technology activities relevant to the content of this Statement of Work. The table below gives an overview of the relevant activities initiated through ESA's Open Space Innovation Platform (OSIP).

ESA will provide the Contractor with the final reports from these activities on request when available.

The estimated completion dates shown in the table below are TBC.

Contract no.	Activity Title	Activity Type	Contractor	Estimated Completion Date
4000137232	SPS Station Keeping Using Solar Radiation Pressure for Propulsion	Study	Emerald Telecommunications	**Q1 2023**
4000136011	The interaction of structural dynamics with the orbital mechanics of Solar Power Satellites	Study	Frazer Nash	**Q4 2022**
4000136309	GE⊕ Lunar Power Station	Study	Swissart	**Q1 2023**
4000136308	Receiv'Air - Bypassing of atmospheric attenuation for SPS with airborne receiver	Study	Thales Alenia Space	**Q1 2023**
4000136664	Skybeam: Assembly of a Space Solar Power system with European Technologies	Study	Space Applications Services	**Q2 2023**
4000136442	Tiled Energy Focus with Solar Concentrators	ETD	Instituto de Telecomunicacoes - University of Aveiro	**Q2 2023**
4000135862	Development of Millimetre Waves Wireless Power Transfer (WPT) System for Lunar Rover Explorations	ETD	Sirin Orbital Systems AG	**Q2 2023**
4000136250	"Disruptive PV power array technology to enable economic viability of SPS" POWERSAIL	ETD	CSEM	**Q2 2023**
4000136603	Photo-irradiation annealing of radiation-induced degradation of multijunction solar cells for space-based power plants	ETD	Photonicity	**Q3/Q4 2023**
4000136187	In-Space Manufacturing of large structures by direct extrusion of UV-curing polymer	Co-Sponsored Research	Munich University of Applied Sciences	**Q4 2024**
4000136018	CORES - COllaborative Recycling of End-of-life Sps	Co-Sponsored Research	University of Strathclyde	**Q4 2024**
4000136441	Solar Array to High Voltage Power Bus: Power Conversion Techniques	Co-Sponsored Research	Miguel Hernandez University of Elche	**Q4 2024**