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POTENTIAL ACTIVITIES FOR THE SPACE BASED SOLAR POWER SPECIFIC AREA IN GSTP ELEMENT 1

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→ THE EUROPEAN SPACE AGENCY

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1. INTRODUCTION

This document provides a list of candidate activities for the GSTP E1 "Develop" Work Plan. The aim is to provide to industry and Delegations a consolidated overview by Competence Domain of the priorities in the development of Space-based Solar Power related technologies.

This document is issued to Delegations of GSTP Participating States and their industries for comments. Such comments will be considered in the following updates of the work plan.

The objective is also to have a good indication of the developments the participants intend to support in order to present updates of the GSTP E1 "Develop" Work Plan with consolidated sets of activities to the IPC for approval.

Space-based Solar Power related technology activities of strategic importance for maturing the feasibility of Space-based Solar Power concepts have been identified and form the basis of this document. The Solaris Breakthrough Technologies Request for Information in Summer 2022 and Industry Day event organised at ESTEC in October 2022 have facilitated the definition and consolidation of the Space-based Solar Power proposed activities by ESA utilising the valuable inputs received from Industry.

Developments in Space-based Solar Power for terrestrial needs include the following:

- **Solar generation**

  The solar generation system on the Solar Power Satellite will be the largest and most critical system overall, driving the size and cost of the space system and ultimately the levelised cost of the electricity that can be generated and delivered to the grid. As the largest contributor to the power loss from in the conversion chain from sunlight in space to power into the Grid, maximising the efficiency of the solar generators is very important to enable cost-effective SBSP. However, the costs and areal mass (kg/m2) of the solar cells and arrays themselves can be a major driver of the overall SBSP system costs and reductions that can be made on cell/array costs and areal masses may outweigh the value of increased efficiency gains. Therefore, two independent paths of development will be pursued with regards to advanced solar cell technologies, i) cost and areal mass reduction of current high-efficiency space-compatible cell technologies, including through industrial supply chain scale-up strategies and ii) efficiency gains and space compatibility of highly cost-effective, lightweight, terrestrial-based cell technologies.

  The development of advanced solar generation systems, with the best combination of efficiency, durability, scalability, low-mass and cost-effectiveness, is an essential enabling technology for SBSP which will also benefit all other space applications where solar power is employed. Such developments may eventually even spin back into terrestrial applications where such characteristics are desired.

- **Power Management and Distribution**

  Power management and distribution system architectures will need to be tailored for SBSP, in particular in terms of the required power and voltage levels and the associated challenges in insulation, power distribution and thermal dissipation. Targeted improvements of the developed components shall enable higher efficiency, higher voltages, and higher operational temperature of the power management and distribution systems, while reducing mass and cost of the individual components. Technologies developed in this area are enabling for efficient high-power solar power conversion and distribution on Solar Power

Satellites and are relevant in other space missions where higher-power and higher-voltage power distribution provide benefits.

- **RF generation and accurate beam forming**

The current baseline choice for the transmission of energy from the Solar Power Satellite (SPS) to the ground is via microwaves, which for a number of reasons has been the chosen method (rather than optical laser) by most of the previous international studies into SBSP for terrestrial use. Current DC-RF conversion technologies (e.g. Solid-state Power Amplifiers used in telecoms and other applications) have insufficiently high efficiencies for SBSP. The aim is to accelerate the advancement of such technologies to achieve the significantly higher efficiencies (>70%) needed to enable economically-viable SBSP.

The other key aspect of the wireless power transmission (WPT) system for the commercial-scale SBSP system is efficiently and accurately phasing the microwaves from thousands of individual antennae over a km-scale array into a directed beam that can be accurately pointed at the receiving station 36,000 km away on the surface of the Earth. This involves a modular architecture where key design and development aspects will the scale-up approach, strategies for feeding sub-array modules while minimizing losses, as well as on-orbit integration considerations. Just as important for the economic feasibility of the final system, as highlighted in the recent ESA Cost vs. benefits studies for SBSP, will be to demonstrate that it will be eventually possible to produce an extremely lightweight and low-cost system for the WPT elements through a high level of miniaturization and integration.

For the MW-scale in-orbit demonstrator, foreseen for launch by 2030, the WPT architecture is anticipated to be based on a very large (>30m diameter), monolithic, deployable antenna, to avoid the necessity for in-orbit assembly. This is beyond the size that is currently being developed by other ESA programmes and therefore a specific activity is proposed to initiate such a development to reach TRL 5 by 2025, which will also be useful in future telecommunications applications.

- **In-orbit Robotic Assembly, Manufacturing & Maintenance of Very Large Structures**

Drawing from previous in-space assembly and maintenance (the ISS) it is safe to assume that the development of space-based solar power (SBSP) satellites by on-orbit assembly, logistics and maintenance will imply two fundamentally different categories of tasks: those that can be automated and those that cannot be automated, or whose automation has failed.

Therefore, in the case of SBSP spacecraft, it is envisaged that two classes of robot systems will be needed: a standard class that can carry out autonomously the vast majority of operations of assembly and maintenance work and a special class that need to have quasi-human operational capabilities to work in those cases cannot be automated or whose automation has failed.

For SBSP, the huge size of the spacecrafts and the multiplicity of tasks are likely to create the need for a variety and large number of robots. Additionally, due to the remoteness of the installation and the needs to attain high availability and autonomy, the robots will need to be based on common components that will allow good maintainability in orbit.

The dimensions of Space-Based Solar Power systems (solar energy collection and wireless power beaming components) is expected to be in the range of kilometers, in order to reach the intended performance in terms of solar energy capture and wireless power transmission. Such structures are well beyond the size of launcher fairings and would bring extreme complexity if implemented in deployable systems. Building these structures directly on orbit therefore appears to be relevant and potentially enabling. This may involve on-orbit manufacturing in conjunction with on-orbit assembly of structural elements manufactured on ground. Adequate in-situ manufacturing processes need to be developed. Important drivers for development include aspects related to process reliability in the space environment, material selection, achievable scale of manufactured structures, thermal management during processing, in-situ process verification, as well as product and quality assurance.

Challenges associated to operating very large structures in space include ensuring the required stiffness to keep the required form, as well as understanding the structural dynamics of very large structures and their relation to the material selection, manufacturing processes and assembly technologies. The Space-Based Solar Power systems are intended to provide energy in a reliable and continuous way. The development of effective on-orbit servicing technologies is therefore key to ensuring availability and maintained performance of the systems.

SBSP represents the largest foreseen application of in-space robotics and on-orbit manufacturing to date. The technical feasibility of SBSP depend critically on the ability to manufacture, assemble, maintain and ultimately recycle the SPS system with robotic means. The variety and number of robotic systems that will be needed by SBSP will drive forward the development of highly-autonomous, highly dexterous, mass produced robotic technologies which will be available for use in a number of other future robotic applications in orbit as well as planetary surfaces.

Advances in on-orbit manufacturing processes and verification capability will have direct benefits in other space applications where structural components exceeding typical launcher fairing sizes provide performance and mission enhancements. This includes large telecommunication satellite antennae with enhanced data throughput and large solar arrays for higher power generation on a given satellite platform.

2. LIST OF ACTIVITIES

GEN - Generic Technologies – Space-based Solar Power

CD2 - Structures, Mechanisms, Materials

	Activity Title	Budget (k€)
In-orbit Robotic Assembly, Manufacturing & Maintenance of Very Large Structures		
To be updated further	Development of on-orbit manufacturing technologies for very large SBSP spacecraft structures	7,000
To be updated further	Development of process verification and part validation approaches for on-orbit manufactured parts in very large SBSP spacecraft structures	3,000
To be updated further	Development of enabling technologies for on-orbit servicing of solar power satellites	5,000
To be updated further	Simulation software for modelling structure/AOCS coupling	300
To be updated further	Structural modelling of very large space structures	500
To be updated further	High load capacity coupling mechanisms	1,500
	Total	**17,300**

CD4 Electrical Architecture and Power

	Activity Title	Budget (k€)
Solar Generation		
	Development of low cost, high efficiency multi-junction space solar cells	2,500
	Development of large scale, lightweight, compact, efficient, cost effective, space compatible solar generators	1,000
	Preliminary development of very large (square kilometre scale) modular solar arrays with solar concentrators	500
	Adaptation of terrestrial-based cell technologies for use in SBSP applications	500
	Study of strategies to develop multiple scalable sources of solar cells and solar arrays	250
	Novel Architecture and components for high-voltage, high power management and distribution for Space-Based Solar Power satellites	4,000
	Total	**8750**

CD5 Radiofrequency & Optical Systems and Products

	Activity Title	Budget (k€)
RF generation and accurate beam forming		
	Antenna for MW demonstrator of Wireless Power Transmission	15,000
To be updated further	Antenna for GW Wireless Power Transmission	10,000
To be updated further	High efficiency Solid State DC to microwave converting device demonstrator	2,500
To be updated further	Vacuum technology-based DC to microwave converting device demonstrator	2,500
	Total	**30,000**

CD6 Life support & Robotics

	Activity Title	Budget (k€)
In-orbit Robotic Assembly, Manufacturing & Maintenance of Very Large Structures		
	Robotics Interfaces and tooling for SBSP Engineering (RISE)	4,000
	End to End Humanoid for Automation Non Compliances and Exceptions in SBSP (ENHANCES)	6,000
	Classes of Robotics Expert Workers for SBSP (CREWS)	5,000
	Total	**15,000**

3. DESCRIPTION OF ACTIVITIES

CD2 - Structures, Mechanisms, Materials

Budget (k€): 3500

Activity Title:	**Development of on-orbit manufacturing technologies for very large SBSP spacecraft structures**
Objectives:	To develop, manufacture and test a breadboard demonstrating on-orbit manufacturing processes suitable for producing very large structures for Space-Based Solar Power applications. The developed processes shall enable on-orbit manufacturing of very large structures with dimensions > 1 km
Description:	The dimensions of Space-Based Solar Power systems (solar energy collection and wireless power beaming components) is expected to be in the range of kilometers, in order to reach the intended performance in terms of solar energy capture and wireless power transmission. Such structures will have to be built directly on orbit and may involve on-orbit manufacturing in conjunction with on-orbit assembly of structural elements manufactured on ground. This activity is intended to focus on the development of adequate manufacturing and joining processes, through the identification, selection and demonstration at TRL 5. Trade off analyses will be conducted on material selection and process choices, taking into consideration the aspects related to process reliability in the space environment, achievable scale of manufactured structures and thermal management. The activity will consist in: - Establishment of requirements for the manufactured structures, with input from the system studies - Trade-off and selection of processes and associated feedstock materials - Process development at specimen and part level - Design, manufacturing and testing of manufacturing process breadboard - Manufacturing and characterization of in-situ manufactured demonstrator parts - Identification of development steps towards implementation in demonstrator mission

	This activity is intended to progress the selected technologies to TRL5, to enable in-orbit demonstration of on-orbit manufacturing as part of the first MW-scale SBSP demonstration mission Parallel activities are recommended, to develop several manufacturing and joining processes for future trade-off.
Deliverables:	Manufacturing process breadboard, manufactured part demonstrator, manufactured specimens, reports
Current TRL:	2 **Target TRL:** 5 **Duration (Months):** 24-30
Target Application/Timeframe:	Space-Based Solar Power, TEL, EOP, EXP, SCI
Applicable THAG Roadmap:	Yes, partially covered in the Additive Manufacturing roadmap

Budget (k€): 3000

Activity Title: **Development of process verification and part validation approaches for on-orbit manufactured parts in very large SBSP spacecraft structures**

Objectives:

To develop and test in-process monitor breadboard demonstrating on-orbit manufacturing processes suitable for producing very large structures for Space-Based Solar Power applications

The developed processes will enable to ensure adequate quality and performance of parts manufactured on orbit, for use in very large structures

Description:

The dimensions of Space-Based Solar Power systems (solar energy collection and wireless power beaming components) is expected to be in the range of kilometers, in order to reach the intended performance in terms of solar energy capture and wireless power transmission.

Such structures will have to be built directly on orbit and may involve on-orbit manufacturing in conjunction with on-orbit assembly of structural elements manufactured on ground. As the parts and structures are manufactured on orbit, usual process verification and part validation practices, with associated material testing and part characterization facilities, cannot be applied. Novel tools and strategies need to be developed, to ensure that the parts produced in situ are fit for their intended purpose. This includes the ability to monitor the process as it is implemented, and the capability to inspect manufactured parts as well as the use of modelling capabilities to compensate for reduced testing possibilities.

This activity intends to focus on the development of tools for process abstraction/Digital Twin of relevant on-orbit manufacturing processes, as well as for in-process monitoring and non-destructive inspection (NDI) of the manufactured parts. The developed technologies shall be demonstrated at TRL 5.

Trade off analyses will conduct a selection of space-graded sensors, NDI methods and software toolchain for stream data processing and digital process abstraction. This shall take into account considerations related to the space environment impact on sensor data and the resolution of NDI instrumentation, to ensure form and function for appropriate part verification in space.

The activity will consist of:

- Trade-off and selection of on-orbit manufacturing processes as application case for this activity

- Establishment of requirements for sensors, sensor integration and large area non/destructive inspection of parts

- Trade-off and selection of software toolchain for sensor data handling, process abstraction simulation, correlation with physical and simulation data, workflow integration within systems engineering

- Design, manufacturing and testing of non-destructive inspection hardware for in-orbit verification

- Integration of hardware and software for in-process monitoring

- Preliminary definition of Product Assurance guidelines based on Virtual Testing/ Digital Twin, NDI in-process monitoring and earth based experimental verification of parts

This activity is intended to progress the selected technologies to TRL5, to enable in-orbit demonstration of on-orbit manufacturing as part of the first MW-scale SBSP demonstration mission

Parallel activities are recommended, to develop multiple IoT and DT integrations with different software frameworks for future trade-off.

Deliverables: Sensor Selection, IoT integration toolchain, Digital Twin abstraction toolchain, NDI inspection concept, reports

Current TRL: 3 **Target TRL:** 5 **Duration (Months):** 24

Target Application/Timeframe: Space-Based Solar Power, TEL, EOP, EXP, SCI, STS

Applicable THAG Roadmap: Yes, partially covered in the Additive Manufacturing roadmap

Budget (k€): 5000

Activity Title:	**Development of enabling technologies for on-orbit servicing of solar power satellites**
Objectives:	Develop technologies related to: target, docking and capture, exchange of modular subsystems, on-orbit repair technologies (e.g. self-healing materials, PV annealing), satellite life extension (life extension module docking, refuelling) Increase the TRL of the robotic technologies related with on-orbit capture, assembling and manufacturing up to TRL 4 by 2025.
Description:	This activity will start after the conclusion of the SBSP Pre-phase A system studies. The system studies will inform the architecture and provide preliminary information on the interfaces of the Space-Based Solar Power system. Based on this information, this activity will focus on the adaptation of existing concepts or design of novel concepts where required, as well as the development of breadboard technologies for docking/capture, on-orbit assembling (e.g., for exchanging of modular subsystems), on-orbit repairing (e.g., self-healing materials, manufacturing technologies) and on-orbit life extension (e.g., refuelling technologies) for the use case of on-orbit servicing of Solar Power Satellites. This activity will comprise: - Assessment of technology gaps on on-orbit servicing from the outcome of the system studies - Identification of existing technologies to be adapted - Design of new concepts from the identified gaps - Breadboard design for the identified technologies - Analysis and tests to perform component and/or breadboard validation in laboratory environment.
Deliverables:	Analysis, test reports and hardware.
Current TRL:	2 **Target TRL:** 4 **Duration (Months):** 24
Target Application/Timeframe:	Space-Based Solar Power, Clean Space, TEL, EO
Applicable THAG Roadmap:	Yes, Clean Space

Budget (k€): 300

Activity Title:	**Simulation software for modelling structure/AOCS coupling**
Objectives:	Develop software toolbox to link Structural modelling software with AOCS control software. Provide seamless coupling of structural modelling software and AOCS control software to enable simulation of control and structural dynamics of large flexible structures.
Description:	Large space structures are expected to exhibit structural modes at low frequency likely to couple with the AOCS control system. The objective of this activity is to couple the structure mathematical model (FEM) with the AOCS control software. This would allow to model the interaction between a large 'flexible' structure with the attitude control system (including investigating the effectiveness of distributed attitude control hardware sensors/actuators).
Deliverables:	Software, TN (software user guide)
Current TRL:	2 **Target TRL:** 4 **Duration (Months):** 18
Target Application/Timeframe:	Space-Based Solar Power - SBSP
Applicable THAG Roadmap:	

Budget (k€): 500

Activity Title:	**Structural modelling of very large space structures.**
Objectives:	Evaluate mechanical loading and control of very large in-orbit structures. Demonstrate feasibility to control very large structures in-orbit in consideration of low frequency structural modes coupling with AOCS and overall requirement for pointing and stability.
Description:	Large space structures are expected to exhibit structural modes at low frequency likely to couple with the AOCS control system. For very large structures it is expected that the attitude control will be achieved by distributed sensors and actuators, which may potentially result in relative high loads and displacements. This activity would assess the critical aspects of very large structures, including: - Interaction between structure and AOCS (criticality of structure stiffness vs. mass). - Feasibility to reduce structural resonance through passive and/or passive structural damping. - Criticality of pointing and stability requirements, e.g. for solar power generation maintaining sun-point for solar generator surface and Earth pointing for power transmission. - ROM evaluation of internal loading on structure to ensure satisfactory capability of structural design, material selection and joining technologies. - Feasibility for redundancy in the design and performance of very large structures, assuming potential failure in structure or structural joining elements over the anticipated in-orbit lifetime.
Deliverables:	
Current TRL:	2 **Target TRL:** 4 **Duration (Months):** 18
Target Application/Timeframe:	Space-Based Solar Power - SBSP
Applicable THAG Roadmap:	

Budget (k€): 1500

Activity Title:	**High load capacity coupling mechanisms**
Objectives:	- Develop high (load) capability coupling mechanisms to join structural elements in orbit. - Improve strength capability of structural coupling mechanisms for in-orbit assembly of large structures.
Description:	Mechanisms to join structural building blocks (individual beam elements or modular sub-structures) will be driven by a number of requirements, including: - High load capability (depending on overall structural design concept, this may be a combination of axial, shear and moment loading). - Compatibility with robotic assembly methods (limited need for precision alignment). - Device should be capable to accommodate a degree of misalignment between modular structural elements. - Zero back lash. - Capability for de-coupling. - Powered vs. non-powered latching/locking system. Activity should identify the most promising solution(s) and demonstrate operational capability with full/sub-scale breadboard model(s).
Deliverables:	Breadboard hardware demonstrator(s), Reports.
Current TRL:	2 **Target TRL:** 4 **Duration (Months):** 18
Target Application/Timeframe:	Space-Based Solar Power - SBSP
Applicable THAG Roadmap:	

CD4 Electrical Architecture and Power

Budget (k€): 2500

Activity Title: **Development of low cost, high efficiency, multi-junction space solar cells for space-based solar power and constellations**

Objectives: Development of multi-junction III-V solar cells with a very low cost and still very high efficiency, targeting the space-based solar power and constellations application where cost is a major driver of economic feasibility.

Decrease solar cell costs by at least a factor of 2 leading to a cost per Watt of 50€/W (ideally targeting 40€/W). Also, end of life (EOL) efficiency of 25% at room temperature shall be targeted.

Description: Space-based solar power (SBSP) systems require a combination of high-efficiency, lightweight and low-cost solar generators in order to be economically feasible. The current costs of highly-efficient space solar cells (~100€/W) are prohibitive for SBSP applications where the overall cost of the system is driven substantially by the cost of the solar generators. Also the constellation market will benefit from the availability of low cost solar cells.

The trend seen nowadays in solar cell development roadmaps for space applications is not necessarily only to increase solar cell efficiency but making current solar cell products much more cost-efficient even at the expense of performance. Solar cells that would be offered at half the price at the expense of a moderate efficiency decrease could be immediately very attractive for constellation missions but would also be potentially enabling for space-based solar power (SBSP) where a very low cost per Watt is one of the important drivers to be able to produce competitively-priced electricity to the terrestrial energy Grid.

Different solutions are being investigated to reduce costs, either by reducing the number of sub-cells or developing a simpler structure of the present triple-junction solar cells; also the recycling of Ge wafer material is considered. For example, a significant cost reduction is currently projected for a dual-junction device that would be lifted off from the mother substrate. In case the mother substrate could be reused several times, this could further contribute to a significant cost reduction. Another potential solution is based on the basic review of the processes in the manufacturing route of the triple-junction solar cells. In both options, a reduction in cost down to 50€/W (maybe more) appears feasible. However, such a product would not reach the same efficiencies at the best solar cells in the world. Realistically, such a new multi-junction cell would have a maximum efficiency potential at EOL, room temperature conditions of not more than 25%. Nevertheless, this efficiency would still be high enough that the drawback of larger solar collecting areas or reduced power output could be compensated by the huge reduction in cost.

Tasks to be performed in this activity would include:

1) Review of all manufacturing steps identifying the highest cost contributors
2) Investigation of how the highest cost contributors can be substituted by cheaper processes. This shall also include a potential substitution by MOVPE (metal organic vapour phase epitaxy) by HVPE (hydride vapor phase epitaxy)
3) Investigation of cost reduction potential for a dual junction solar cell including lift-off process and wafer reuse
4) Development of dual-junction solar cell process including lift-off process and wafer reuse
5) Development/replacement of high cost processes by lower cost processes
6) Implementation of cost-efficient processes in production of low-cost dual-junction solar cell
7) Final assessment of further cost reduction potential

Considerations to the environmental impact of the investigated solution (e.g., through LCA) will be included.

The development of such type of solar cells shall be carried out in parallel contracts with different entities (2.5M€ each).

Deliverables: Prototype solar cells, documentation

Current TRL: 2 **Target TRL:** 4 **Duration (Months):** 30

Target Application/Timeframe: Space-based Solar Power and Generic Technologies

Applicable THAG Roadmap: Yes (see Technology Harmonisation Dossier Solar Generators and Solar Cells)

Budget (k€): 1000

Activity Title: **Development of large scale, lightweight, compact, efficient, cost effective, space compatible solar generators**

Objectives: The objective is to develop compact solar generators of exceptionally high specific power, suitable for space-based solar power applications.

This would require targeting a substantial increase in specific power mass and stowage volume, beyond the current state of the art of space solar generators. An adequate concept for large dimensions (typically 1 MW ≈ 4000 m^2) would also need to be developed.

Parallel activities are recommended for future trade-off.

Description: Space-based solar power (SBSP) systems require lightweight and compact solar generators in order to reduce the overall system mass – which drives launch costs - to levels compatible with economic feasibility. The current state-of-the-art in specific power of solar generators, even for high-power applications is far from what is needed for SBSP applications. By exploiting existing technologies of fully flexible and semi-rigid solar arrays, concepts (including modular ones) are to be derived, which lend themselves to space based solar power applications.

The following tasks need to be performed:

- Derivation of a mechanical concept, including a means of deployment.

- Analysis of array in stowed configuration, subjected to a typical launch environment: sine, acoustic, quasi-static, thermos-elastic.

- Analysis of the array in deployed configuration: in-orbit loads, natural frequencies.

- Analysis of the array deployment.

- Analysis of thermal behavior, in both stowed and deployed configurations.

- Definition of preliminary electrical and mechanical interfaces

- Manufacture of a breadboard, to illustrate the means of deployment and to assess preliminary mechanical and electrical performances.

Deliverables: Breadboard, documentation

Current TRL:	3-4	**Target TRL:** 5	**Duration (Months):** 30
Target Application/Timeframe:	Space-based Solar Power and Generic Technologies		
Applicable THAG Roadmap:	Yes (see Technology Harmonisation Dossier Solar Generators and Solar Cells)		

Budget (k€): 500

Activity Title:	**Preliminary development of very large (square kilometre scale) modular solar arrays with solar concentrators**

Objectives:

The objective is to develop a concept of a modular solar generator that can be applied to the very-large scale required for space-based solar power applications.

The targeted improvements are:

Substantial increase in specific power mass beyond the current state of the art of space solar generators. Low concentration elements are to be considered as a means of power enhancement.

Derivation of a cost-effective, modular concept (with an area typically at the km^2 scale), suitable for in-orbit assembly.

Parallel activities are recommended for future trade-off.

Description:

The huge scale of SBSP (1000's of tonnes, km^2 of area) concepts generally requires the use of innovative modular architectures for the satellite system in particular for the solar generators and the wireless power transmitting antenna. This requires a paradigm shift in terms of spacecraft design compared to almost all other foreseen applications. By exploiting existing technologies or proposing novel concepts for fully flexible and semi-rigid solar arrays, supplemented by solar concentrators, modular concepts for such large arrays are to be derived, which lend themselves to the in-orbit assembly of space based solar power systems.

The following tasks need to be performed:

- Derivation of a mechanical concept, for both module and concentrator elements, including a means of deployment and grappling points to assist in-orbit assembly.

- Analysis of the module in stowed configuration, subjected to a typical launch environment: sine, acoustic, quasi-static, thermos-elastic.

- Analysis of the module in deployed configuration: in-orbit loads, natural frequencies.

- Analysis of the array module deployment.

- Analysis of thermal behavior, in both stowed and deployed configurations.

- Definition of preliminary inter-module electrical and mechanical interfaces

- Manufacture of a breadboard, to illustrate the means of deployment and to assess preliminary mechanical and electrical performances.

Deliverables: Breadboard, documentation

Current TRL: 2 **Target TRL:** 3 **Duration (Months):** 24

Target Application/Timeframe: Space-based Solar Power and Generic Technologies

Applicable THAG Roadmap: Yes (see Technology Harmonisation Dossier Solar Generators and Solar Cells)

Budget (k€): 500

Activity Title:	**Adaptation of terrestrial-based cell technologies for use in SBSP applications**
Objectives:	The objective is to adapt terrestrial solar cell technologies in order to meet the additional requirements associated with use for space based solar power applications. The targeted improvements are: Increase in end-of-life conversion efficiency in the space environment while maintaining low-cost. Compatibility with interface requirements for space solar array manufacturers (e.g. Cell connection technology).
Description:	Space based solar power will require a much higher scale of production than for traditional space applications, at low cost. One path that is being pursued (subject of another activity proposal) is to attempt to significantly reduce the cost of current space solar cell technology. Another potential path is to try to make space-compatible solar cells out of already low-cost cells that are being developed for terrestrial applications (for which the market is dominated by silicon solar cells but includes other cell technologies such as CdTe, CuInGaSe). It may be favourable (or necessary) to make modifications before these cells can meet the requirements for use in space based solar power applications Parallel activities are recommended for future trade-off. Tasks to be performed in this activity would include: - Review and trade-off of relevant terrestrial cell technologies - Establishment of requirements for adapted terrestrial cells - Manufacturing and testing of adapted terrestrial cell specimens - Conclusions and development plan
Deliverables:	Prototype solar cells, documentation
Current TRL:	2-4 depending on technology **Target TRL:** 3-5 depending on technology **Duration (Months):** 30
Target Application/Timeframe:	Space-based Solar Power and Generic Technologies

Applicable THAG Roadmap: Yes (see Technology Harmonisation Dossier Solar Generators and Solar Cells)

Budget (k€): 250

Activity Title:	**Study of strategies to develop multiple scalable sources of solar cells and solar arrays**
Objectives:	Study on strategies to ensure the development of multiple sources for solar cells and solar arrays and the industrial supply chain scale-up required to achieve the production capacity needed for space-based solar power (i.e., 5 km^2/annum by 2035) The targeted improvement is: Annual "10GW-range" production capability of space solar cells and solar generators
Description:	Space based solar power will require a yearly production capability of space solar cells, photovoltaic assemblies, solar panels and relevant mechanisms in the order of 10GW. The present yearly production capability of the complete supply chain of space solar cells is less than 1 MW. The study shall analyse the strategies to develop multiple scalable sources of solar cells and solar arrays. It is proposed to have two parallel contracts.
Deliverables:	Documentation
Current TRL:	N/A **Target TRL:** N/A **Duration (Months):** 12
Target Application/Timeframe:	Space-based Solar Power and Generic Technologies

Applicable THAG Roadmap: No

Budget (k€): 4000

Activity Title: **Novel Architecture and components for high-voltage, high power management and distribution for Space-Based Solar Power satellites**

Objectives: Development of novel power system architecture and associated EEE components to manage the voltage levels required for SBSP (i.e. 300 V power bus). Multiple developments needed: components (e.g mosfets, diodes, capacitors); insulation methods (to mitigate arcing issues); novel distribution systems.

Description: In power systems it is well known that, the higher the power to be processed, the higher the voltage should be. In space applications, the maximum spacecraft power so far is 20 kW and the special case of the ISS is 120 kW. For those power levels, a bus voltage between 120 V and 140 V has been used. However, this is insufficient to build a power system of higher power levels. The next voltage value is 300 V. This can multiply by almost 10 the power capability. However, beyond 200 V there are arcing phenomena appearing that could create a number of problems in the electrical system. Thus, it has to be understood how to deal with higher voltages. The activity will focus on creating the full picture of the optimum power system for MW spacecrafts. Apart from the voltage level and the techniques needed to manage it, the activity should focus on the system level aspects, studying the bus distribution in the spacecraft, the protections and the load distribution in the various buses.

The next level is to focus on the topologies needed to manage high power and high voltage to the levels deduced before. Apart from the relevant trade offs, the activity shall produce an EM of the power conversion stage and the distribution stage. The EM level is important since the thermal aspects for high power dissipation are key for the feasibility of the concept.

Further down, the activity should analyse the EEE components needed to build the EM, understanding which technologies are missing and triggering the relevant developments to make the concept feasible. The activity shall perform trade-offs and tests at component level operating at high voltage and high power.

Overall, this activity shall produce a comprehensive view of the power system, conversion topologies and EEE components needed to build a MW level spacecraft.

Tasks

- Trade off analysis at power system level

- Simulation of best power system options
- Trade off analysis of power conversion topologies
- Trade off analysis of power distribution systems
- Analysis of power protection systems
- Trade off analysis of EEE components for high voltage / high power
- Design and build an EM of a power conversion board
- Design and build an EM of a power distribution board
- Roadmap of technologies and systems needed to increase the power level and the performance

Deliverables: Report and EMs of power conversion and power distribution boards

Current TRL: 3 **Target TRL:** 5 **Duration (Months):** 24

Target Application/Timeframe: Space-Based Solar Power - SBSP

Applicable THAG Roadmap: Yes

CD5 Radiofrequency & Optical Systems and Products

Budget (k€): 15000

Activity Title: **Antenna for MW demonstrator of Wireless Power Transmission**

Objectives: Manufacturing and testing of very large antenna array (single piece, deployable, size > state-of-the-art of 30 m) for a MW output solar power satellite demonstration. Targeted Improvements: Enable very large antennas in space, beyond the state of the art in ESA programmes

Description: An SBSP in-orbit demonstrator mission, to be launched by 2030, would benefit from the use of a deployable antenna rather than a modular one that would require in-orbit robotic assembly. In order to reduce power density levels at the antenna as well as the size of the receiving area on the ground, the antenna size required is expected to be significantly larger than the current state-of-the-art or in development. As such, a new, very large, deployable antenna is to be developed that could meet the needs of the SBSP in-orbit demonstrator and to reach TRL5 in order to enter the potential development phase after 2025 with controlled risks.

Reflector antennas are in general known to provide a high gain over a desired area, while being broadband and lightweight. The antenna accommodation constraints are mostly stemming from both the available volume under the launcher fairing and the volume occupied by the spacecraft platform. The need for unfurlable reflector antennas is dictated by the performance requirements requiring an antenna aperture size that is not compatible with the accommodation constraints in the case the reflector aperture would be made of a single rigid piece. The unfurlable reflector antennas are therefore made of multiple pieces that can either be solid and/or flexible. In that way, the deployable reflector antenna can be accommodated on the platform while it is stowed under the launcher fairing, and its radiofrequency radiating aperture can be unfurled once the satellite is placed in orbit.

Among the possible reflector concepts and deployable structures, ESA has identified promising deployable concepts which are the conical or cylindrical ring based reflector. These reflector concepts have been developed in different R&D activities and are currently being further matured.

As far as the reflector based on conical or cylindrical ring structure, it can be deployed by either V-folding bars, single or double layer pantographs; deployable tetrahedrons forming a ring when deployed; or unit cells arranged next to each other as a modular assembly.

The activity will consist of the following tasks:

Phase 1 (**Budget (k€): 5000)**

- Requirements Definition:

This task will consist of deriving the associated antenna and reflector level requirements for the in-orbit demonstrator mission.

It is mandatory that a multi-disciplinary approach is put in place since a broad perimeter of engineering expertise such as electromagnetic, thermo-mechanical and technological ones is necessary for the design and development of unfurlable reflector antennas. Furthermore, a closely coordinated approach between all these engineering fields is needed such that this complex system meets the stringent reliability requirements imposed by the space missions.

- Preliminary Design Definition:

This task will consist of providing a preliminary RF, thermal and mechanical design of the corresponding antenna by identifying critical areas deserving specific design, analysis, and bread boarding.

This tasks will be divided into sub-tasks addressing each identified subsystem, and will include as a minimum the following subsystems:

  - Antenna deployable arm and HDRM.
  - Reflector deployable structure
  - Reflector mesh
  - Reflector carrying net and tensioning ties
  - Antenna feed system.
  - Antenna de-spin and pointing system and associated mechanism

For each subsystem design formulation, analysis, critical breadboard manufacturing and testing will be conducted

- Critical Breadboarding

Phase 2 (**Budget (k€): 10000)**

- Design Validation:
- Manufacturing of demonstrator
- Testing
- Development Plan:

This task will consist of proposing a development plan and a roadmap for identified critical elements, taking into account the potential of the technology to be scaled up to dimensions >30m.

- Propose measurement techniques and technologies for the LDA.

Parallel activities are recommended to develop several concepts for future trade-off.

Deliverables: Large deployable antenna breadboard, reports

Current TRL: 3 **Target TRL:** 5 (by 2025) **Duration (Months):** 24

Target Application/Timeframe: Space-Based Solar Power, TEL, EO

Applicable THAG Roadmap: Yes, Antenna Reflector

Budget (k€): 10000

Activity Title: **Antenna for GW Wireless Power Transmission**

Objectives: Develop, manufacture and test a scaled breadboard (at scale > 1/10) of a modular antenna intended for a commercial-scale space-based solar power system (with phased-array efficiency well above current state-of-the-art). The activity shall address scale-up aspects, technologies for feeding sub-array modules while minimizing losses, as well as on-orbit integration aspects. Targeted Improvements: Enable very large modular antennas in space, substantially beyond the state of the art.

Description: The wireless power transmission antenna on the Solar Power Satellite is a major element that drives the mass and dimensions of the satellite. As a critical driver of the technical feasibility, and due to the novel nature of the application which requires a high antenna efficiency, accurate beam forming, very lightweight and low cost and compatibility with on-orbit assembly, it is necessary to undertake early technology development in this area to feed future system-level assessments of both technical and economic feasibility of SPSP systems.

The activity will consist in:

- Derive the associated antenna level requirements for a SBSP system.

- Providing a preliminary design of the corresponding antenna by identifying critical areas deserving specific design, analysis, and breadboarding.

This shall include as a minimum the following subsystems:

- Solar to microwave conversion
- Antenna RF
- Array feeding
- Amplification
- Antenna deployment
- Antenna Pointing TBC
- Antenna de-spin mechanism TBC
- Thermo-mechanical hardware
- In-orbit assembly strategy

- Propose measurement techniques and technologies for the antenna.

- Develop, manufacture and test a scaled breadboard

- Proposing a development plan and a roadmap for identified critical elements

Deliverables: Solar Power antenna

Current TRL: 2 **Target TRL:** 5 (by 2025) **Duration (Months):** 24

Target Application/Timeframe: Space-Based Solar Power

Applicable THAG Roadmap: No

Budget (k€): 2500

Activity Title:	**High efficiency Solid State DC to microwave converting device demonstrator**
Objectives:	Demonstrate the feasibility of a high efficiency Solid State DC to microwave converting device for space-based solar power. As an example, making use of high voltage, high power density GaN devices and/or GaN-on-Diamond thermal management as proposed under the EEE sovereignity initiative (THRUST). Targeted Improvements: >75% conversion efficiency
Description:	One of the key drivers of the performance of SBSP systems is the DC-RF conversion on the Solar Power Satellite where high conversion efficiency is required to minimize loss of power to heat on the spacecraft. This activity aims to design develop and manufacture a hybrid circuit based on Solid State technology focusing on improved device electrical and thermal performance and narrowband matching networks to maximize efficiency for SBSP applications, targeting conversion efficiency of >75%. Parallel activities are recommended to develop several designs for future trade-off.
Deliverables:	Solid State DC to microwave converting device demonstrator
Current TRL:	2-3 **Target TRL:** 4 **Duration (Months):** 24
Target Application/Timeframe:	Space-Based Solar Power
Applicable THAG Roadmap:	

Budget (k€): 2500

Activity Title:	**Vacuum technology-based DC to microwave converting device demonstrator**
Objectives:	Demonstrate the feasibility of a high efficiency vacuum technology-based DC to microwave converting device. Targeted Improvements: >75% conversion efficiency
Description:	One of the key drivers of the performance of SBSP systems is the DC-RF conversion on the Solar Power Satellite where high conversion efficiency is required to minimize loss of power to heat on the spacecraft. In contrast to a solid-state power amplifier solution (which is proposed to be pursued in an alternative activity proposal), this activity aims to design develop and manufacture a vacuum technology based DC to microwave converting device focusing on conversion efficiency, for application in a solar power satellite system. In addition to Space-Based Solar Power, such development would also have applications in wireless power transfer to support lunar exploration.
Deliverables:	Vacuum technology-based DC to microwave converting device demonstrator

Current TRL: 2-3 **Target TRL:** 5 **Duration (Months):** 24

Target Application/Timeframe: Space-Based Solar Power

Applicable THAG Roadmap:

CD6 Life support & Robotics

Budget (k€): 4000

Activity Title: **Robotics Interfaces and tooling for SBSP Engineering (RISE)**

Objectives: Develop robotics systems interfaces (grippers/grappling fixtures) and tools to allow:

- Robot locomotion (walk on stepping stones)
- Handling of large payload (attach, detach, transport)
- for structural element joining/fastening,
- for fastening/connecting cable and equipment
- for fastening/unfastening by means of screwed fasteners
- handling of retention tethers/loops
- handling of Velcro
- handling/mending of thermal blankets mirror films

while considering space environmental factors and debris mitigation

Description: The development of robotics systems with capability for on-orbit assembly, logistics and maintenance for space-based solar power (SBSP) satellites requires the development of standard robotic interfaces and tools.

While the structure of and SBSP is yet to be designed, the fundamental operations of assembly are notionally known from previous in-space assembly operations (ISS).

In the ISS case the early development of standard robotics interfaces allowed the follow-on development of assembly and installation procedures.

Similarly to the ISS case the activity in subject aims at developing designs of standard robotics interfaces that will be integrated in the design of any hardware that will need to be robotically operated.

There are important differences though with the ISS case: due to the larger scale of SBSP installations, several thousands of robotics interface elements will be needed. Hence the design of the robotics interfaces will need to be highly optimised in order to reduce resources (mass, volume) and hence impose minimal overhead on the SBSP system.

The activity shall encompass the following Tasks:

- SBSP Robotics activity analysis
- Review of the state of the art (space and terrestrial)
- System Requirements Formulation
- Preliminary design and optimisation
- Detailed design including functional tesbed
- Breadboarding and functional testing
- Detailed design iteration
- Manufacturing, Assembly and Integration
- Functional and Environmental tests
- Final Demonstration

Deliverables: Detail Design of Standard Interfaces (Open standard)

Reference Hardware implementations (breadboards and engineering models)

Current TRL: 2 **Target TRL:** 6 **Duration (Months):** 30

Target Application/ Timeframe Space-based Solar Power

Applicable THAG Roadmap:

Budget (k€): 6000

Activity Title: **End to End Humanoid for Automation Non Compliances and Exceptions in SBSP (ENHANCES)**

Objectives: Develop an end-to-end humanoid robot system capable of operating on SBSP station to:

- Perform troubleshooting of autonomous/automatic operations gone wrong
- Perform highly dexterous repair/refurbish operations not possible with the standard SBSP robots
- Provide inspection capabilities

all with highly immersive teleoperation from ground that enables 'haptics telepresence'.

Description: Drawing from previous in-space assembly and maintenance (the ISS) it is safe to assume that the development of space-based solar power (SBSP) satellites by on-orbit assembly, logistics and maintenance will imply two fundamentally different categories of tasks: those that can be automated and those that cannot be automated or whose automation has failed.

In the ISS case, the automated cases were carried out by robots while the remaining were done by astronauts in EVA. Human dexterity and ingenuity were necessary to cope with the unpredictable nature of non/failed automation tasks.

Therefore in the case of SBSP spacecraft, it is envisaged that 2 classes of robot systems will be needed: a standard class that can carry out autonomously the vast majority of operations of assembly and maintenance work and a special class that need to have quasi-human operational capabilities to work in those cases cannot be automated or whose automation has failed.

The second class will be made by humanoid robots that by means of their physical correspondence with an operator body and by their highly immersive teleoperation, will allow operators on ground to be physically 'telepresent' on the SBSP spacecraft.

The activity shall develop a breadboard of a space humanoid robot and its related ground segment, in order to demonstrate, in the context of SBSP tasks, the ability to perform:

- troubleshooting of autonomous/automatic operations gone wrong
- highly dexterous repair/refurbish operations not possible with the standard SBSP robots

- inspection of equipment

The humanoid robot system shall allow state of the art 'haptics telepresence' in the context of SBSP, considering also telecommunication constraints associated with the SBSP system orbit.

The breadboard of End to End Humanoid Robotics for SBSP shall be composed by

- a humanoid robot designed to be form, fit and function representative to the flight design
- ground station equipped with dedicated Human-Robot Interaction devices (i.e. full torso/arms/head/hands exoskeleton, head mounted display and body tracking)
- target environment physical simulator, allowing the operator to experience the applicable environmental effects

The activity shall encompass the following Tasks:

Review of the state of the art (space and terrestrial)

System Requirements Formulation

- Preliminary design and optimisation
- Detailed design including functional testbed
- Breadboarding and functional testing

Final Demonstration

Deliverables: Breadboard of End to End Humanoid Robotics for SBSP

EGSE, MGSE

Reports

Current TRL: 2 **Target TRL:** 5 **Duration (Months):** 30

Target Application/Timeframe: Space-Based Solar Power - SBSP

Applicable THAG Roadmap:

Budget (k€): 5000

Activity Title: **Classes of Robotics Expert Workers for SBSP (CREWS)**

Objectives: Define the class of autonomous manipulators to implement the assembly and maintenance of SBSP spacecraft. Develop breadboards of every element of the class and demonstrate its use.

Description: Drawing from previous in-space assembly and maintenance (the ISS) it is safe to assume that the development of space-based solar power (SBSP) satellites by on-orbit assembly, logistics and maintenance will imply two fundamentally different categories of tasks: those that can be automated and those that cannot be automated, or whose automation has failed.

The automated tasks will be executed by crews of robots that will likely have degrees of specialisation. The ISS experience, for example, demonstrated the need for large robot manipulators to cope with large reach and large masses, finer two-arm dexterous manipulators for two-hand operations and finally a mobile base system.

For SBSP, the huge size of the spacecrafts and the multiplicity of tasks are likely to create the need for more variety and larger number of robots. Additionally, due to the remoteness of the installation and the needs to attain high availability and autonomy, the robots will need to be based on common components that will allow good maintainability in orbit. Finally the large number and diversity of robots belonging to a crew, requires a control system coordinating the individual robot implementing a task, as well as a system allowing programming, commanding and control from ground.

The activity shall develop a breadboard of robot crew and its related control system and ground segment, in order to demonstrate, in the context of SBSP tasks, the ability to perform:

- Logistic tasks: inbound material handling, transport and warehousing
- Assembly tasks: construction of structure (i.e. modular truss), populating the structure with elements (modular equipment, harness), deployment of thin-film mirrors,
- Maintenance tasks: inspection, metering, scheduled and unscheduled replacement of modules, repair of thin film mirrors, replacement of other robots components.

The activity shall encompass the following Tasks:

- SBSP Robotics activity analysis
- Review of the state of the art (space and terrestrial)
- System Requirements Formulation
- Preliminary design and optimisation of the robot class members, common components and overarching control, programming and commanding system
- Detailed design including functional testbed
- Breadboarding and functional testing
- Final Demonstration

Deliverables: Breadboards of robot crew and its related control system and ground segment. Test results, Reports.

Current TRL: 2 **Target TRL:** 5 (by 2025) **Duration (Months):** 30

Target Application/Timeframe: Space-Based Solar Power

Applicable THAG Roadmap: