Request for Information

Research Activities in support of Space-Based Solar Power for terrestrial needs

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1 Introduction

1.1 Background Information

ESA is proceeding with the SOLARIS initiative to further investigate and mature the feasibility of Space-based Solar Power, a concept that has the potential to deliver clean energy from space to Earth in support of Europe's and the world's efforts to mitigate the climate crisis.

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, technology developments, research activities and stakeholder engagement.

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.

The Solaris Activity Plan [RD1] has been published in Dec 2022 and provides an overview of the currently proposed technical activities to be undertaken during 2023-2025. Early phase System study activities, to be funded through the Preparation Element of ESA's Basic Activities, are underway through the issue in Dec 2022 of an Invitation to Tender (ITT) of a "Pre-Phase A system study of Commercial-scale Space-based Solar Power systems for terrestrial needs". Technology activities, to be funded through the General Support Technology Programme (GSTP) Element 1, are currently in definition at ESA and invitation to tenders are expected to be issued for these beginning in Q2 2023.

The third line of technical enquiry to be pursued within SOLARIS is Research Activities which cover Environmental and Socioeconomic issues as shown in Figure 1. It is this area which is the subject of the present Request for Information.

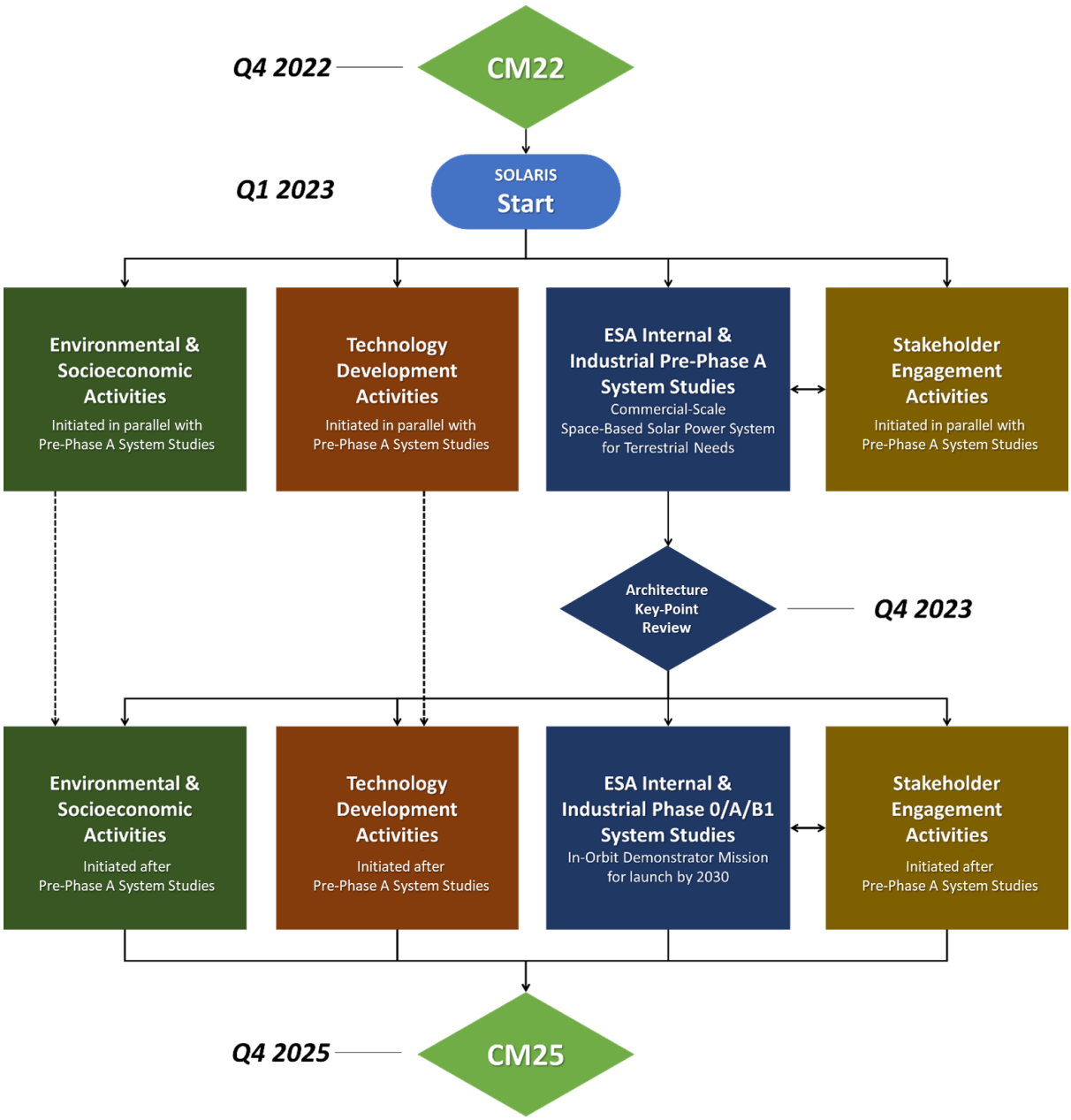

Figure 1: Overview of SOLARIS activities proposed between 2023 and 2025. For more details on the SOLARIS initiative refer to www.esa.int/solaris.

1.2 Purpose of this Request for Information

This Request for Information (RFI) is being issued to get feedback from the international scientific and industrial community on ESA's draft research plan for SOLARIS, a roadmap of which is shown in Figure 2 below, with detailed descriptions provided in Section 5 of this RFI.

The research plan has been formulated with the objective of covering, by mid-2025, the main areas of uncertainty that have been identified from previous ESA and international studies on SBSP regarding environmental and socioeconomic aspects of SBSP for terrestrial needs, in particular the use of radiofrequency power beaming within the Earth's environment. **It is the intention that, at the end of the implementation of the SOLARIS research plan in mid-2025, ESA should have sufficient information to inform any future proposal for further development of SBSP for terrestrial needs.**

Given the novelty of the topic of Space-Based Solar Power and the nature of the research-based activities that would need to be conducted to complement and support the planned ESA system and technology development activities, ESA would find it valuable to have the scientific & engineering communities' views on the completeness and effectiveness of the proposed research plan.

This RFI is specifically intended to:

1. Provide the international research community with further information on ESA's priorities with regards to SBSP research in the areas of environmental and socioeconomic effects of SBSP.

2. Solicit feedback from the international research community about the Solaris research plan, which will be considered in ESA's future planning for such activities.

This RFI does not bind ESA to any present or future procurements actions, nor does it create any rights for respondents in relation to any present or future ESA procurements.

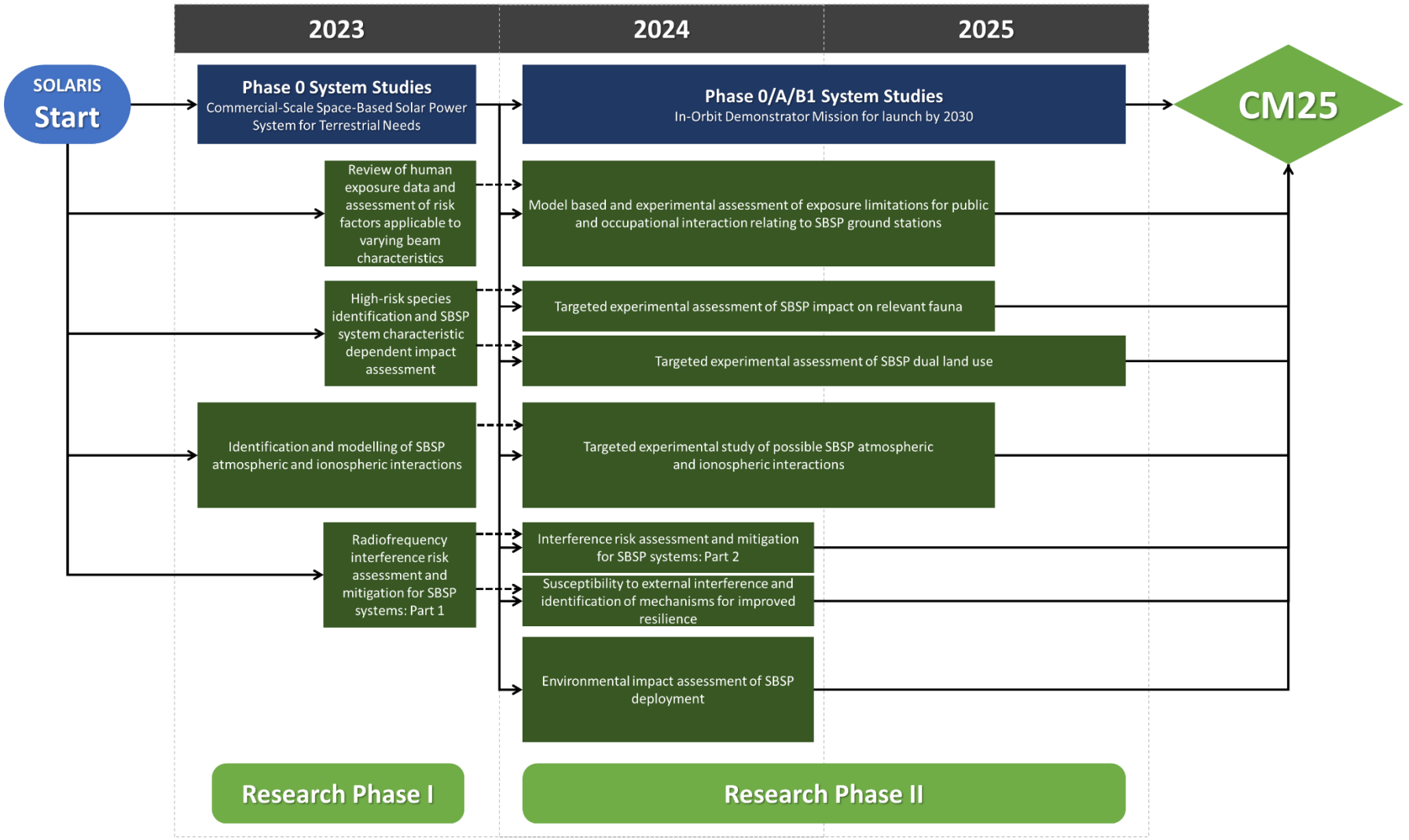

Figure 2: Draft Roadmap for Environmental, Health and Safety Research Activities

1.3 Reference Documents

[RD1] Solaris Activity Plan 2023-2025, ESA-TECSF-PL-2022-004006

[RD2] PRE-PHASE A SYSTEM STUDY OF A COMMERCIAL-SCALE SPACE-BASED SOLAR POWER SYSTEM (SBSP) FOR TERRESTRIAL NEEDS, ESA ITT 1-11606

2 Information Requested

Information is requested in response to the *Solaris Research Plan* show in Figure 2 above and described further in Section 5 of this document.

2.1 Information requested on the Research Plan

Any academic or industrial entities, internationally, with expertise in areas relevant to the proposed SOLARIS Research Activities are invited to reply to this request.

The table below should be used as a guide to prepare the response(s) to **any or all content within the Research Plan presented in Section 5**.

Responses shall be limited to a maximum of 10 pages and shall be free of any proprietary information. Responses shall be provided exclusively in electronic format through the process outlined in section 3.

Section Title	Information Requested
Scope and planning of Activities	• Feedback on the Research Activities roadmap presented in Figure 1 with a view to successfully achieving the objectives specified in Section 1.2 • Feedback on the scope of the proposed research activities, duration of the activities and proposed ESA budget allocation. • Feedback on the requested deliverable items. • Feedback on the sensitivity of the research activity to the outputs of the planned ESA SBSP Pre-Phase A System Studies [RD2].
Additional Tasks and Research Questions	• Identification and description of potentially important research tasks or topics not currently addressed within the proposed scope of research activities considering the SOLARIS objectives.
Potential Risks	Identification of potential challenges and risks with the implementation of the proposed research activities.
Responder Interest & Expertise	Identification of level of interest and expertise of the responder related to each of the research activities proposed in the research plan.
Implementation Ideas	Novel ideas to expediate the SOLARIS research plan and/or to accelerate delivery of research activity outputs.

Other Inputs	Any inputs or feedback that does not fit within the sections described above is welcome.

3 Submission and Evaluation

Please provide your response to this RFI in a single, electronically searchable PDF file based on the section titles in the table shown in **Section 2** above and submitted through ESA Interact.

Please provide your **responses by 27 February 2023, 18:00 CET** at the latest.

Please include details of a contact person, that ESA can contact for further clarification regarding the RFI response, if necessary.

ESA will use any personal data included in the RFI responses (e.g., names and contact details of the persons having prepared the response) exclusively for contacting those persons in case it became necessary in relation to their RFI submission. ESA will not disclose those personal data to third parties without prior agreement of the party that had submitted the RFI response.

Once received, ESA will review the submissions. It is the intent of the Agency to use the information contained in the responses for internal planning purposes and to update the SOLARIS Research Plan.

ESA may contact respondents to the RFI following submission, but does not intend to do so unless further clarification is required. Respondents are advised that ESA is under no obligation to acknowledge receipt of the information received or provide feedback to respondents with respect to any information submitted under this RFI.

By submitting their responses, respondents agree that ESA may use material received to inform and support its further actions concerning the development of its programmes, which may include releasing part of it in the context of exchanges between ESA and its Member States, interactions with the industrial and scientific communities and future requests for information or tender actions. ESA will not release individual RFI responses.

The submission of RFI responses does not commit ESA to placing any contract, nor prevents ESA from pursuing or employing those concepts, directly or indirectly, in any present or future ESA activities.

4 SOLARIS Research Day – March 2023

Following the close of the RFI, ESA intends to hold a half-day, online-only event, titled “Solaris Research Day”, to provide the opportunity for direct community feedback and discussion with ESA on the research activity planning. The aim of the event would be for ESA to have the opportunity to discuss some of the feedback received in the RFI with the interested communities with a view to consolidating and making the best use of the input received during the update of the Research Plan.

The Solaris Research Day event is tentatively planned for mid-March 2023. Further information and opportunity for registration will be provided in an upcoming announcement on the ESA Interacts website.

5 Description of Research Activities

Human Health

Ref. Number:	**HH-1**		**Budget (k€): 100**
Activity Title:	**Review of human exposure data and assessment of risk factors applicable to varying beam characteristics**		
Objectives:	Identify existing data pertaining to human health risks from RF exposure and assess the applicability to SBSP systems. Identify knowledge gaps that exist.		
Description:	This activity will contain the following tasks: • State of the art review on the impact of RF on short- and long-term human health within SBSP relevant boundaries (1-10 GHz) and assess the applicability of each study to exposure characteristics of a SBSP system. • Identify specific beam characteristics or exposure mechanisms that are likely to have the largest impact on human health and safety. • Produce a set of recommendations for human health protection to be considered in the SBSP system design phase. • Identify knowledge gaps that exist that pertain specifically to SBSP systems.		
Deliverables:	Mid-study report – State of the art review of potential human health impacts and beam characteristic recommendations Final report		
Current TRL:	N/A	**Target TRL:** N/A	**Duration (Months):** 6

Ref. Number:	**HH-2**	**Budget (k€): 500**
Activity Title:	**Model based and experimental assessment of exposure limitations for public and occupational interaction relating to SBSP ground stations**	
Objectives:	Assess and quantify the risk to public health and safety that SBSP may pose and examine the suitability of proposed safety mechanisms for preventing any negative impact on human health.	
Description:	This activity will contain the following tasks: • Assess all possible routes by which humans could be exposed to electromagnetic radiation (EMR) originating from long-range wireless power transfer from space, based on selected SBSP architectures (Phase 0 system studies). Model the exposure characteristics for each scenario. • Apply a representative human model to characterize the physical and biological effects that a given SBSP architecture may have resulting from public or occupational EMR exposure (at relevant wavelengths). • Determine the applicability of the above model to at risk population (e.g., young children, those with medical devices, etc.) and identify any factors that may increase risk relative to artificial EMR exposure (at relevant wavelengths) from other sources. • Devise and implement a set of targeted experimental studies that would address knowledge gaps relating to existing models and their applicability to SBSP; these experiments may make use of artificial tissue emulating materials where appropriate.	

	• Using the above data determine whether the proposed safety mechanisms, such as exclusion zones, are sufficient to ensure human safety. • Quantify the risk that the proposed architectures would lead to EMR exposure greater than the safe limits identified by experts in the field and international regulations for a given wavelength range. • Propose any additional factors that would lower risk to human safety, such as alteration of beam characteristics, redefined exclusion zones, or passive or active shielding.		
Deliverables:	Technical notes – model-based results and proposed experimental plan Model of exposure characteristics and human biological response Final report		
Current TRL:	N/A	**Target TRL:** N/A	**Duration (Months):** 18

Impact on ecosystem

Ref. Number:	**ECO-1**	**Budget (k€): 150**
Activity Title:	**High-risk species identification and SBSP system characteristic dependent impact assessment**	
Objectives:	Identify the species in Europe that would most likely be impacted by interactions with SBSP and examine the variability of the predicted impact on species across a range of beam characteristics relevant to SBSP	
Description:	The majority of SBSP architectures conduct wireless power transfer using microwave beams with wavelengths in the radiofrequency (RF) range of the electromagnetic spectrum. The primary mechanism for the absorption of RF energy by biological material is tissue heating, as RF is too low energy for cellular stimulation (i.e., it is non-ionising radiation). This can cause tissue damage or unwanted thermal responses, particularly in species without thermoregulation ability. Additionally, non-thermal effects on biological processes and behaviour resulting from non-ionising radiation have also been reported. Multiple factors impact the way in which biological material interacts with RF, such as the characteristics of the RF (i.e., the frequency and intensity), the duration of exposure, the size and behaviour of the species in question, or the susceptibility of a specific material or biological response to be impacted by RF. This activity will contain the following tasks: • State of the art review on the impact of anthropogenic radiofrequency electromagnetic fields on animals and plant and assess the limits of the applicability of existing literature to high-power, localised beams originating from a space-based solar power satellite and culminating at a ground power station. • Based on the existing literature and within SBSP relevant boundaries (1-10 GHz), identify specific beam and rectenna characteristics or limits that are more/less likely to produce negative responses in the natural ecosystem. • Conduct a systematic review of existing data to identify species of interest that may be negatively impacted by deployment of SBSP in Europe, i.e., identify species or attributes that would be most sensitive to	

	RF exposure in combination with identifying the species that would be most likely to encounter a SBSP beam. This task is only applicable to natural ecosystems and should include definition of the upper and lower bounds of realistic interaction characteristics for a given sub-set of the ecosystem (e.g., the power density encountered may be different for land-based species to high-altitude migratory birds, residence time may vary with different exposure conditions, etc.). • Identify knowledge gaps relevant to the interaction of SBSP with the natural ecosystem and define a set of experimental tasks that could address those knowledge gaps.		
Deliverables:	Mid-study report – State of the art review literature review of biological responses and beam characteristic recommendations Final report		
Current TRL:	N/A	**Target TRL:** N/A	**Duration (Months):** 6

Ref. Number:	**ECO-2**	**Budget (k€): 400**
Activity Title:	**Targeted experimental assessment of SBSP impact on relevant fauna**	
Objectives:	Quantification of the impact that the deployment of commercial-scale Space Based Solar Power in Europe would have on fauna using specific system architectures as reference cases.	
Description:	Space based solar power (SBSP) will involve the transfer of significant quantities of power from space to Earth and will interact with multiple subsets of the ecosystem; the specific interactions will be dependent on the SBSP architecture characteristics and on the local ecosystem. The SOLARIS Phase 0 system studies will identify two to four SBSP architectures that will be used as input for this study. There are currently no recognised guidelines for exposure limits to specifically protect fauna (i.e., all land animals, aquatic life, birds, and insects) from electromagnetic fields. Therefore, a detailed assessment must be made to identify the safe limitations and ensure that the deployment of SBSP will not have a significant negative impact on the ecosystem. Using the SBSP architectures identified in the SOLARIS Phase 0 system studies as reference cases, this activity will include: • Identify the specific local fauna that will likely encounter each SBSP system and consolidate of the bounds of likely interaction (intensity, duration etc.) • Identify knowledge gaps relating the impact that a given system will have on the identified species • Propose and implement a set of experimental tests that aim to fill the identified knowledge gaps relating to specific species or attributes. • Quantify the likely impact each SBSP architecture would have on the natural ecosystem. • Compare the predicted impacts with other energy generation infrastructure. • Propose specific SBSP system characteristics or additional measures that may mitigate or reduce any identified impact on fauna. Parallel studies intended	
Deliverables:	Experimental test report Final report	

Current TRL:	N/A	**Target TRL:** N/A	**Duration (Months):** 18

Ref. Number:	**ECO-3**		**Budget (k€): 300**
Activity Title:	**Targeted experimental assessment of SBSP dual land use**		
Objectives:	Determine if the dual use of land under and/or around SBSP ground stations is viable.		
Description:	The utilisation of the land under or around SBSP ground stations would reduce the land use burden. Possible dual uses include (but are not limited to) agriculture or solar panel installation. The safety and functionality of a given application, when carried out in combination with the environmental conditions at a ground station imposed by a SBSP beam, must be assessed. This activity will consist of the following tasks: • Based on the SBSP concepts proposed in the Phase 0 system studies, model the location dependent environmental characteristics in and around the beam ground station. • Assess existing literature on the susceptibility of agricultural species to exposure to relevant electromagnetic radiation and suggest between three and five species for targeted experimental examination. • Assess other non-agricultural dual uses for ground station land, including but not limited to solar panel installation. • Carry out a series of experiments to determine whether dual land use is viable, and if so, what the limitations are to that dual use. These tests shall be run for a period of time that is deemed to be relevant to extrapolation to long term operations. • Propose the most beneficial application or combination of applications for each SBSP concept, depending on the varying ground station characteristics. Compare expected land use burden across systems.		
Deliverables:	Technical notes – literature assessment and proposed experimental plan, mid test report Final report		
Current TRL:	N/A	**Target TRL:** N/A	**Duration (Months):** 24

Ionosphere and Atmosphere

Ref. Number:	**ATM-1**		**Budget (k€): 200**
Activity Title:	**Identification and modelling of SBSP atmospheric and ionospheric interactions**		
Objectives:	Carry out a programme of directed study to identify, understand and elaborate on possible SBSP power beam interactions with the atmosphere and ionosphere.		
Description:	In the studies that have been carried out relating to ionospheric and atmospheric interactions, a number of potential effects have been proposed as relevant to the technical challenge of atmospheric power beaming:		

	• Ohmic Heating, whereby MW absorption in the atmosphere causes an increase in the electron density and electron-neutral species collision distribution. Depending on the MW frequency used for power beaming, the local temperature could rise notably with cascading effects, e.g., it was reported [1] that for 3 GHz waves at 16 mW/cm2 the electron temperature could rise from 200K in the E region of the ionosphere to about 1000K – this would promote local O2 and NO2 recombination, and alter the local electron density (i.e., the local plasma state and related chemical processes, potentially deleteriously so). • Self-Focusing Effects, where small density fluctuations as a function of the MW energy give rise to local spatial changes in the refractive index and a defocusing of the MW. Such effects are known and have been studied for high-frequency heating experiments, but it is unclear how important this would be over the large distances in atmosphere the MW would traverse and the general behaviour of this phenomena in terms of the atmospheric plasma. • Multi-wave interactions, where high power MW induced plasma effects can lead to resonant phenomena, e.g., Raman and Brillouin scattering, ultimately leading to loss of energy into the atmosphere in unknown ways. • Local weather impacts, rain, hail and thunderstorms leading to near surface scattering of the MW and also uncontrolled attenuation and waveguiding (e.g., lightning strikes). In this study, the following tasks should be addressed: • State of the art report on the current understanding of MW/atmospheric interactions as it pertains to SBSP and varying beam parameters. • Ab-initio modelling of such effects as they relate to energy power beaming from SBSP elements to address knowledge gaps. • Assess the impact of abnormal atmospheric conditions (e.g., weather events, electrical storms, solar/magnetic storms, atmospheric pollutants) on the predicted beam interactions. • Derivation of technical considerations for SBSP architecture (e.g., proposed frequencies to examine with minimum atmospheric impact based on best known science). Development of a roadmap for further research and elaboration around the topic of SBSP atmospheric interactions, including possible empirical experiments or demonstrations.		
Deliverables:	Final report		
Current TRL:	N/A	**Target TRL:** N/A	**Duration (Months):** 12

Ref. Number:	**ATM-2**	**Budget (k€):400**
Activity Title:	**Targeted experimental study of possible SBSP atmospheric and ionospheric interactions**	
Objectives:	Derivation and implementation of targeted experimental tests to support model development of atmospheric and ionospheric interactions	
Description:	Interaction of wireless power transfer with the various layers of the atmosphere, including the ionosphere, are anticipated and need to be	

	understood. The magnitude and potential impact of such interactions must be quantified to assess the safety of a SBSP system. Models developed to predict beam interactions with the atmosphere and ionosphere will require validation and improvement with empirical studies. Experimental studies on such interactions may include weather balloons, sounding rockets, or ground-based chamber facilities and may examine one or multiple interactions at once. Parallel studies shall allow for a range of experimental techniques to be employed. Input studies: • Identification and modelling of SBSP atmospheric and ionospheric interactions • Phase 0 parallel SBSP system studies • PROTEIN: Preliminary Elements on European Reusable and Cost-Effective Heavy Lift Transportation This activity shall address the following: • Using the developed model as a baseline for the possible interactions of interest, derive a set of empirical tests that will help to validate and further develop the models predicting beam interactions. • Using the beam characteristics identified in the Phase 0 system study, carry out targeted experimental work and input the findings into the existing model. • Consider the impact of abnormal atmospheric conditions (e.g., weather events, electrical storms, magnetic storms, atmospheric pollution) on beam interactions and account for these where necessary in experimental study. Particular attention shall be given to atmospheric pollution that may arise from the launch cadence that would support SBSP deployment. • Identify and quantify the likely impact of beam-atmosphere/ionosphere interactions. Parallel studies intended		
Deliverables:	Technical notes – experimental development, implementation plan Updated model of beam interactions Final report		
Current TRL:	N/A	**Target TRL:** N/A	**Duration (Months):** 18

Infrastructure and Interference

Ref. Number:	**INF-1**	**Budget (k€):100**
Activity Title:	**Radiofrequency interference risk assessment and mitigation for SBSP systems: Part 1**	
Objectives:	Identify the most high-risk technology (in space and on ground) that may be impacted by SBSP and recommend system characteristics that may avoid or mitigate the risk.	
Description:	Considering the range identified as most likely for SBSP systems (1 – 10 GHz), the following tasks shall be completed:	

	• Identify the technology or applications that would be at risk of interference from a SBSP system and define assumptions and boundary conditions relevant to potential interference for each case. • Assess the impact that variation in SBSP RF parameters would have on the likelihood and severity of interference with other technology • Define a risk matrix for the result of SBSP interference with other technology (likelihood and severity), considering possible variations in system architectures (e.g., number, orbit, characteristics of SBSP satellites) • Propose solutions to minimise the risk of impact on other technology		
Deliverables:	Technical notes – preliminary risk assessment and system recommendations Final report		
Current TRL:	N/A	**Target TRL:** N/A	**Duration (Months):** 6

Ref. Number:	**INF-2**	**Budget (k€):300**
Activity Title:	**Radiofrequency (or other frequency) interference risk assessment and mitigation for SBSP systems: Part 2**	
Objectives:	Identify the most high-risk technology (in space and on ground) that may be impacted by the proposed SBSP architectures and recommend system adaptations or strategies that may avoid or mitigate the risk.	
Description:	This activity will include the following teaks: • Using the SBSP system concepts identified in Phase 0 system studies, identify existing technology or applications that would be at risk from interference caused by the operation of each SBSP system, and define assumptions and boundary conditions relevant to potential interference for each case. • Define a risk matrix for the result of SBSP interference with other technology (likelihood and severity). • With particular focus on the applications identified as high-risk, estimate the expected interference conditions, and predict the impact on performance. • Propose risk mitigation strategies. Carry out tests to validate predictions and proposed mitigation techniques.	
Deliverables:	Technical notes – experimental development, implementation plan, interference prediction data Final report	

Ref. Number:	**INF-3**	**Budget (k€):200**
Activity Title:	**Susceptibility of SBSP systems to external interference and identification of mechanisms for improved resilience**	
Objectives:	Examine whether SBSP systems will be susceptible to external interference, quantify the risk posed to the system, and propose mitigation strategies.	
Description:	This activity will include the following teaks:	

	• Define scenarios and associated assumptions/conditions that may lead to interference from an intentional, unintentional, or natural source. • Define the interference characteristics for each scenario. • Predict the impact of the identified interference on the SBSP reference architectures performance and functionality. • Propose and validate mitigation strategies.		
Deliverables:	Technical notes – risk assessment, test plan Final report		
Current TRL:	N/A	**Target TRL:** N/A	**Duration (Months):** 12

Deployment and Environment

Ref. Number:	**ENV-1**	**Budget (k€):300**
Activity Title:	**Environmental impact assessment of SBSP deployment**	
Objectives:	Assess the environmental impact of deployment of SBSP across all phases of deployment lifecycle and assess the environmental impact in comparison to other energy sources.	
Description:	Assessment of the environmental impact of system concepts at an early stage in the development process (i.e., Phase 0) is challenging and cannot be based solely on existing frameworks developed for environmental assessment at later developmental stages. In the frame of SBSP, where two to four system architectures will be proposed in parallel Phase 0 system studies, simultaneous assessment of the environmental impact of these concepts by a single independent entity is valuable to ensure that the assumptions, methodology, and results are comparable. This activity will contain the following tasks: • Conduct an LCA for each proposed SBSP system architecture and output environmental impact values across a range of metrics by project implementation phase. • Identify key environmental design drivers in each design at system, sub-system, and unit level. Identify where certain assumptions define these design drivers. • Identify and rank the most critical architecture agnostic environmental hotspots that will likely be relevant to a range of SBSP system architectures. • Propose specific solutions and/or research that could improve the environmental impact of each system, without shifting burdens between locations, ecosystems, of deployment phases. • Propose and implement a methodology to predict how the LCA inputs and assumptions may change over the SBSP deployment timescale and also considering the impact of full-scale SBSP deployment (e.g., the impact the system itself may have on resource availability or technology development). This assessment should include predicted future developments in relation to all life cycle steps.	

	• Compare the environmental impact of SBSP deployment with known terrestrial energy systems (using both current LCA inputs and the application of the above proposed predictive inputs for comparison) and quantify the environmental impact that may be displaced by the deployment of SBSP. Parallel studies intended.		
Deliverables:	Technical notes Final report		
Current TRL:	N/A	**Target TRL:** N/A	**Duration (Months):** 12