PRE-PHASE A SYSTEM STUDY OF A COMMERCIAL-SCALE SPACE-BASED SOLAR POWER (SBSP) SYSTEM FOR TERRESTRIAL NEEDS

TN5 – RECOMMENDATIONS FOR SUB-SCALE DEMONSTRATOR MISSION

REPORT TO
EUROPEAN SPACE AGENCY (ESA)

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1. CONTEXT & OBJECTIVES

1.1 INTRODUCTION

Based on the architecture designed after the ASR review, the objective of the document is the identification of recommendations and requirements for a Sub-Scale Demonstrator mission (here after designed as **SSD**), especially:

- 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.

To deploy the DSR concept, a long way is required to reach this objective. A demonstrator which consists of launching a constellation of 10 reduced mirrors in space, will allow to understand the major challenges and risks related to the deployment of the complete DSR system.

This demonstrator is also important to determine the needs on adaptation and development on the ground infrastructures: PV plants, grid connection, H2 electrolysers or Solar Fuel Technologies.

1.2 KEY PRINCIPLES OF THE SSD

1/ The SSD program can split in three main workstreams:

- Secure the environmental impact on ground segment, in order to maximize the chance to convince public and private stakeholders,
- Validate the feasibility of DSR concept on space,
- Assess some back-up technologies in case of major issues raised by the two other workstreams.

2/ In terms of timeline, the approach is based on 6-month iterations with clear hardware deliverables in complement of document & models delivered to demonstrate the outputs of the studies
3/ Our objective is to be on the market with an MVP as soon as possible. Based on estimation, we could be able to provide a minimum value to ground operators in 2033.

2. GLOBAL APPROACH OF SSD PROGRAM

This preliminary study allowed to identify the technology gaps or uncertainties to be consolidated. In this part we propose to address them in a roadmap illustrating what could be the next steps paving the way towards space based solar power.

The global roadmap is structured around 6 main phases with a key milestones at the end of each:

- **Phase 0/A/B1 study** to analyze further the SBSP concept and propose a sub-scale space based demonstrator
  - *Milestone ADD (Architecture Detail Definition)*

- **CONOPS and mission analysis** of the demonstration
  - *Milestone (SSDD SubScale Demonstator Definition)*

- **Ground demonstrations** when possible,
    - Simulation modelling of the system: mission analysis, AOCS, formation flying, mechanical, thermal
    - Structural mechanical testing
    - Zero-G demonstration with ground support equipment for structure deployment
    - If need be, Zero-G parabolic flights
  - *Milestone GDV (Ground Demonstration Validation)*

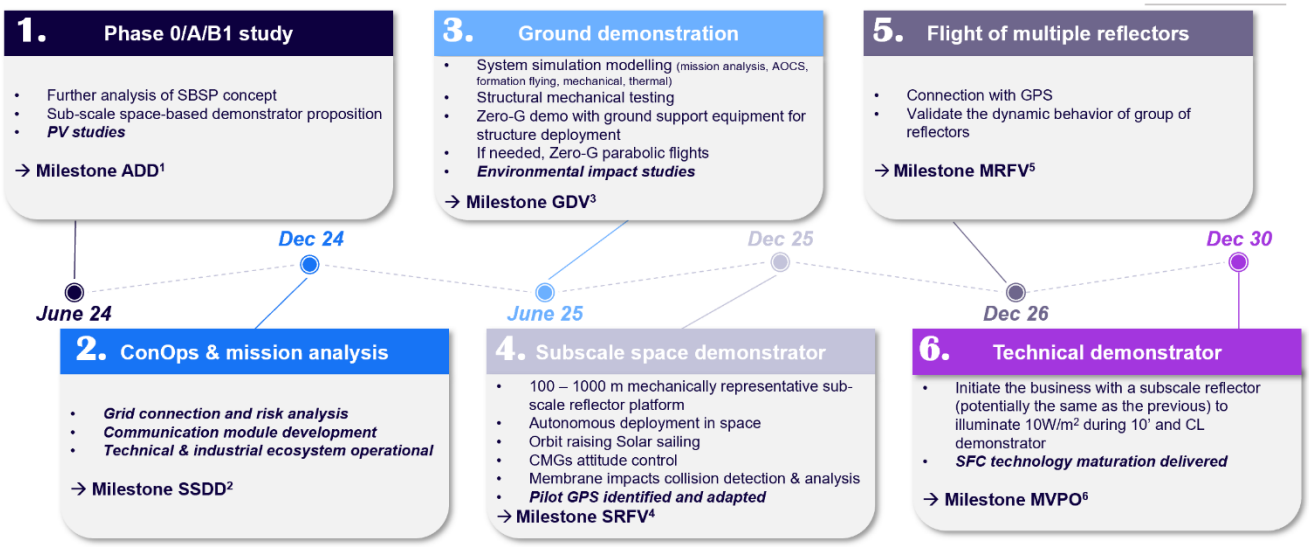
- **Subscale space demonstrator**
    - 100 – 1000 m mechanically representative sub-scale reflector platform
    - Autonomous deployment in space
    - Orbit raising Solar sailing
    - CMGs attitude control
    - Membrane impacts collision detection and analysis
    - Connection with ground station
  - *Milestone SRFV (Single Reflector Fly Validation)*

- **Flight validation of multiple reflectors**
    - Connection with ground stations
    - Validation of the dynamic behaviour of group of reflectors
  - *Milestone MRFV (Multiple Reflector Fly Validation)*

- **Minimum Viable Product**: to initiate the business with a subscale reflector (potentially the same as the previous) to illuminate 10W/m^2 during 10’
  - *Milestone MVPO (MVP Operational)*

Our approach is to keep the momentum of the project with key milestones until MVP end of 2030 at the latest

PRELIMINARY



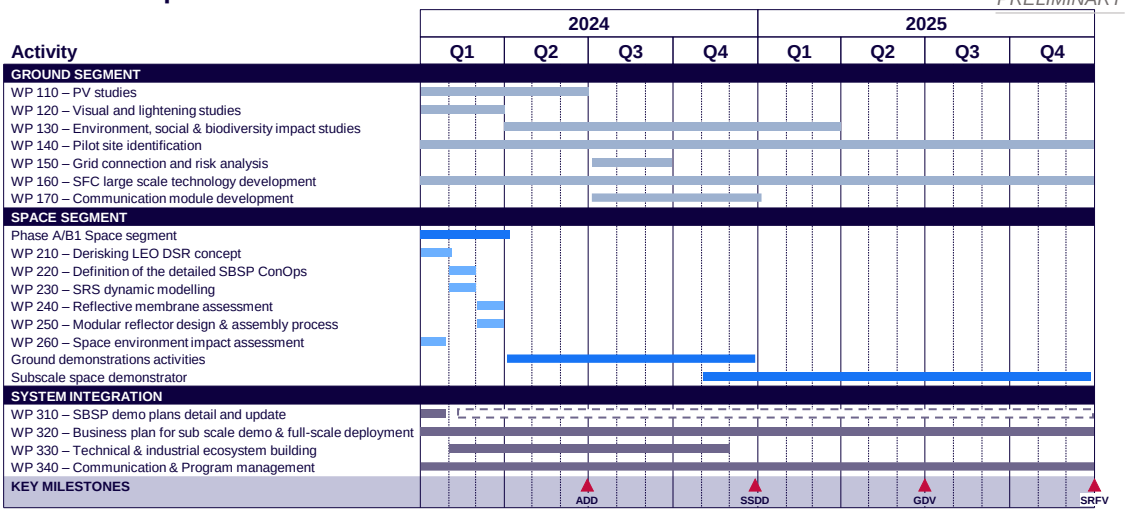
Note: 1) Architecture demonstrator definition ; 2) Subscale demonstrator definition ; 3) Ground demonstrator validation ; 4) Single reflector fly validation ; 5) Multiple reflector fly validation ; 6) MVP operational

3. DESCRIPTION OF THE KEY WORK PACKAGES

The graph below list the main workstreams to manage in the next two years. Each of them are described in the following pages

Proposed Design Phase Roadmap for the Sub Scale Demonstrator target a first reflector in space end of 2025

PRELIMINARY



For the first phase (Phase 0/A/B1 study) which aims to analyze further the SBSP concept and propose a sub-scale space based demonstrator, the main activities are the following for space segment:

- Desrisk the LEO Direct Solar Reflection on risk collision issue and assess the back-up solution (GEO Solar Pumped Laser) to the light of the pre-phase A outcomes (current study) that spotted, post ASR, unforeseen technical difficulties in the DSR concept.
- Propose a detailed concept of operations and preliminary mission analysis
- Modelling of the AOCS and structural design in order to assess the slew and pointing performance. This is a crucial point as the reflector agility drives the number GPS that could be fed by the reflectors and so impacts directly the business model.
- Select and assess the reflecting membrane design
- Elaborate an optimized reflector architecture in order to be dismantled in kit for launch, then assembled in orbit by robotics means and then deployed autonomously.
- Analyse the space environment effects on the reflector, and particularly radiation and thermal effects on electronics, membrane and structure fatigue and collision risk and effects from micrometeoroids and debris. For debris collision an analysis of the generation of new debris vs. sweep effect should also be performed.

3.1 WORKSTREAMS FOR GROUND SEGMENT

The following tasks for ground segment should be performed during the demonstrator preparation phases.

Work Package #	WP 110
WP Title	Studies on PV: Optimal PV technology and expected yield
Duration	6 months
Work Package Objectives	- Identify and complete a study on the behaviour of solar panels under prolonged light exposure (extra hours of illumination) - Benchmark of different available PV technologies - Show the behaviour under different possible situations such as the difference in light exposure in summer compared to winter and combination of DSR and natural sunlight during day, sunrise and sunset - Simulate the PV behaviour on different sites: model the expected yield of the pilot constellation.
Required Inputs	- General inputs: site locations, weather conditions, PV manufacturers' data, satellite positioning, light intensity, mirror characteristics (wavelength reflection) - Knowledge of the Consortium members - Desk research
Interactions / Interfaces with other WP	Pre study WP
Outputs / Deliverables	- TN11 – Detailed studies on PV panels exposed to the DSR - TN12 – Recommendation to allocate new sites with PV panels combined with DSR - RP11 – Review Presentation

Work package description:

This work package is composed of detailed studies to limit risk by coupling the PV technologies to the DSR.

The aim of the studies is to gain a better understanding the behaviour of PV panel with extra hours of exposition, with an exposure composed of naturel sun combined to the light reflected by the mirror.

Different PV technologies will be identified and classified in order to propose an appropriate list of PV technologies compliant with DSR for new sites.

Work Package #	WP 120
WP Title	Visual and lightning studies
Duration	3 months
Work Package Objectives	- Define the visual and lightning impact in the illuminated spot but also on short, middle and long distance of it. - Discussion of the impact of the mirror during normal operation and during reorientation

Required Inputs	- Deliverables of the pre-study - Knowledge of the Consortium members - Public information concerning mirror reflection in space - Norms on lightening (air traffic etc)
Interactions / Interfaces with other WP	- NA

Outputs / Deliverables	- TN13 – Visual and lightening studies and Report - TN14 – Recommendation to correctly define the mirror architecture

Work package description:

This work package is composed of detailed studies and report to define the lightening emits by the mirror in direction of the spot size on the earth.

The aim is to know the light intensity received inside the illuminated spot, and what it is possible to see outside the spot.

Work Package #	WP 130
WP Title	Environmental, social and biological/ biodiversity impact studies
Duration	12 months

Work Package Objectives	- Study and characterise the impact of the DSR concept regarding the following topics :
	  - Environment
	  - Temperature radiations
	  - Social
	  - Biodiversity / biological
	  - …
	- Define the measures to avoid, reduce or compensate negative impact.

Required Inputs	- Knowledge of the Consortium members - Knowledge of the Environment and Biodiversity organism
Interactions / Interfaces with other WP	- WP520

Outputs / Deliverables	- TN15 – Environment impact studies - RP12 – Review Presentation

Work package description:

This work package is composed of studies to have an complete environment impact study. The aim is to identify the impact of the DSR concept on the environment aspect, on social, on temperature radiations, on biodiversity…aspects

Several discussions are possible with environment and biodiversity organism to collect feedback and knowledges for these studies.

Work Package #	WP 140
WP Title	Identification of a pilot site
Duration	24 months max
Work Package Objectives	- Define the requirements and identify a pilot site where it is possible to deploy the DSR technologies.

Required Inputs	- Knowledge of the Consortium members - PV sites and site contacts
Interactions / Interfaces with other WP	- WP510 - WP520 - WP530

Outputs / Deliverables	- TN16 - Technical specification to collect and select a PV plant as a pilot. - RP13 – Review Presentation

Work package description:

This work package is composed of discussions and tasks to identify a PV plant which could be a pilot.

The aim is to collect the site information and requirements to select the best solution to deploy a pilot with all safety conditions.

Work Package #	WP 150
WP Title	Connection to the grid / Risk analysis
Duration	3 months
Work Package Objectives	- Identify the risk to connect a PV plant combined with the DSR to the grid - Simulate the behaviour of a such installation on the grid. - Provide recommendations

Required Inputs	- Knowledge of the Consortium members
Interactions / Interfaces with other WP	WP510

Outputs / Deliverables	- TN17 - Technical Report with a risk analysis and recommendations - RP14 – Review Presentation

Work package description:

This work package is composed of studies and simulations of a PV plant combined with the DSR which is connected to the grid.
The aim is to identify the risk to connect a PV plant combined with the DSR to the grid.
Thanks to simulation of the behaviour of a such installation on the grid and for different scenario (transitory, ..)
These studies lead to provide recommendation to avoid and eliminate all the risks.

Work Package #	WP 160
WP Title	Mature the Solar Fuel Technologies for a pilot
Duration	24 months
Work Package Objectives	- Develop the SFC technology until TRL 5 to deploy SFC plants in new locations after the demonstrator phase

Required Inputs	- Deliverables of the pre-study - Agreelent with partners developing this technology
Interactions / Interfaces with other WP	- none

Outputs / Deliverables	- DM11- Design of the panels - DM12-Performance and efficiency studies to produce hydrogen and estimated LCOH - RP15- Industrialization plan

Work package description:

The work package consists of working with industrial partners working on SFC to accelerate the pace of the development until TR5.
It supposes an R&D agreement with one or several of them

Work Package #	WP 170
WP Title	Develop the communication module between PV plant and the mirror constellation.
Duration	6 months
Work Package Objectives	- Define the process of communication between SRS and ground station (pointing and panels moving)

Required Inputs	- Pre study
Interactions / Interfaces with other WP	-

Outputs / Deliverables	- TN18- process of communication and detailed ConOps - TN19 – Test report

Work package description:

- Based on the protocol selected in the pre-study, define the detailed ConOps between space and ground
- Evaluate the communication need between the GPS and SPS which essentially aims to ensure the pointing performance of the SPS towards the GPS
- Test the communication and the capacity to panels to change their orientations
- Specify the hardware needed in the ground stations
- Develop the communication system solution which could be based on RF measurements through quartets of dedicated beams placed on the platform, centred on a number of fixed ground beacons

3.2 WORKSTREAMS FOR SPACE SEGMENT

Work Package #	WP 210
WP Title	Desrisking LEO DSR concept on critical issues
Duration	1 month
Work Package Objectives	- Reassessment of the LEO DSR on collision risks management

Required Inputs	- Knowledge of the Consortium members - Desk research - Outcomes from SBSP Pre Phase A Study
Interactions / Interfaces with other WP	- Pres-study - DRAMA simulation - Feeding all the WPs for space

Outputs / Deliverables	- TN21 – Trade-off report
	  ○ Assessment for DSR of the risk collision and the actions to mitigate it
	  ○ Assessment for SPL of the security risk and the benefit of these concept compared to DSR

Work package description:

Update and complete the LEO Direct Solar Reflection to the light of the pre-phase A outcomes (current study) that spotted, post ASR, unforeseen technical difficulties in the DSR concept. This should also includes a comparison with the GEO Solar Pumped Laser as back-up solution (and the approach to avoid any risk on security)

Work Package #	WP 220
WP Title	Definition of the detailed SBSP CONOPS
Duration	3 weeks
Work Package Objectives	- Elaborate SBSP mission analysis and CONOPS

Required Inputs	- Knowledge of the Consortium members - Desk research - Outcomes from SBSP Pre Phase A Study
Interactions / Interfaces with other WP	- Needs for the results of WP 210

Outputs / Deliverables	- DM21 – MBSE model of the detailed conOps

Work package description:

Propose a detailed concept of operations and preliminary mission analysis

- Validate the optimal launch strategy, especially the fairing loading
- Detail the SBSP ecosystem operations and elaborate delta-V budget for each component
- Demonstrate the constraints concept of formation flying with solar sail

Work Package #	WP 230
WP Title	SRS dynamic modelling
Duration	3 weeks
Work Package Objectives	- Perform SRS AOCS and structural design and modelling for simulation and system sizing

Required Inputs	- Knowledge of the Consortium members - Desk research - Outcomes from SBSP Pre Phase A Study
Interactions / Interfaces with other WP	- Interacts with WP220, WP240, WP250 and WP260 - Needs for the results of WP220 and WP260

Outputs / Deliverables	- DM22 – Slew & pointing model

Work package description:

Modelling of the AOCS and structural design in order to assess the slew and pointing performance. This is a crucial point as the reflector agility drives the number GPS that could be fed by the reflectors and so impacts directly the business model.

- Evaluate the resulting mechanical loads on structure and CMGs actuators during the mission.
- Evaluate the pointing performance of the beam and resulting spot shape and irradiance.
- Evaluate in detail the solar sailing orbit raising strategy

Work Package #	WP 240
WP Title	Reflective membrane assessment
Duration	3 weeks
Work Package Objectives	- Perform the specific design of the membrane and related trade-offs.

Required Inputs	- Knowledge of the Consortium members - Desk research - Outcomes from SBSP Pre Phase A Study
Interactions / Interfaces with other WP	- Interacts with WP220, WP250, WP230 and WP260 - Needs for the results of WP220 and WP260

Outputs / Deliverables	- TN23 – reflecting membrane assessment report

Work package description:

Reflective membrane design

- Evaluate the possibility to manage dynamical membrane shape for stabilization, beam control and potentially focusing
- Select the reflector membrane material, thickness and tension system to ensure 95% of reflectivity

Work Package #	WP 250
WP Title	Modular reflector design & assembly process
Duration	3 weeks
Work Package Objectives	- Elaborate an optimized reflector architecture

Required Inputs	- Knowledge of the Consortium members - Desk research - Outcomes from SBSP Pre Phase A Study
Interactions / Interfaces with other WP	- Interacts with WP220, WP240, WP230 and WP260 - Needs for the results of WP220 and WP240

Outputs / Deliverables	- TN 24- Deployment process - DM 24 – Detailed CAD model of the modular reflector design

Work package description:

Elaborate an optimized reflector architecture in order to be dismantled in kit for launch, then assembled in orbit by robotics means and then deployed autonomously.

- Identification and modelling of mechanical elements and
- Splitting/folding of the platform in kit elements

Work Package #	WP 260
WP Title	Space environment Impact assessment
Duration	3 weeks
Work Package Objectives	- Assessment of space environment effects and countermeasures elaboration

Required Inputs	- Knowledge of the Consortium members - Desk research - Outcomes from SBSP Pre Phase A Study
Interactions / Interfaces with other WP	- Interacts with WP220, WP250, WP230 and WP240 - Needs for the results of WP210

Outputs / Deliverables	- TN35 – Space environment Impact Report

Work package description:

Analyse the space environment effects on the reflector, and particularly radiation and thermal effects on electronics, membrane and structure fatigue and collision risk and effects from micrometeoroids and debris.
For debris collision an analysis of the generation of new debris vs. sweep effect should also be performed.

3.3 WORKSTREAMS FOR SYSTEM INTEGRATION

The following tasks for ground segment should be performed during the demonstrator preparation phases.

Work Package #	WP 310
WP Title	Detail and update SBSP demo plans
Duration	3 weeks
Work Package Objectives	- Elaboration of a sub-scale demonstration plans (ground, space, MVP) for SBSP technologies

Required Inputs	- Knowledge of the Consortium members - Desk research - Outcomes from SBSP Pre Phase A Study
Interactions / Interfaces with other WP	- Interacts with WP220, WP240, WP230, WP250 and WP260 - Needs for the results of WP210

Outputs / Deliverables	- RP1 – SBSP Demo Plan Présentation

Work package description:

Propose a demonstration plan (leadtime, resources, organization, budget) for which the steps could be:

- CONOPS and mission analysis of the demonstration

- Ground demonstrations when possible,
  - Simulation modelling of the system: mission analysis, AOCS, formation flying, mechanical, thermal
  - Structural mechanical testing
  - Zero-G demonstration with ground support equipment for structure deployment
  - If need be, Zero-G parabolic flights

- Subscale space demonstrator
  - 100 – 1000 m² mechanically representative sub-scale reflector platform
  - Autonomous deployment in space
  - Orbit raising Solar sailing
  - CMGs attitude control
  - Membrane impacts collision detection and analysis

- Minimum Viable Product: to initiate the business with a subscale reflector (potentially the same as the previous)

Work Package #	WP 320
WP Title	Business Plan for Sub Scale demo and Full-scale deployment
Duration	24 months over the period of the SSD design
Work Package Objectives	- Update the optimum business cased for a competitive Commercial-scale SBSP system Define the conditions for competitiveness compared to alternative solutions

Required Inputs	- Knowledge of the Consortium members - Desk research
Interactions / Interfaces with other WP	Pre study WP

Outputs / Deliverables	- Business case of the reference architecture (Parametric model in an Excel file) - Programmatic roadmap

Work package description:

- Update the business case for the reference use case and the reference architecture and ConOps option
  - Cost (i.e., relative cost of options, LCOE and LCOH).
  - Energy expenditure (i.e., ERoEI across the system lifetime).
  - RC and NRC items for the global system
  - Design and Launching costs forecast
  - Funding needs

Work Package #	WP 330
WP Title	Building the technical and industrial ecosystem for SSD
Duration	6 months
Work Package Objectives	Identify external partners required for designing and producing the SSD deliveries

Required Inputs	- Knowledge of the Consortium members - Desk research
Interactions / Interfaces with other WP	Pre study WP

Outputs / Deliverables	- Contract for specific work packages - Management specification on the program management

Work package description:

- Identify the work packages needing external expertise not present in the consortium
- Screen the market to identify potential partners or suppliers
- Select the appropriate partner
- Contract the work package for each

Work Package #	WP 340
WP Title	Communication & Program management
Duration	24 months
Work Package Objectives	- Coordinate and steer the work of the different work packages to ensure that deliverables are produced on-time and on quality, to fulfil all ESA requirements for management, reporting and meetings. - Act as the interface between the Consortium and ESA - Produce the main final outputs of the SSD - Convince the involved stakeholders of the benefits of the SBSP system and help to their participate to the program

Required Inputs	- Knowledge of the Consortium members - Desk research - Pre study DSR
Interactions / Interfaces with other WP	Al other WP

Outputs / Deliverables	- Management specification on the program management - Production of project deliverables, compliant with the deadlines specified in SoW - Management Reporting, Meetings and Deliverables requirements from ESA fully met in study execution

Work package description:

- Communicate the project to major stakeholders
- Facilitate the collaboration between Consortium members during the execution of the project
- Create a PMO team, process and organization
- Ensure timely and relevant communication between the Consortium and ESA team
- Define the key messages of the SSD
- Formalize the key documents