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META-LUNA: Disruptive ISRU for Building Future Solar Power Satellites

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Abstract

In situ utilisation (ISRU) of space resources is increasingly becoming a central consideration for long-duration space missions. The efficient and sustainable use of these resources must play a prominent role in our discussion of space exploration and development. Regolith represents the most accessible and utilisable resource on the Lunar, Martian and Asteroidal surfaces. Regolith is an abundant and diverse resource, and multiple use cases have been proposed from water or oxygen generation to its use in structural materials. In response to this opportunity, Metasat presents a novel approach to development of power sources needed to employ Regolith by designing and building solar power satellites (SPS) utilizing these resources for construction based on the Multi-domain Operations using Rapidly-responsive PHased Energy Universally Synchronized (MORPHEUS) Solar Power Satellite architecture, a Sandwich Type SPS solution providing an alternative energy source for sustainable energy. The proposed solution leverages advancements in photovoltaic and wireless power transmission technologies, enabling the collection of solar energy in the sunlit regions of space without the constraints of atmospheric interference or nighttime limitations, to deliver clean, abundant, affordable and secure energy. Combined with the use of regolith a sustainable approach to space- based energy harvesting is provided, addressing the needs of in-space manufacturing, with the aim of continually reducing the reliance on Earth-launched resources, decrease launch costs, and minimizing the environmental impact associated with traditional space missions. This paper will update paths forward for the MORPHEUS SPS architecture and introduces leveraging ISRU for building future solar power satellites.

Keywords: Solar Power Satellite, Space-Based Solar Power, Life Cycle Assessment, Circular Economy, In-Situ Space Utilization

Acronyms/Abbreviations

AI	Artificial Intelligence
CONOPS	Concept of Operations
DOE	Department of Energy
GEO	Geosynchronous Earth Orbit
LCA	Life Cycle Assessment
LEO	Low Earth Orbit
MCDA	Multi-Criteria Decision Analysis
MIT	Massachusetts Institute of Technology
NASA	National Aeronautics & Space Administration
SBSP	Space-Based Solar Power
SDGs	Sustainable Development Goals
SPS	Solar Power Satellite
SSSD	Strathclyde Space Systems Database
UNFCCC	United Nations Framework Convention on Climate Change

1. INTRODUCTION

The global energy demand is rapidly increasing due to population growth, industrialization of developing nations, and rising living standards. Simultaneously, may counties are looking to phase out fossil fuels by the end of the upcoming decades. Additionally, with traditional renewable energy sources on Earth remaining limited by factors such as geographic availability and intermittency, new sources of clean energy generation for baseload capacity are needed. Space-based solar power (SBSP) offers a promising solution to the pressing global challenges, particularly in the context of sustainability, energy demand, and can serve as a key enabler to decarbonizing the energy sector in the coming decades. SBSP offers an abundant, continuous, and clean source of energy, one that is free from the constraints of weather conditions or the day-night cycle. SBSP has the potential to significantly reduce global carbon emissions, providing an environmentally sustainable energy source to provide baseload power.

These capabilities align with the ongoing efforts to combat climate change by reducing reliance on carbon-intensive energy sources, mitigate the concentrations of atmospheric greenhouse gases, reduce elevating average global temperatures, to meet the current climate goals such as Paris Agreement, adopted under the United Nations Framework Convention on Climate Change (UNFCCC) [1], and accelerate the transition towards Net-Zero by 2050.

1.1 Solar Power Satellites

SBSP harvests sunlight, via orbiting power plants in space, continuously capture solar energy, convert it to microwaves and are then transmitted wirelessly to ground-based receiving stations, made of arrays of rectifying antennas or rectennas. These rectennas are connected into the electrical grids that run to our homes, offices, and factories, meeting our daily power needs on Earth. [2]. These solar power satellites (SPS) can continuously provide power by taking advantage of the availability of sunlight in space virtually 24 hours a day, 7 days a week. SBSP is highly compatible with grid integration and offers a scalable, safe, resilient, and secure energy source.

1.2. MORPHEUS Solar Power Satellite Architecture

Metasat presents a novel approach for designing and building solar power satellites using sustainability principles to achieve greater resilience, reduce environmental impact and increase economic value. The Multi-domain Operations using Rapidly-Responsive Phased Energy Universally Synchronized (MORPHEUS) SPS is a Sandwich-type Solar Power Satellite (see Figure 1), providing an alternative energy source for limitless clean, secure, and sustainable energy [2].

MOPHEUS is the first SPS Architecture that is designed using sustainability principles, optimized using Life Cycle Assessment (LCA) and eco-design methods to optimize the environmental footprint. LCA is a systematic method used to evaluate environmental impacts across the life cycle of the system from design through to end-of-life management. Eco-design is an approach used to design products with the goal of reducing the environmental impacts throughout the entire life cycle, while maintaining or improving the products functionality, quality and economic viability. To do this, LCA and eco-design can be integrated as part of the space mission design process, as a mission driver. This offers substantial advantages in the design of MORPHEUS, allowing for environmental impacts of the SPS to monitored continuously and systematically reduced, enabling stakeholders and key decision-makers to gain an in depth understanding on where the hotspots are in the life cycle, and mostly importantly provides an opportunity to address them before finalizing the design.

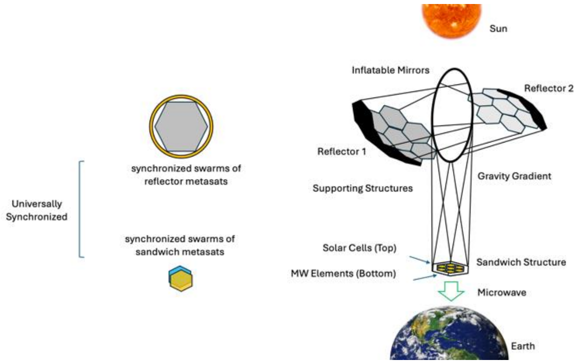

Figure 1: MORPHEUS Solar Power Satellite – A Sandwich Type SPS

1.3 Manufacturing in Space and Solar Power Satellites

To further minimize the environmental footprint, we investigate the use of space resources, with the goals of moving the majority of the manufacturing of the SPS to space.

The concept of utilizing space resources to build SPS was first proposed by Dr. Gerard O’Neill. In 1975, O’Neill proposed the construction SPS using Lunar materials and then transporting them to Earth orbit, reducing the impact of transportation costs from the Earth [3]. The raw materials from the Moon would be launched via electromagnetic launchers or mass drivers to a space manufacturing facility. This project envisioned the creation of large colonies or communities at gravitationally stable points in the Earth-Moon system (at the Earth-Moon L4 or L5 libration points) to provide labour for building further such structures and SPS on an ongoing economically driven basis. In 1980, with rising launch costs of NASA’s space shuttle program, O’Neill et. al explored other options to minimize research and development, costs and developmental risks. They explore three potential scenarios to begin operations Case 1) Partially self-replication system, with industrial operations only on the lunar surface Case 2) Totally automated lunar-based system Case 3) Partially self-replication system on Moon and in orbit; Equipment on Moon used for replication of mass-drivers; Equipment in space used for replication of wide range of components. They concluded Case 3 offered the best option [5]. Lunar manufacturing of SPS would require building a base on the Moon and mass drivers to send material to a Space Manufacturing Facility. Further studies were conducted into self-replication growing lunar factories in the subsequent years [6,7].

The recent developments of manufacturing, artificial intelligence and machine learning, autonomous drone and robotic technologies for self-replicating construction has considerably updated the need for this model whereas the need for sustainable energy has increased rapidly, shifting the focus.

2. STATE OF THE ART

2.1 Lunar SPS Concepts

Several Solar Power Satellite concepts have been proposed offering a different approach to utilizing the Moon to implement space-based solar power. They can be separated into two category types – the first type transforms the Moon into a power generation and distribution station, where solar collectors are placed on the Lunar surface, solar energy is converted to microwave or laser energy and transmitted to receiving stations on Earth, the second type utilizes the resources of the Moon to build solar power satellites.

The first type, Lunar Power System was described by Mueller in 1984 [8] and developed in detail by Waldon and Criswell in 1985 [9]. Further development on this concept lead to the use of orbital reflectors/retransmitters, to send low intensity microwave power to rectennas on Earth, Criswell has further expanded on this concept as described in several subsequent publications [10,11,12]. The Lunar Power Station would consist of lunar power bases on the Eastern and Western edges of the Moon as viewed from the Earth, delivering 20 terrawatts of received power. In 2009, the Shimizu Corporation proposed the “Luna Ring,” consisting of developing a 400 km wide ring of photovoltaics around the lunar equator to continuously transmit microwave and laser power to receivers on Earth, the system would be capable of transmitting 13,000 terawatts [13].

The second type are Lunar-based SPS are architectures that use in situ resource utilization and the Moon to reduce the amount of materials launched from the Earth. NASA supported several studies to leverage the Moon to build SPS, in 1979, General Dynamics and MIT completed analysis of scenarios of utilizing the Moon to build the NASA/DOE reference design. General Dynamics concluded that 90% of the mass of the SPS could be build using lunar material [14], and MIT concluded that 96% of the SPS mass could come from the Moon [15]. In 1985, commissioned by the Space Studies Institute, the Space Research Associates designed a solar power satellite that optimized the use of lunar material, and with over 99% of materials used in construction of the SPS being from lunar materials[16].

In 2015, Schubert et. al. introduced, the Tin-Can SPS, an open cylinderical shell approximately 6.4 kilometers in both diameter and height, with the wireless power transmission module 1 km in diameter, the architecture components would be sourced from the Earth and the Moon [17]. Additionally, the design assumed an existing cislunar infrastructure to move materials electromagnetically, and a large-scale manufacturing capability which operated robotically, powered by sunlight that can provide: solar panels made of single crystal are single crystal silicon with a silicon dioxide protective and anti-reflective layer; iron for the shell surface, which are fabricated in orbit from the spherical payload canisters carrying the lunar sourced PV, they are extruded from a solar-powered smelter, T-shaped beams are formed, cut to length and welded together, iron would also be used for the fasteners that linked the framed to house the PV, manufactured by extrusion in zero-gravity; and aluminum sourced from the Moon used for making electrical connections with the frames, slotted waveguides, and aluminum wire for transport of DC power to the central spite. Electrical components too complex for the factory to manufacture would be sourced from Earth (e.g. amplifiers, polymer wires, transformer-converter units).

In 2016, Lewis-Weber, proposed the development of a Lunar-Based Self-Replicating Solar Factory using the SPS Alpha architecture, where the space solar power components would be manufacturing on the Moon and then launched using mass drivers, the space solar power components would self-assemble in geosynchronous orbit (GEO) and wirelessly transmit microwave energy to receivers on the Earth [18].

In 2022, Ellery explored the notion of constructing SPS from lunar resources, and identified that two core components would be essential to SPS, the magnetron and the rotary joint which may be applicable to several SPS concepts [19]. The magnetron may be constructed from lunar resources using a CaO-coated tungsten cathode, Ni control grid and anode, fused silica glass tube with elements of the electric motor. The rotary joint may be constructed using AlNiCo alloy, ferrites, and kovar wiring respectively which can be sourced from lunar material. Applicable SPS concepts may include NASA Suntower SPS, European Space Agency Sail Tower SPS Concept, Multi-Rotary Joints Solar Power Satellite from Chinese Academy of Space Technology, Korea Aerospace Research Institute’s Korea Space Solar Power Satellite, and Thales Alenia Solar Array Matrix SPS Concept.

In 2023, Switzerland’s Astrostrom, proposed the Greater Earth Lunar Power Station concept which includes a habitable solar power satellite orbiting the Moon, a rectenna station on the lunar surface, surface mining, processing, and manufacturing, and a lunar surface-to-Earth Moon Lagrange point 1 transportation system (lunar space elevator). Raw materials (e.g. aluminum, oxygen, silica, and various other metal silicates, glasses and basalts, geopolymers (lunar polymers) components from lunar regolith would be processed into PV and structural elements, transported to orbit and assembled robotically in a Lunar halo orbit at the Earth-Moon Lagrange point 1 (EM-L1). At EM-L1, all of the manufactured components from the Lunar Surface would be assembled. The solar panels are based on iron pyrite monograin solar cells produced on the Moon, structural elements made from basalt fibres, rectennas on the Moon will be constructed using basalt and aluminum via robotic 3D printing manufacturing processes. Complex items such as microwave generators and amplifiers, and control computers that cannot be manufactured on the Moon will be shipped from Earth to a cargo hub at EM-L1 and integrated into the assembly process, additionally it is envisioned that fuel from the Earth may be transport to the Moon to support initial Lunar Surface to Orbit operations, a cargo shuttle to transport materials between Earth and the Moon, towards the implementation of a Lunar Space Elevator [20].

2.2 LCA applied to Lunar SPS Concepts

To date, only a handful of LCA studies have been conducted on SBSP concepts. Wilson et al. (2024) [21] provided the most up-to-date literature review into such studies, expanding on a review initially conducted by Wilson et al. (2020) [22] and followed up by Oqab, et al. (2023). Wilson, et al. (2024) identified a total of eight LCA studies on SBSP which have taken place (including the case study of that paper). However, none of these studies have specifically addressed the environmental impacts of lunar-based SPS concepts.

Despite this, from these known studies, of relevance to this paper is the study of Oqab, et al. (2023) [3], which publicly introduced the MORPHEUS SPS concept for the first time. Given the evolution of this concept towards lunar-based applications (outlined further in Section 3), its environmental impact becomes relevant here. In this regard, Oqab, et al. (2023) [3] revealed that process-based LCAs had been run at the end of each design iteration using the Strathclyde Space Systems Database (SSSD). The SSSD is a space-specific LCA tool which was developed at the University of Strathclyde and is now maintained by Metasat. The tool was used to determine the environmental footprint of the system and guide the next design iteration in an effort to both improve the system and reduce adverse impacts as far as practically possible without compromising technical aspects. Based on this approach, it was revealed that when the system is fully deployed, it is capable of producing a carbon footprint of just 6.42 gCO_2e/kWh – the lowest reported GHG footprint of an SPS concept to date (although the reported carbon footprints of all these studies are not directly comparable). From the latest analysis, climate change is relatively insignificant compared to ozone depletion or water use. In terms of ozone depletion, >99% of the impact comes from the launch event due to the release of aluminium oxide, black carbon and radical emissions. For water use, 62.25% of the impact from production of the rectennas and a further 16.77% from the production of the SPS units during the production & manufacturing of the aluminium and electronic components. This is primarily due the large volume of distilled water which is used to spin turbines to produce electricity, and the amount of water used in cooling loops for the steam exiting the turbines. Regardless, the concept has been updated since to improve on this score.

Although the conventional MORPHEUS concept for delivery of power to Earth (META-PRIME) provides promising results, due to the difference in application, there is a distinct need to recalculate the environmental impacts of the new META-LUNA concept to ensure that the technology is in-line with ongoing environmental footprint reduction efforts.

3. META-LUNA CONCEPT

3.1 Benefit of Lunar Manufacturing

Building solar power satellites using the Moon offers benefits for Earth and the future of space exploration. Some of the potential benefits associated with utilizing Lunar resources include: (1) Lower energy requirements for delivery of materials from the Moon to GEO than Earth to GEO, resulting in reduced number of launches which in turn translates to major reductions in the emission and environmental impacts of launches and reducing transportation costs; (2) Increases in the efficiency of deploying SPS; (3) Establish a new supply chain for building SPS and reducing the depletion of resource of Earth; (4) The Moon's unique environment, with no atmosphere, water, or weather disturbances, allows equipment and infrastructure to have a much longer operational life, free from the corrosion and wear experienced on Earth, this translates into lower maintenance costs and more durable technologies; (5) In addition, operating on the Moon presents reduced risks from major environmental catastrophes, such as earthquakes, floods, or other natural disasters, which could disrupt Earth-based manufacturing and supply chains. By shifting manufacturing of SPS to space, the risks associated with terrestrial disasters are avoided, ensuring a more stable and secure production process.

3.2 Meta-Luna Overview – CONOPS

To further reduce the environmental footprint of the SPS on Earth, we propose the utilization of the resources on the Moon. The META-LUNA concept aims to create a Self-Replicating Modular Lunar Factory capable of autonomously producing Space Solar Power components, while also creating developing its own modules to expand manufacturing capacity overtime, sustaining itself using lunar resources. It is envisioned that materials from the Earth are transported to the Moon to set up the initial components of the Lunar Factory. The Lunar Factory is envisioned to grow overtime by using not only the materials from the Moon, but also including recycling space solar power satellite, space debris, space systems at the end of life in space such as satellites and lunar infrastructure, and other space resources like solar wind, materials from Mars and asteroids. Figure 2 provides an updated concept of operations for the MORPHEUS SPS architecture.

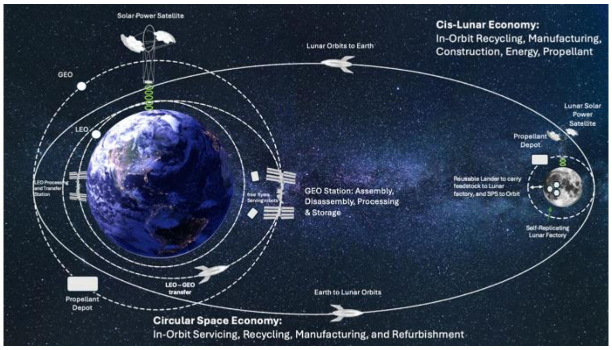

Figure 2: The MORPHEUS SPS Architecture Concept of Operations

3.2 Common Architecture Elements

The META-LUNA Concept consists of a Self-Replicating Modular Lunar Factory for manufacturing and recycling of space systems, and Transportation Network and autonomous robotics for logistics and construction of SPS. The Lunar factory is designed as a modular system, where each module performs a specific function. The factory is envisioned to be self-replicating, where an initial set of modules are launched from Earth to serve as a seed to kick start manufacturing and production. As the need to produce more SPS or other products increase, the factory can produce more modules and scale and expand its production capabilities over time to meet demand. The factory output can match the implementation and decommissioning plans of SPS architectures. The modular design would also ensure that parts and machinery can be replaced or upgraded, the interchangeable parts also allow for easy repair and maintenance, to reduce down time for continuous operations. The concept involves integrating various technologies such as autonomous robotics, artificial intelligence (AI), materials extraction, processing, and additive manufacturing (3D printing) for fabrication of SPS, and to make the factory capable of replicating all the necessary components and machines to reproduce itself. Powered by sustainable energy sources like electricity generated by solar power satellites in Lunar orbit and solar power, the factory would extract raw materials from the Moon, manufacture its own parts, and assemble new factory modules. The Lunar factory fully automated construction of solar power satellites (SPS), leveraging robotics and advanced manufacturing techniques to build and assemble complex structures without human intervention. It is envisioned that the Lunar factory would have increasing levels of autonomy, with the goal of reducing human involvement to remote monitoring, with the factory capable of managing most or all operations independently. The system would also develop magnetic and other protection for the factories from the harsh environment, paving the way for future human integration. The factory would incorporate AI driven processes with learning capabilities. A digital twin of the factory will be created to enable operations are continuously managed, with logistics and maintenance schedules adhered to optimize operation and maximize production, additionally new operational processes can be simulated in a virtual environment to ensure continuous performance. This virtual environment can also serve as a testing ground for new algorithms for expanding processing, manufacturing, and recycling operations.

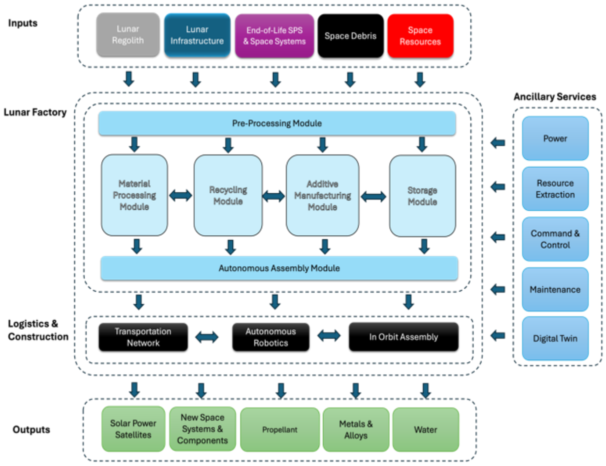

Figure 3: Conceptual Design for Meta-Luna

Figure 3 provides an overview of the common architecture elements for the META-LUNA concept, it also includes the components required for a self-replicated factory.

3.2.1 Inputs

Feedstock for the factory will include Lunar regolith, solar power satellites or space system components at the end of life, space debris captured and transported to a processing site, lunar infrastructure, other space resources (e.g. Mars or Asteroidal materials) and waste products from the increasing human activity on the Moon.

3.2.2 Pre-processing module

The pre-processing module would sort input feedstock. This involves classifying materials by size, density, and composition (for example separating metals, metal oxides, silicates, and volatiles). Automated ai-driven sensor-based sorting systems would identify different material types for optimized processing methods. Before refining, large materials of lunar regolith would need to be broken down into smaller, manageable sizes. The pre-processing module would include systems to crush and grind these materials into fine particles or powders. The separator sub-modules would include: 1) magnetic separators to pull out valuable ferrous materials for further refinement. 2) electrostatic separators could be used to further separate materials based on their charge properties. Additionally, subsystems using electromagnetic radiation for dewatering and drying may be implemented to remove excess water from feedstock, especially from lunar regolith.

3.2.3 Material Processing Module

Materials from the pre-processing module undergo transformations using in-situ resources processing methodologies such as: carbo-thermal methods, molten-regolith electrolysis, FFC Cambridge Method, Vapor Phase Pyrolysis, Water Electrolysis [23], Solar Smelting [32] to create high-purity metals, ceramics, oxygen, ceramic, glass, semiconductors, polymers, alloys or maintaining and replicating the Lunar Factory itself.

3.2.4 Additive Manufacturing Module

This module is responsible for fabricating a wide variety of parts, tools, and structures directly from raw materials. Regolith-based additive manufacturing or 3D printing can be used to produce structures and machinery parts. Sintering of regolith using induction systems, where the material is heated to bond without fully melting, can be utilized to build durable components like the factory walls, structural components, equipment housings. Manufacturing of a range of equipment, satellite components, propulsion systems can be developed using lunar-derived metals (e.g., silicon, aluminum, iron, calcium, magnesium and titanium) and metal-oxides (SO_2, Al_2SO_2, TiO_2, MgO, CaO, FeO, Na_2O, K_2O, P_2O_2, Cr2O3, MnO). 3D Printing technologies can be used for on-demand manufacturing of robotic systems, satellite components, factory parts and tools could be derived directly from metal powders extracted from lunar soil, or metals created via processing of feedstock. Using advanced 3D printing techniques (e.g. microwave sintering, laser sintering and electron beam melting etc.), would produce the key components necessary to construct SPS. The sandwich structure, with one side solar cells, made of silicone, and the other side made of microwave elements would be printed using thin-film materials or composites derived from lunar resources. Aluminum would be used for the supporting structures as well as the reflectors. Initially, complex items such as elements for the phased array transceivers, electronics, amplifiers, and computer systems that cannot be manufactured on the Moon will be shipped from Earth, but over time these materials will built using lunar regolith and recycled materials from other space systems that are processed by the Lunar factory.

3.2.5 Recycling Module

This module is designed to process and repurpose waste materials, defective parts, and space systems components at the end of their life. Its primary function would be to ensure a closed-loop system that minimizes waste and maximizes resource efficiency, which is essential for sustained operations in the resource-scarce environment of the Moon. Similar to production processes, the materials processing module would also handle the recycling of materials from solar power satellites at the end of life, space debris, failed or decommissioned components. Metals, ceramics, and silicon can be melted down and reused, while other waste materials could be processed and reintegrated into the production loop. This would include space debris from Earth orbit or Cis-Lunar space which may be transported to the Lunar factory to be processed and repurposed. The factory would employ systems to recycle and reuse materials from obsolete equipment, failed parts, and even waste from the manufacturing processes. The MORPHEUS SPS is designed to be fully recyclable, reusable and incorporates recoverable materials. Each satellite module is easily assembled and disassembled. Recycling modules would break down materials to their base components, which are then reprocessed and reused in the factory to build new SPS components or replicate a component of the factory.

3.2.6 Storage Modules

These modules will include storing processed materials, different propellants for later use, pressurized tanks for volatiles and gas storage, and temperature-controlled storage for transportation. Storage modules in the form of batteries may also be incorporated into the design to provide power and serve as back-up system when the primary sources are not available.

3.2.7 Autonomous Assembly Module

This module would integrate the parts produced by the materials processing additive manufacturing module, recycling module, and storage modules, transforming them into fully operational components of the solar power satellites, the Metasat Sandwich and Metasat Reflectors would be ready for deployment and assembly in space. Robotic arms would assemble the additively manufactured satellite components. This module would also include automated quality control and testing with automated quality control tests on each part such as vibration testing, thermal stress tests, and radiation shielding tests. Sensors and AI systems would detect and correct any issues, such as misalignments, weak connections, or malfunctioning components. The assembly module would operate in a flexible, on-demand manner, adjusting production schedules based on resource availability, energy conditions, or operational needs. For instance, it could prioritize building smaller satellite components when resources are limited, or focus on larger components, more complex assemblies when sufficient materials are available.

3.2.8 Transportation Network

The network would include transportation services extending from the Lunar Surface to Earth Orbit. Fully assembled SPS modules would be transported via space tugs and reusable lunar landers. Materials would be transported from the Lunar surface to Lunar orbit to rendezvous with the space tugs acting as cyclers, which would ferry them from Lunar Orbits to Earth Orbits. Afterwards, the cyclers would carry materials, space debris, recyclable materials, and customer payloads back to the Moon. The propellant to power the network would be manufactured using the Lunar factory and or from recycled materials. Propulsion systems would be additively manufactured and combustion profiles would be calculated with propulsion systems calibrated to the specific use case [24]. Additionally, propellant depots will be built in Lunar orbits and Earth orbits to support the transportation network, where cyclers would refuel in orbit, to transport materials to the desired SPS location for example GEO, and or transport SPS at the end of life or decommissioning phase, or other materials to the Lunar Factory to be recycled. Furthermore, these propellant depots can support other space activities for commercial operations. Other configurations for transporting materials from the Moon may include electromagnetic launchers or mass launchers or lunar elevator to orbit combined with space tugs, or a hybrid configuration of lunar landers, mass drivers, and lunar elevator, in combination with cyclers and space tugs.

3.2.9 Autonomous Robotics

The integration of autonomous robotics in the lunar factory revolutionizes the manufacturing of solar power satellites by enabling efficient, continuous, and precise production without the need for human oversight. These include manufacturing of autonomous rovers that can transport materials between mine sites, processing plants, and launching pads. They would be ai-driven and wireless powered to operate independently on the Moon’s surface. These robots could handle everything from material transport, component fabrication, to assembly, optimizing resource use and minimizing waste. They would be equipped with ai-driven control systems and robotic arms allow for precision tasks such as welding, cutting, and electrical integration, while adaptive systems enable on-the-fly adjustments to production demands. Additionally, the robots are equipped with self-diagnostic capabilities for real-time maintenance and repair, ensuring uninterrupted operations and are networked so they learn from each other and optimize overall processes. With the ability to perform complex assembly quality control tasks, and learn over time, utilizing autonomous robotics would enable the Lunar factory to produce highly efficient and scalable systems for self-replication, that would be capable of supporting the manufacturing of satellites tailored to mission requirements of producing new SPS while optimizing for end-of-life operation of the overall architecture with the use of lunar resources effectively.

3.2.10 In-Orbit Assembly & Disassembly

Autonomous ai-powered robotics play a crucial role in assembling and deploying SPS in space with the MORPHEUS architecture. Once satellite components are manufactured and sent from the Lunar factory, in-orbit servicing robots manage the logistics of the self-assembly of the reflector arrays, structural frames, and sandwich panel. The service robots are equipped with zero-gravity manipulation tools and AI-driven precision command and control, that can autonomously cut, weld, bolt, and secure SPS components in space. They ensure the smooth self-assembly, deployment of kinetic and inflatable structures, preparing them for operational energy collection and transmission. Additionally, in-orbit servicing robots can perform maintenance tasks and repairs, extending the lifespan of SPS components already in service. This autonomous approach reduces the need for human to manage maintenance and logistics, in the case issues may arise in the operation of independent satellites, leading to increased safety, and allows for the rapid construction and deconstruction of entire sections of solar power stations, on an as needed basis. New tasks can also be performed and learned in a virtual environment to streamline operations.

3.3 Environmental modelling of META-LUNA

LCA results for META-LUNA were calculated over a 30-year time period and is relevant for twenty-five full-scale MORPHEUS systems which are capable of generating 2 gigawatts (GW) of power to the lunar surface. This mirrors the system boundary of META-PRIME, outlined in [3]. The study assumes an average lifetime of thirty years for each SPS, incorporating replacement of components due to maintenance and rapid response events. The Falcon Heavy was used as a launcher for transporting the initial equipment need to a lunar base. It was assumed that 50% of the materials required to build the rectennas and SPS units were produced by the lunar factory, as a conservative estimate. The LCI was modelled using SSSD v1.0.3, with the LCIA phase using new impact categories based on the European Commission’s Environmental Footprint (EF) approach [25]. As such, the results cannot be compared the previous SPS LCA studies outlined in Subsection 2.2 because they are not comparable.

Overall, results were collected across a total of 29 midpoint environmental impact categories defined by the SSSD, based on the EF recommended impact categories [26] and ESA LCA Handbook [27], as recommended by Wilson et al. (2021) [28]. To determine the most critical impact categories to address, multi-criteria decision analysis (MCDA) was applied. MCDA can be used in decision-making to address multidimensional results and reach conclusions. To do this, firstly the results were normalised according to the annual consumption of an average global citizen, which is based on JRC guidance issued by the European Commission [29]. They were then weighted according to the perceived relative importance of each impact category (meta-weighting), which is also based on JRC guidance issued by the European Commission [30]. This approach then allowed the severity of 16 impact categories to be gauged.

4. ENVIRONMENTAL IMPACT

4.1 LCA study

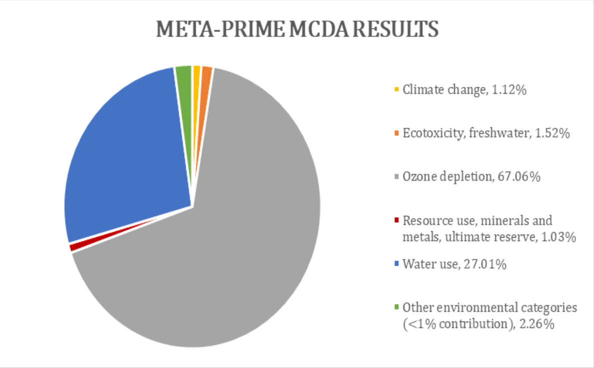

Figure 4: Meta-Prime MCDA Results

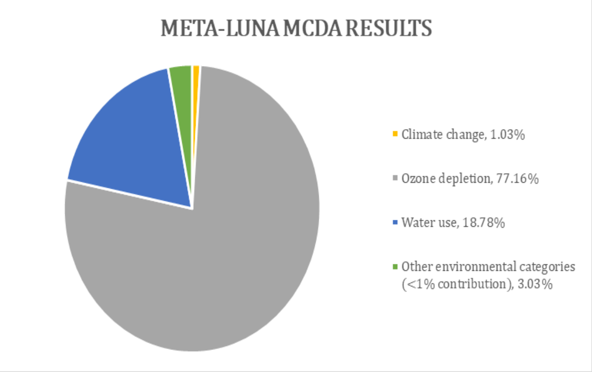

Figure 5: Meta-Luna MCDA Results

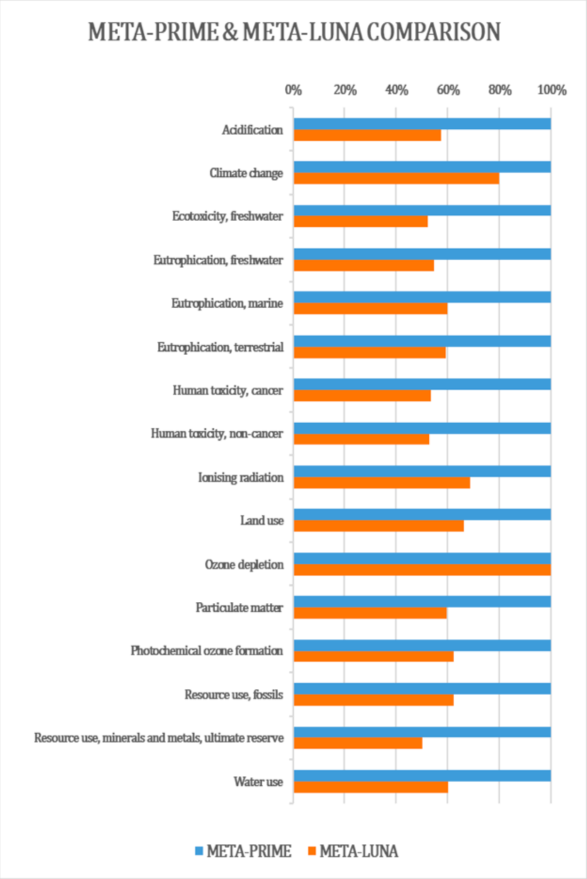

Figure 6: Comparing Meta-Prime and Meta-Luna

From the comparisons shown in Figure 4, Figure 5 and Figure 6, there was an average reduction in environmental impacts of 37.48% across all indicators. Note that there is no significant difference on ozone depletion impact category as the additional launches required to deliver lunar-based infrastructure for META-LUNA balanced out the launches required for META-PRIME. This leads to ozone depletion becoming an even more critical impact category to address in future design sessions. As 99.99% of the ozone depletion impact comes from launch, this may mean looking into the feasibility of alternative launcher options.

However, the drop in environmental impacts are mainly due to the fact that manufacturing begins to take place away from Earth. As space LCA currently only considers ecospheric impacts, this lends weight to the argument that perhaps new metrics for measuring the environmental effects of in-space operations should be developed. Regardless, as a result, it was found that the carbon footprint of the META-LUNA concept could drop to as low as 5.13 gCO_2e/kWh for the system boundary outlined in Section 3.3.

4.2 Meta Platforms for Space Circular Economy

As shown in Figure 7, to date, three platforms of the MORPHEUS SPS Architecture have been introduced, META-PRIME is developing SPS to deliver power to Earth where the SPS is deployed from Earth to LEO and transported to GEO for self-assembly [3], META-ALCHEMIST is an in-orbit manufacturing and recycling facility with autonomous in-orbit servicing robots to reuse and repurpose materials space debris and deal with logistics, assembly and disassembly of end-of-life components and decommissioning of SPS [31], and lastly, META-LUNA which features a Self-Replicating Modular Lunar Factory for manufacturing and recycling of SPS, a transportation network, and autonomous robotics for logistics, maintenance and construction of SPS. Each platform is envisioned to operate independently to facilitate a range of useful applications in space. Whereas by combining the platforms we propose the creation of a space circular economy to build, recycle and continually replenish Solar Power Satellites to provide an inexhaustive source of clean energy on Earth and in Space.

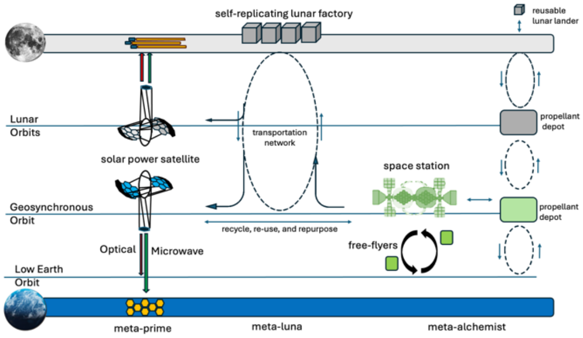

Figure 7: Conceptual operations for MORPHEUS meta platforms

5. SUMMARY

By moving manufacturing of Solar Power Satellites to space, we can further reduce the environment impact of developing SPS to deliver power to the Earth (see Figure 8).

The META-LUNA concept aims to create a system capable of autonomously producing SPS and its own components, to expand capacity over time, and sustain itself using Lunar resources. It features a Self-Replicating Lunar factory for manufacturing and recycling of SPS, Transportation Network and autonomous robotics for logistics, maintenance and construction of SPS. Initially, materials from the Earth are transported to the Moon to set up the initial components of the Lunar factory. The Lunar factory is envisioned to grow overtime using the materials from the Moon and recycling space debris, space systems at the end of life in space such as SPS, satellites and lunar infrastructure.

By leveraging the Moon's abundant materials, the factory can operate sustainably and with reducing reliance on Earth-based supply chains. By utilizing local lunar resources for SPS production, recycling materials, and minimizing waste, we can create a closed-loop system in space that mirrors sustainable practices on Earth. This is a critical step towards developing a future sustainable space economy, where space exploration and industrialization become self-reliant, reducing the need to constantly transport supplies from Earth.

Finally, META-LUNA is a crucial stepping stone to unlocking the broader resources of the solar system. It serves as a launchpad for future exploration and mining of asteroids, moons, and other planetary bodies, opening up vast opportunities for resource extraction and use in space. This will support the long-term growth of human presence in space, ultimately enabling humanity to migrate to space and become a multi-planetary species.

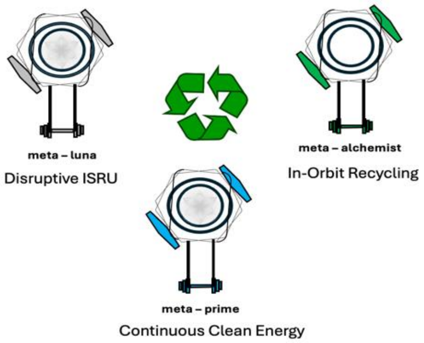

Figure 8: MORPHEUS meta-platforms powering the circular space economy

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