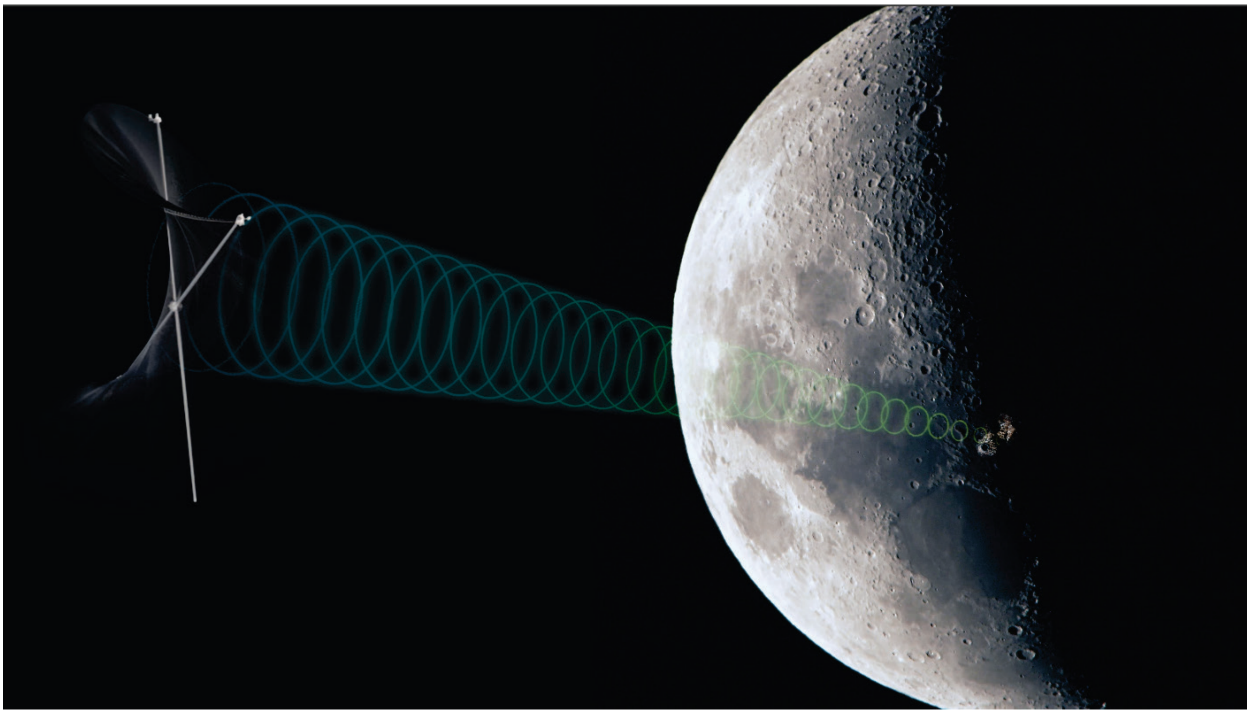
Greater Earth Lunar Power Station (GE⊕-LPS)

– EXECUTIVE SUMMARY –



Contract No: ESA STAR 2-1789/21/NL/GLC/ov - GE⊕-LPS

Final Report

Astrostrom GmbH

May 2023

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1. Introduction

This study was conducted by Astrostrom GmbH from November 2021 to March 2023 under ESA Contract No. ESA STAR 2-1789/21/NL/GLC/ov - GE⊕-LPS awarded via the Discovery programme which issued a call for ideas through the Agency's Open Space Innovation Platform (OSIP) called *"Clean Energy - New Ideas for Solar Power from Space".*

Note: ⊕ – a circle divided by a central cross - is the Greek astronomical symbol for planet Earth and is the symbolic form of the Greater Earth Lunar Power Station (GE⊕-LPS). *Greater Earth* - GE⊕ - is a new perception of our planet that is based on Earth's true cosmic dimensions as defined by the laws of physics and celestial mechanics.

The legally binding international treaty of the "Paris agreement" to hold the increase in the global average temperature to well below 2°C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels by 2050 has put many governments under intense pressure. However, when this study started, there was no anticipated limitation on using inexpensive Russian natural gas, and consequently only very few people seemed seriously concerned about the impending **'Energy Dilemma'** – having sufficient and secure access to energy for sustaining European and other societies without producing carbon emissions. The fallout from the Ukraine conflict is hitting generations of Europeans who never experienced the ravages of war nor a decrease in wealth during their lifetimes. Achieving Europe's **"net-zero"** energy goals by 2050 relying mostly on intermittent renewable energy sources for the electrification of transport, industry, and heating poses an enormous challenge for policy makers. The previous economic growth was so generous, that many have become 'future blind' and believed without retrospection that perpetual growth was a natural state of existence. But now, more than ever before, and **especially in Europe**, the current situation and, indeed, the future of western civilization needs serious attention.

Ambitious political plans to massively accelerate wind and solar power installations have been recently announced in Germany: *"We need to put up four to five new wind turbines a day by 2030 and the equivalent of more than 40 football fields full of solar panels a day,"* the German chancellor announced in March 2023. (https://www.dw.com/en/germany-cabinet-meeting-focuses-on-energy-transition-ai/a-64894279)

However, bureaucratic and democratic deliberations in the planning and permission processes alone have extended the period from plan to realisation by more than 8 years. Furthermore, all substantial plans for large scale energy storage projects in the last decade, have been scrubbed since available energy from Russian gas was too inexpensive to justify the investment. The last three nuclear plants in Germany were taken off-grid as of April 15th, 2023 and, due to drought and maintenance issues, half of France's nuclear power plants have been off-grid since last year.

This developing and complex situation has stimulated **renewed interest in the feasibility of Space-Based Solar Power (SBSP)** to significantly contribute to humanity's energy needs. The cost of launching satellites has been reduced by 90% in the past decade by companies such as SpaceX. Additionally, space hardware costs have also declined significantly and automation and robotics, including software control are experiencing exponential growth in capability. Consequently, new SBSP initiatives have appeared in various parts of the world. A **'Window of Opportunity'** appears to have opened if SBSP development plans can be introduced with sufficient urgency and commitment. Indeed, the recent ESA sponsored Cost Benefit Analysis concluded that **SBSP could provide competitively priced electricity to European homes and businesses by 2040**, displacing fossil-fuel sources of power and complementing existing renewables such as solar PV and wind, reducing the need for large-scale storage solutions. When deployed at scale, **SBSP would provide substantial environmental, economic, and strategic benefits for Europe, including energy security.**

The present study began with a review of the considerable number of books and papers, starting at the beginning of the space age, through the 1970's oil crisis, when **SBSP** was first studied, and when the industrialisation of the Moon was initially considered in post-Apollo investigations, and proceeded to include the most recent research on these topics. In the space development sector today, we see companies like SpaceX igniting new aspirations for an expanded vision of space exploration in the West, while China has become a rapidly emerging space nation with competing economic and geopolitical agendas.

With this study we present an exciting **'Space Energy Option'** which not only could reduce geopolitical tensions over energy resources, help to mitigate the climate crisis and the energy dilemma, avoid the de-industrialization that would result in an energy poor world, but one that provides **hope for future generations** to achieve their aspirations and potentially initiate a new cislunar space economy with untold access to resources and energy. The available resources, the know-how, the new technologies, which have all accelerated in the last 25 years, have never been in a better constellation than today to fulfil human energy needs on Earth while pursuing space development and exploration objectives and creating an unparalleled business case by making such a **bold and innovative step to utilise the Moon**.

2. Study Objectives

The main objective of the study is to investigate the **technological feasibility** of implementing the GE⊕-LPS concept, and its role as a prototype for proposed cislunar scenarios supplying electric power to Earth. The methodological approach to the study has been to identify and validate the most simple and effective solutions which could be practically implemented with known and existing technologies and approaches.

Another objective was the evaluation of the **economic feasibility**. Would the implementation of the GE⊕-LPS be worth the initial investment? Simply providing power to a modest lunar operation would most probably not justify nor attract the necessary investment and commitment needed for its implementation. Therefore, the study has analyzed the GE⊕-LPS concept in its macro-economic context that considers competing approaches to terrestrial and space-based power producing systems.

In addition to the technical and economic objectives, the development of the GE⊕-LPS concept in all its stages will likely have a tremendous **cultural impact.** For most people, the idea of harvesting energy in space and beaming it to Earth via Solar Power Satellites (SPS) is already a step into the realm of science fiction. To do this by going to the Moon and utilizing lunar resources to build the SPSs will pose an even greater intellectual challenge in all areas of society and to all cultures around the world. Therefore, exploring the cultural dimensions of this project was another major objective of the study.

Finally, due to the potential impact that the results of this study may have on the discussion related to SBSP, another of the main study objectives has been the **visualization and distribution of the results.** Many facts and figures have emerged in the course of the research, but the study is essentially a conceptual approach that goes far beyond the original proposal with many implications for approaches to the climate and energy crises, as well as to the future of humanity as a spacefaring species. Therefore, to make the

Key Findings

- The GE⊕-LPS is a technically and economically feasible concept that is sustainable and scalable.
- It represents an innovative approach to addressing the climate and energy crises.
- It is cost-competitive with any terrestrial energy alternative.
- It will help to mitigate the launch bottleneck facing Earth-launched Solar Power Systems.
- It proposes a cislunar transportation infrastructure.
- It establishes an Earth-Moon economy.
- It may reduce geopolitical tensions over the control of energy resources.
- It provides inspiration and hope for future generations.
- It could become a powerful impetus for future space development.

results easily understandable and accessible to a large audience, different media approaches are being developed. These include online databases of relevant information, press releases, book and video production, and others.

The **Greater Earth Lunar Power Station (GE⊕-LPS)** as proposed in this study is a multi-purpose concept that addresses several critical issues related to lunar development and terrestrial energy production. Briefly stated, the GE⊕ Lunar Power Station is a solar power satellite to deliver MWs of microwave power to the lunar surface with a small integrated habitable space station. GE⊕-LPS will be constructed primarily from lunar resources and materials using lunar based automatized manufacturing processes. As such, the GE⊕-LPS can provide needed electrical power for lunar based activities, serve as a gateway between Earth and Moon operations, provide artificial gravity for adaptive health purposes, serve as an attractive tourist destination and possibly become the prototype for future space settlements in geolunar space. Perhaps more importantly, as the GE⊕-LPS concept and its energy production functions may be scaled to any dimension, larger versions could be positioned in Earth orbit and provide much needed clean solar energy for terrestrial purposes.

As such, the GE⊕-LPS unites the aims of lunar development with widely shared aspirations of spaceflight while addressing the critical energy and environmental needs of human civilization on Earth.

3. Study Methodology

The study approach has been to follow the work package descriptions detailed in the initial technical proposal to arrive at a technically feasible and defensible plan. Due to the breath and complexity of the concept and the vast amount of available literature, the focus has been to find the most simple and feasible solution to each aspect.

- **Work Package 1** comprised a review of the proposed concept, a definition of the design and functions, a review of the relevant technological heritage and an overview of the potential economic and cultural impact.
- **Work Package 2** established the basis for an analysis of the system architecture leading to an initial design configuration detailing the associated and anticipated technological challenges as well as an assessment of the potential market.
- **Work Package 3** provided a fusion of the technical results and outlined the developmental steps and potential synergies.
- **Work Package 4** considered additional uses and potential extensibility of the concept and developed various outreach products.
- **Work Package 5** was dedicated to study management, coordination, and reporting.

Assumptions

The following assumptions directed the focus of the study:

- Energy use is directly correlated with prosperity.
- Demand for clean energy solutions will continue to grow in proportion to increases in population and demand for economic growth.
- Energy related issues such as climate, environment, energy security and energy supply require viable and sustainable solutions which are not yet being considered by policymakers.
- As opposed to nuclear fusion energy supply, SBSP does not need any major technical breakthroughs to be realized.
- The launch bottleneck for massive SBSP deployment remains unsolved in the foreseeable future.
- The accelerated developments in the last decade in PV technology, robotics and automation will continue, fed by strong world demand.
- Energy markets have sufficient financial means to develop and deploy new and innovative sources of clean and sustainable energy such as SBSP.
- The geopolitical competition for energy and other strategic resources will continue to intensify.

4. Electricity Demand in Europe

Due to the net-zero goals and new digital technologies, electricity demand evolution is one of the biggest uncertainties for the electric power supply sector. This is a result of the interplay of a multitude of drivers such as: electric vehicles, production of hydrogen via electrolysis, deployment of heat pumps and other electrical heating solutions which increase electricity demand. Considering the planned electrification of transportation, heating, construction, and industry, as well as the ever-increasing demand for electronic data-services, the demand for electricity in Europe is widely **predicted to increase by at least 50%, but more realistically by 100% by 2050.** Thus, Europe's annual electricity demand could increase from 4032.5 TWh (2021) to approximately 8,065 TWh in the year 2050. This would require an overall electrical power-generation capacity of approximately 920 GWe.

The overall 2050 European energy mix anticipates an increase of renewables, a decrease in the use of fossil fuels while contributions from hydroelectricity and nuclear power remain constant. In 2021 nuclear power supplied 883 TWh. Therefore, this study considered that a useful goal for SBSP would be to provide Europe with at least the same amount of baseload electrical power as nuclear power provided in 2021, approximately 101 GWe or 11% of the 2050 energy mix. Clearly, the demand for new sources of clean energy while also providing energy security are compelling factors supporting the urgent development of SBSP in Europe.

5. ESA, SBSP and SOLARIS

In 2020 the European Space Agency (ESA) signalled its renewed interest in SBSP via its future-oriented Discovery Programme which issued a call for ideas through the Agency's Open Space Innovation Platform (OSIP) called ***"Clean Energy - New Ideas for Solar Power from Space".*** From the 85 submitted proposals 16 were selected and 13 were awarded contracts in 2021 to research various aspects related to SBSP, an extremely interdisciplinary topic involving a wide range of technologies at various stages of development.

In the summer of 2022, ESA announced its proposed **SOLARIS programme** with the goal to prepare for a possible decision in 2025 on a full development programme by establishing the technical, political, and programmatic viability of SBSP for terrestrial needs. ESA would, through an initial investment, undertake additional studies and technology developments, in partnership with European industry, to mature the technical feasibility and assess the benefits, implementation options, commercial opportunities and risks of SBSP as a contributor to terrestrial energy supply.

In addition to the 13 studies that were funded from the OSIP call, ESA commissioned two Cost versus Benefit Assessments (CBA) which were carried out by Frazer Nash Consultancy and London Economics in the UK and Roland Berger and OHB in Germany. Both assessments included analyses of future electricity demand in Europe and the potential economic role of SBSP.

Frazer-Nash and London Economics predicted that electricity demand in 2050 will be about 4,000 TWh/year under their Net-Zero (NZ) scenario, and 8,000 TWh/year under their Business as Usual (BAU) scenario requiring between 457 GWe to 913 GWe of power respectively. They suggest that 54 SPS 1.44 GW systems could provide 70 GWe of power or ca. 610 TWh/yr by the year 2050. The total launch mass that is needed to put a 1.44 GW SBSP system into orbit is 2,491 metric tons. Thus, launching **54 SPSs would require between 4,644 and 6,426 launches** to place a total of 136,514 **MT** into to a Geostationary Transfer Orbit (GTO). To put this into perspective, since the beginning of the space age in 1957, only about 20,000 MT in total have been launched into orbit, mostly into LEO. Frazer Nash estimated that the 54 SPS systems would cost **approximately €418 billion.** *(LE-SBSP-TN4 and FNC/LE, (2022). Frazer Nash Consultancy and London Economics, Space-Based Solar Power: A Future Source of Energy For Europe? Brochure (EN))*

Based on the EU Reference Scenario 2020, the Roland Berger/OHB study estimates electricity demand for the year 2050 at 3,500 TWh, which would require approximately 400 GWe of power generating capacity. To meet approximately 10% of the EU's gross electricity demand of around 3,500 TWh/yr in 2050 would require 20–25 operational 1.8 GW SPS-ALPHA systems with a total generation capacity of 36 GWe-45 GWe and output of 314–390 TWh/year. In their analysis the total cost per SPS unit varies between €8.07 billion and €33.41 billion. For 25 SPS systems this range is **between €200 billion and €835 billion.** Using SPS-ALPHA MK-

III as their example, with a launch mass of 7,600 MT and a delivery estimate of 21 tons to GTO would require 362 Starship launches per SPS or **9,050 Starship launches for 25 SPSs.** *(Roland Berge-OHB: System breakdown, costs and technical feasibility of a SPS, (SBSP-OHB-TN-003))*

As seen in the above examples, a main obstacle to implementing the *Space Energy Option* is not only the substantial cost and technical scaling of the system but also the enormous logistical effort needed to launch the many gigawatt-scale SPSs from the surface of Earth into geostationary orbit requiring thousands of launches. The non-availability of the necessary heavy lift launch capacity in Europe and/or abroad is an additional limiting logistical factor in this situation. This **launch capacity bottleneck** is also a stimulus for other innovative approaches to realizing SBSP on the scale needed to provide Europe and the world with much needed clean energy.

6. Results of the Study

During the GE⊕-LPS study the technical and financial feasibility were tested and no need for fundamental technological breakthroughs was identified although many technological challenges were identified. Most of the core technologies for lunar surface mining, beneficiation and fabrication operations are already in use or under development on Earth today. These technologies could be extrapolated and adapted to the lunar environment, delivered in modular form and managed tele-robotically on the lunar surface. Although no technological breakthroughs may be needed, due to the lack of experience operating in the lunar environment and direct in-situ access to lunar materials, substantial engineering development would be required. Financially, the scaled version of the GE⊕-LPS - the GE⊕-SPS - was shown to not only be more economically attractive than a comparable Earth-launched SPS, but also **cost-competitive with any terrestrial energy alternative.** If further research confirms this, then the impact on the global energy economy and society in general would be as important as was the introduction of fossil fuels.

6.1. The GE⊕-LPS Concept

The GE⊕-LPS concept proposes to mitigate this logistical and environmental obstacle by manufacturing a substantial portion of the SPSs from lunar materials and robotically assembling these in lunar orbit. If GE⊕-LPS proves to be technically feasible and then successful at delivering energy to the lunar surface, it is foreseeable that the concept can be scaled up to manufacture large parts of SPSs from lunar resources to supply energy to Earth at a significant level. This would also create many other benefits in addition to providing sufficient clean energy for Earth, such as a commitment to achieving a peaceful energy transition, the development of a cislunar transportation system, mining, processing, and manufacturing facilities on the Moon and in orbit resulting in a two-planet economy and the birth of a spacefaring civilization. The key components of the GE⊕-LPS system include the orbital structure which will be constructed using advanced robotics at the Earth-Moon Lagrange point (EM-L1) located approximately ~61,350 km from the Moon and in line with the Earth. This structure encompasses the energy collection and power transmission components as well as an integrated habitat module for human management of the GE⨁-LPS orbital operations and which also will serve as a transit station for the station and surface crews and for visitors from Earth. As such, it will also include a docking port and cargo storage facilities.

The lunar surface components of the GE⨁-LPS system consist of a base station habitat for the ground crew, mining operations, processing and manufacturing facilities, materials storage and a rectenna to receive microwave power from the orbital station. The rectenna will convert the received power into electricity for lunar operations including life-support, surface transportation, mining, processing, and manufacturing activities. Additionally, the surface components will include rocket landing pads and prepared roads, and rovers for surface transportation.

Initially, transportation between the GE⨁-LPS and the lunar surface base station will rely on rocket powered vehicles. Reusable cargo landers can initially bring cargo for a lunar base down to the surface, using propellant brought from Earth, and then, when a lunar propellant production system is operating, use and bring propellant from the base up to EM-L1, as well as bringing additional equipment down to the lunar surface at greatly reduced cost.

Eventually, cargo transportation will be via a Lunar Space Elevator (LSE) which will deliver the LPS elements manufactured on the lunar surface to orbit and, vice versa, for the delivery of cargo from Earth that has been deposited and stored at the LSE hub station. It is foreseen that the LSE will be reinforced and expanded to become an Earth-to-Moon transportation system for cargo delivery in both directions, i.e., from the Moon to High Earth Orbit (HEO). Unlike the often-proposed 'mass driver', a LSE offers much more flexibility for transporting cargo in both directions. Together with the EM-L1 transportation hub this will create a promising business case.

6.2. The GE⨁-LPS System Architecture

6.2.1. The Reference Design of the GE⨁-LPS

The GE⨁-LPS configuration went through a series of geometrical design iterations. After examining various geometric configurations for the GE⨁-LPS, the study team arrived at an optimized helical design concept with an integrated phased-array transmitter and an optimized photovoltaic deployment using a solid-state **V-Shaped photovoltaic design inspired by the heat collection of butterflies** with a V-shaped wing position. As such, this biomimicry-inspired design is called the 'Butterfly' concept. It consists of a spherical habitat in the center, from where two axes deploy. The longer axis forms the longitudinal rotation axis for a helix shape. The rotation from end to end is 180 degrees and forms a ring beam. Between the longitudinal axis and the ring beam the hybrid PV-Antenna elements are spanned. The helix-based shape has the advantage that, no matter how the inclination angle to the Sun changes, always the same amount of solar energy is received. At the same time the beam-forming antenna elements can directly face the rectenna and therefore does not need to be switched continuously.

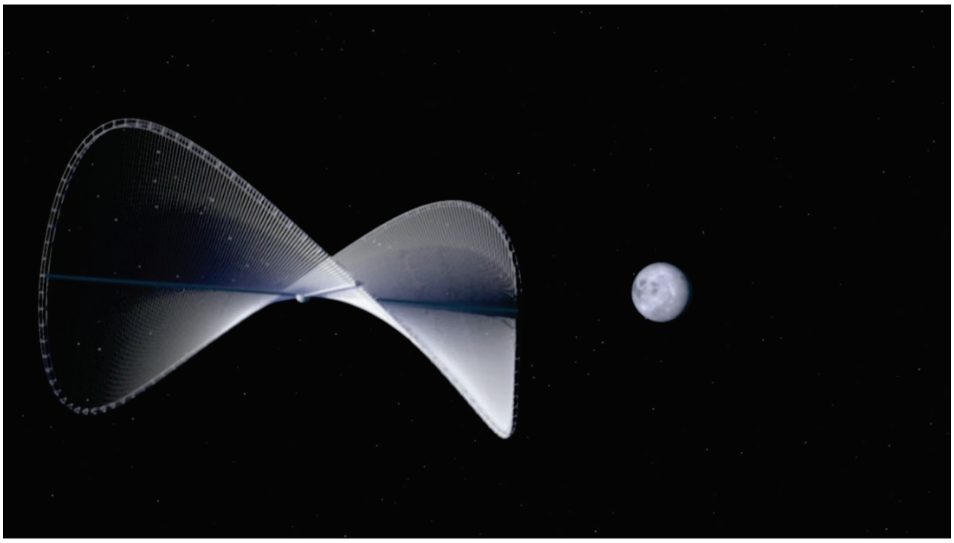

Figure 1: 'Butterfly' Reference Design of the GE⊕-LPS. (Credit: Astrostrom)

As a baseline for power supply to the lunar surface a requirement was established for the **GE⊕-LPS of 1.5 MW of continuous power for initial lunar operations**, allowing some margin for additional storage. To deliver this amount of power, the solar collector of the GE⊕-LPS would require a diameter of 300 m giving an optimized PV surface area of 29,339 m^2. Using PVs with a specific output of 91W/m^2 this would generate 3.6 MWe at the SPS and deliver 2.0 MWe at the rectenna with a 57% DC-DC efficiency. However, since more power is always useful, a larger SPS may be considered economically and technically advantageous for future operations.

To provide power to the lunar surface from EM-L1 (~61,350 km from the lunar surface) will be a trade-off between antenna size and rectenna size, i.e., the smaller the transmission antenna the larger the rectenna on the surface and vice versa. A transmitting antenna a diameter of 900-1,200 meters at EM-L1 will require a rectenna on the Moon with a diameter of about 4 kilometers, assuming use of 5.8 GHz microwaves.

The helical shape optimizes the orientation aspect of the GE⊕-LPS by minimizing the need to constantly point the solar collectors toward the Sun. The reduction of about 33.3% in utilisation of the solar panels as a result of the geometry is offset via the use of V-Shaped photovoltaic arrays which increase both the surface area and efficiency of the photovoltaics, resulting in a higher power output (+ 1.35) than a flat PV surface. Thus, the reference design indicates that by transmitting microwave power with a frequency of 5.8 GHz from EM-L1 to the rectenna, a GE⊕-LPS with a diameter of 1000 x 1174 meters and a mass of 1,342 MT will generate ca. 40 MW at SPS and deliver ca. 23 MWe at the rectenna at 91W/m^2 with a solar cell efficiency of 6.7%.

The main components of the GE⊕-LPS are the supporting structure, which is proposed to be built with basalt tubes and the hybrid PV-antenna elements, where the photovoltaics constitute the main element. Thus, the study has focused on these elements.

6.2.2. Solar Panels from Lunar Materials

As the lunar in-situ production of photovoltaics from silicon was shown to be highly problematical, a more feasible alternative approach to lunar solar cell production was identified. **Monograin layer (MGL) solar cells** are a single-crystalline type of solar cell which has a very simple production process based on crystallization. Scientists at Estonia's Tallinn University of Technology (TalTech) have developed a monograin layer solar cell based on a semiconductor compound made of microcrystalline powders that is known under the chemical formula Cu2CdGe(SxSe1-x)4. The monograin layer (MGL) solar cell concept for semiconductor compounds was proposed more than 50 years ago by researchers of the Philips Company.

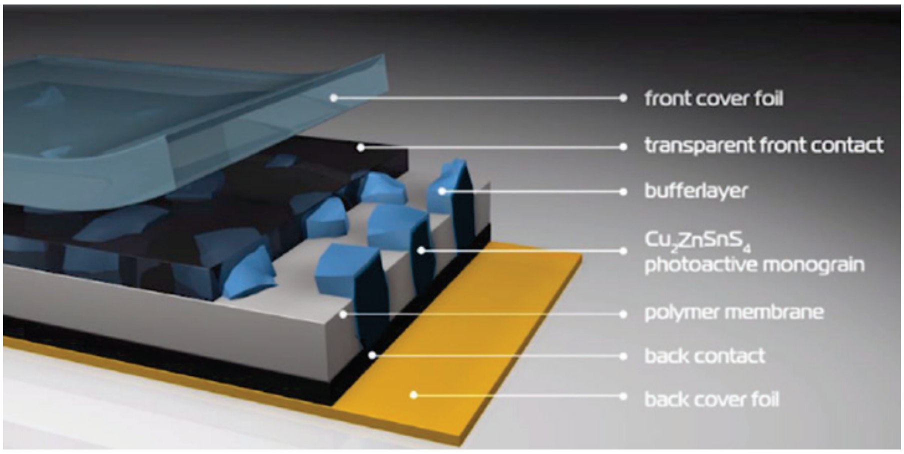

Figure 2: Monograin Layer Composition (Credit: Crystalsol GmbH)

Additional developments, modifications and patents were taken by the TalTech researchers and crystalsol GmbH in Vienna, Austria. MGL technology allows to cover vast areas with minimum cost. As shown in Figure 3 every semiconductor particle in this powder is coated with an extremely thin buffer layer for creating the p/n junction it is already a tiny photovoltaic cell. Therefore, the MGL technology has an advantage compared to all thin film technologies because it allows to separate powder production from module finishing.

Lightweight flexible solar cell module rolls could be transported to the Moon or produced *in situ* from lunar regolith. TalTech has carried out preliminary tests with semi-finished MGL solar cells based on kesterite absorber crystals, in a simulated lunar environment. The results of preliminary tests were considered promising enough to prepare the technology for extra-terrestrial usage. MGL solar cells have the additional advantage that they can be recycled for future use.

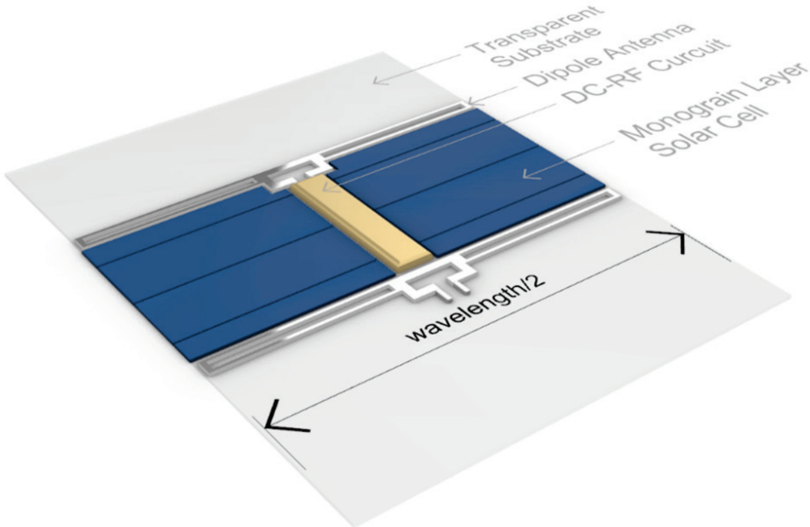

Figure 3: Baseline design of the solar-antenna element. (Credit: Astrostrom)

Currently, researchers at TalTech are testing the use of pyrite for a lunar solar cell production. Pyrite can be synthesised from troilite, which has a presence of about 1% in lunar Apollo samples. The pull-technology idea is to print the photovoltaics, the electronics and the antenna onto a transparent thin film substrate as shown in Figure 4. Polyimide is used on Earth as the substrate, and it needs to be investigated to what extent this or a similar carrier could be produced from lunar materials like chemically strengthened glass.

The MGL solar cells can be applied onto this substrate. The solar cell is connected to the DC-RF integrated circuit which itself is connected to the 3D printed dipole antenna. Mass production could be realized with a roll-to-roll process as shown in Figure 5.

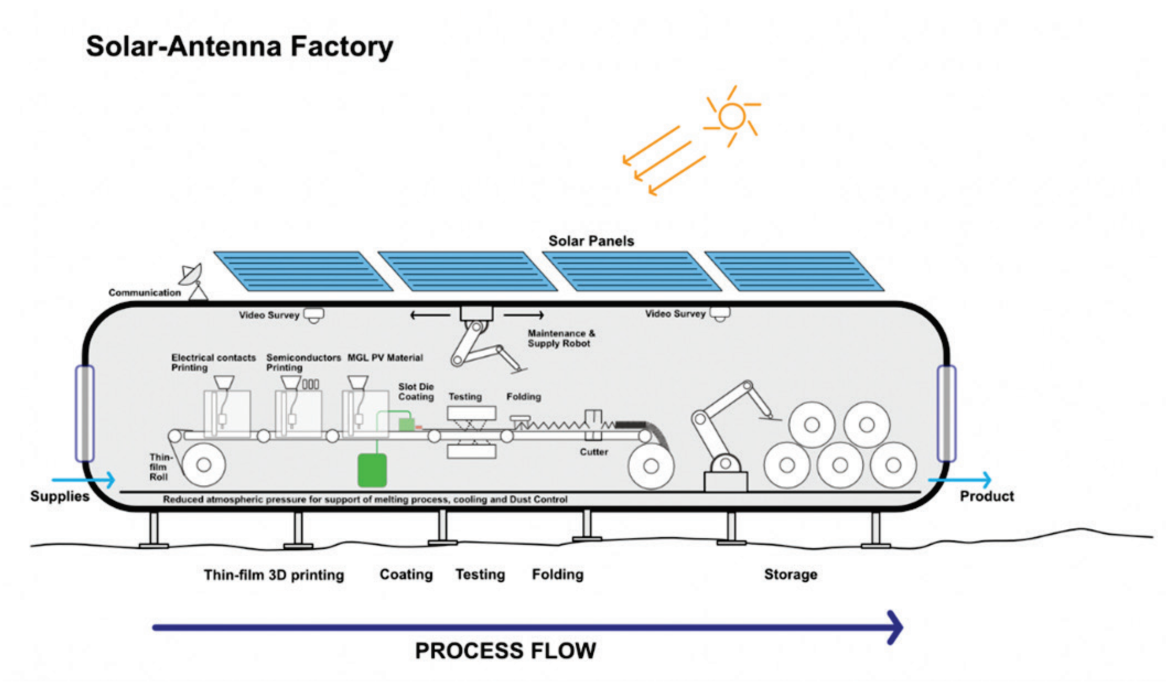

Figure 4: Concept design for a lunar solar-antenna element factory. (Credit: Astrostrom)

6.2.3. Structural Elements from Basalt Fibres

Basalt fibre, very similar to fibreglass, is made of volcanic rock, mainly found in the lunar maria. It is composed of the minerals plagioclase, pyroxene, and olivine. As much as glass and carbon fibres have revolutionized light construction technologies on Earth, basalt fibre technology could do the same on the Moon. However, a solution for the matrix to be produced on the Moon must be found.

The fibres produced in the lunar environment, in fact, may have better mechanical properties than basalt fibres produced on Earth. A number of previous studies have suggested that the fibres may reach higher tensile strength properties when produced in lunar environmental conditions of high vacuum and low-gravity. Basalt fibre pultrusion tubes which can be assembled in space to form large trusses as needed for constructing the GE⊕-LPS supporting structure are proposed.

Initially a node-based construction system for the basic structure was foreseen. 8m long basalt fibre tubes would be joined with a multi-directional node by the robots. However, to reduce weight and complexity, a bonding system where the tubes are bonded in space directly without the need for nodes could be more promising. Both approaches need further research and development. Fibres can also be used to reinforce other materials and for production of insulation mats in the insulation factory. The use of basalt engineering and modern production technologies such as additive manufacturing seems to be very promising in a future space economy, and these technologies will stimulate lunar industry towards the production of structural and basic utility products. The same will be true for mining and processing of iron, oxygen, and aluminium.

6.2.4. Mining

Due to the lack of deep-drilled regolith samples from the Moon for precise analysis, the study chose only to mine loose lunar soil and avoid rocks. The driver has been the 1% of troilite in the soil to produce the pyrite MGL photovoltaics. We identified the NASA KSC Swamp Work Regolith Advanced Surface Systems Operations Robot (RASSOR) as an already quite far developed lightweight lunar soil collecting robot. RASSORs can be used as single mining and transportation robots. Their design incorporates net-zero reaction force, thus allowing them to load, haul, and dump space regolith even under low gravity conditions with high reliability. The current NASA RASSOR prototype can carry 90 kg of regolith. For GE⊕-LPS we would use a slightly larger version, which could carry 150 kg. To ensure the material flow defined by the transportation throughput from the Moon to EM-L1, a fleet of 20 RASSOR will be needed. This corresponds to about 1 SPS to be built per year and the production process can be scaled up correspondingly.

6.2.5. Beneficiation and Processing

Numerous processes for extracting oxygen and metals from lunar regolith have been proposed in past studies. Most of these use chemical reagents like HF, fluorine, chlorine and other substances not common on the Moon. Since the GE⊕-LPS mining operations are at the equator, polar water must be imported. Therefore, a process that does not require water and/or large quantities of corrosive and imported chemicals is desirable.

A flow chart for the material flow in the GE⊕-LPS production system is shown in Figure 6. The mined lunar soil will be roasted at between 500 and 700 degrees Celsius to extract the volatiles, which will be separated through liquefaction and condensation. After this the material is divided for further roasting processes, mechanical and electrostatic separation of troilite and ilmenite, and for further processes to gain metals. Troilite is further processed to gain pyrite for the PV production. The ilmenite is processed into iron and titanium dioxide. Future developments may lead to the successful use of ilmenite as a valuable semiconductor on the Moon. Fluorine imported from Earth would be needed for the main production of the metals, iron, aluminium, titanium and silicon. This can be imported as potassium fluorine in solid form and can be recovered during the reduction processes. Mare regolith can be excavated, pressed into forms and sintered with heat from solar or electrical furnaces, or melted and cast to make numerous basalt items.

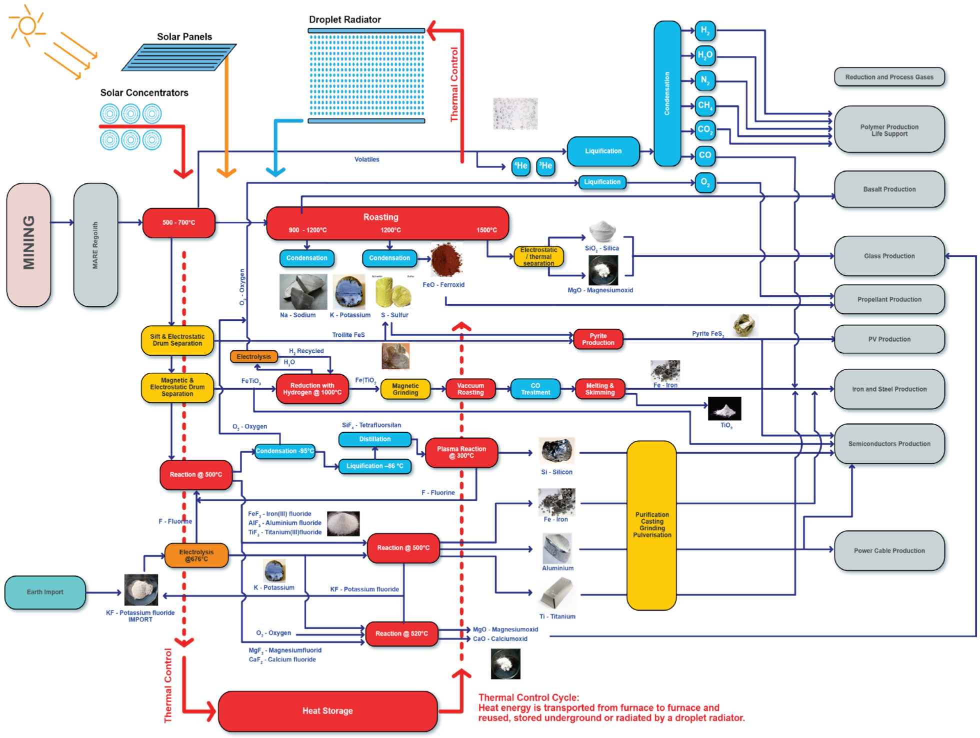

Figure 5: Flow chart of the material flows in the GE⊕-LPS beneficiation plant. Most processes are only heat based to avoid terrestrial imports. Also shown is a heat management system with heat storage.

Industrial-scale lunar material processing will require a considerable amount of solar heated furnaces, piping, cryo-chillers, insulated tanks, etc. At first, precursor demonstrators and experimental ISRU facilities will be needed to better understand the processing of regolith on the Moon. Later, building up modular plants for industrial-scale production, which are expandable and adaptable over time will be appropriate.

Since many of the heating and condensation processes are vertically organized, a rack building system as shown in Figure 7, which can be accessed on different levels both by astronauts as well as by robots, seems likely to be optimal. Such chemical plants on Earth are built in a similar manner. The rack structure can be realized with elements made from basalt. Initially, furnaces, valves, pipes, chillers, pumps, and tanks will be imported from Earth. As production capacity grows more and more metal powders will be available for 3D printing. Thus, further piping and machine parts can be produced by 3D printing from aluminium, iron and steel.

The organization of the processing plant into a constructive racks system also allows the bundling of the heat and electricity generation on the highest level, and the introduction of a heat management system which can direct heat from high-temperature processes to lower temperature processes, and also to a heat storage system underground. The heat storage system should be designed to keep the critical devices like the furnaces above a planned minimum temperature during lunar night to avoid cracks due to extreme temperature differences.

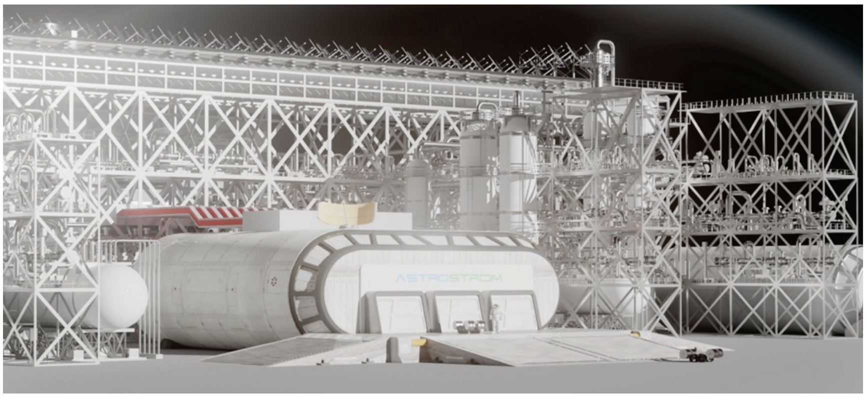

Figure 6: Proposed GE⊕-LPS beneficiation plant. The basalt racks system allows for modular scalability. (Credit: Astrostrom)

The construction of SPS elements from lunar materials with a potential for scalability will shift ISRU from a laboratory level to an industrial level. However, processes have only been tested in terrestrial laboratories with regolith simulant, and, as yet there is no experience of ISRU on the lunar surface. Mining and ISRU for fabrication are the very first steps to a lunar industrial economy which can boost spaceflight well beyond science and exploration.

6.2.6. Fabrication

For the construction of the GE⊕-LPS system two main areas of fabrication have been identified:

1. Fabrication of the structural elements with basalt castings and basalt fibres
2. Fabrication of the solid-state PV-Antenna elements

More specifically the following fabrication facilities will be necessary.

- Basalt Casting Factory
- Basalt fibre and Pultrusion Factory
- Regolith Sintering Factory
- Electric Wiring Factory
- Polymer Factory
- Hybrid PV-Antenna Factory
- Additive Manufacturing Factory

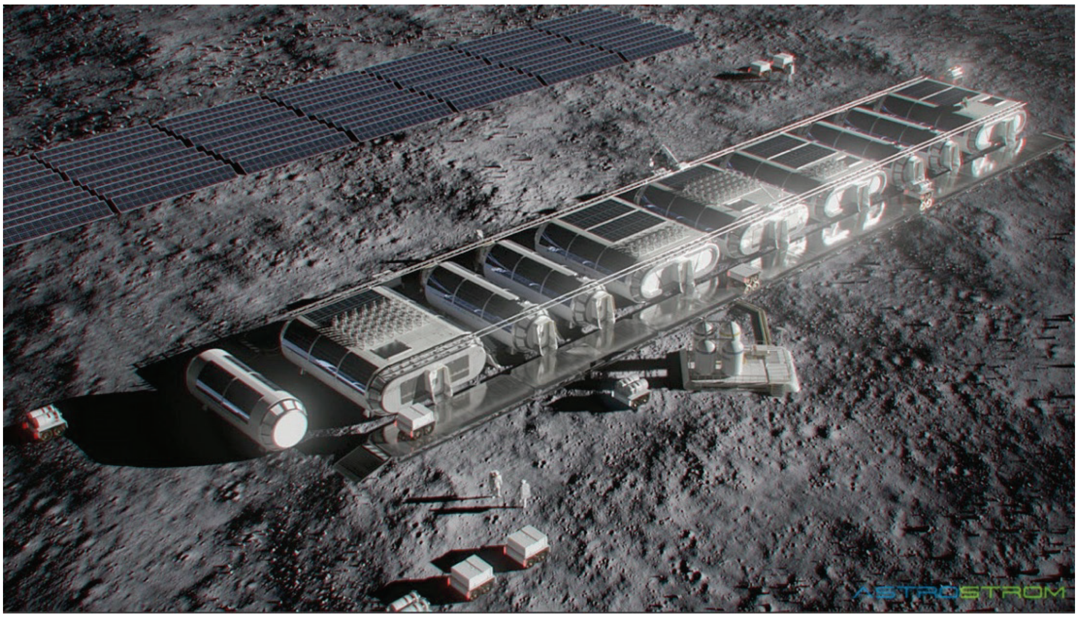

Figure 7: Linear organisation of factory modules. (Credit: Astrostrom)

All non-propellant production will be located at a linearly organized fabrication zone as shown in Figure 8 to create synergies for material logistics, energy, and heat management. Ground solar is arranged alongside the factories. In between the factories there are heat radiators. Along the factories there is a rail on each side with a handling robotic arm on it, allowing loading and unloading transportation robots as well as material hand over from one to the other factory. Material supplies are loaded from above. The finished products are released over ports on the opposite side to transportation rovers. On the roof there are further solar panels and solar concentrators, where process heat is needed. The factories are slightly pressurized with nitrogen for fire and dust protection. Factories can be accessed by maintenance engineers through a spacesuit port. For this, the atmospheric pressure will be raised to 1/3 sea level and the astronaut would have to use an oxygen breathing mask.

6.2.7. Site Considerations

The site foreseen for GE⊕-LPS operations is the Sinus Medii at the crossing point of the prime meridian with the lunar equator, which is the logical anchoring point of the GE⊕-LSE. Very close in the north will be the fabrication site, where the final cargo from EM-L1 arrives. Moreover, the site seems very suitable since it is topographically smooth with few meteorite craters. At the same time, it provides access to different topographical forms as well as to other resources. Access to the large mares in the North and West directions also seems topographically easy as seen in Figure 9.

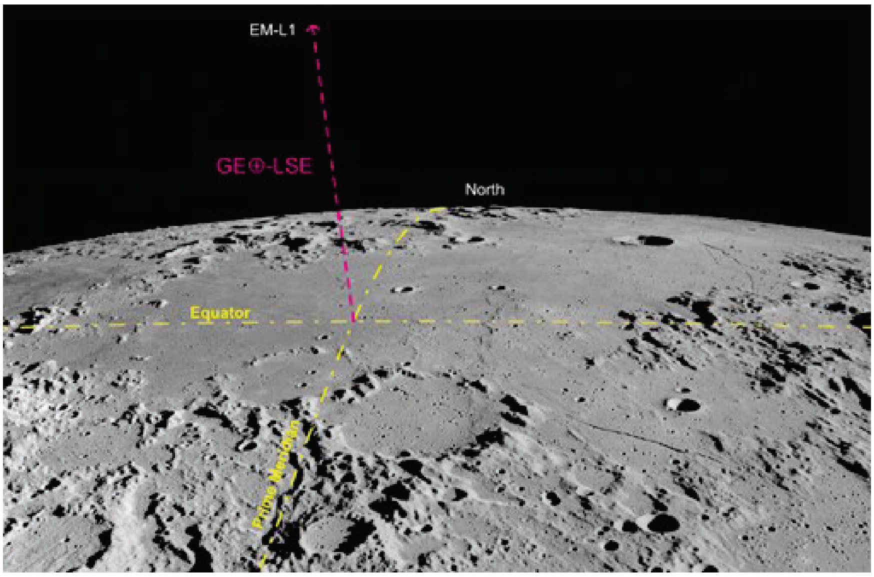

Figure 8: View of Sinus Medii with equator and prime meridian. Also shown is the tether of the GE⊕-LSE. (Background image: Wikipedia)

6.2.8. Transfer of GE⊕-LPS Components to the Assembly Location at EM-L1

The GE⊕-LPS system has chosen EM-L1 as its main operation hub. The proximity to Earth is one reason. Earlier Moon mining studies from the 1970s have proposed EM-L2 as an arrival point for lunar construction material. The main reason for this was because these concepts were based on the use of "mass-drivers", and cargo catapulted from the Moon should not be directed towards Earth in case the mass catcher failed to capture it. Upon examination, the mass driver approach turned out to be a much more limited means of transportation from the lunar surface than a lunar space elevator, which has much greater potential for flexibility and growth. EM-L1 will be the natural deployment point for such a space elevator and will become its natural main cislunar cargo hub.

The **Greater Earth Lunar Space Elevator (GE⊕-LSE)** which is a transportation system that uses cables or tethers to move materials from an anchor point on the surface of the Moon to a docking station at EM-L1. The means of transportation consists of vehicles that will climb between these two locations powered by electrical energy using wheeled "crawlers" as shown in Figure 10. The GE⊕-LSE)'s main function is to allow for a reusable, controlled means of transporting cargo payloads between a base station at the bottom of the gravity well on the surface of the Moon and the docking port at EM-L1. The GE⊕-LSE potentially offers an economical and reliable means to deliver lunar manufactured elements to a relatively stable orbital assembly point. A GE⊕-LSE would revolutionize operations in cislunar space and can be a key piece in the development of the Moon and the use of its resources for advanced space development. As such, a GE⊕-LSE will contribute to lunar development by:

- Providing lunar materials in Earth orbit at less cost than launching from the Earth
- Providing a solid and steady supply of construction material in Earth orbit
- Providing continuous supplies from Earth to lunar installations
- Supporting SPS construction for supplying terrestrial energy needs
- Providing an important infrastructure basis for new business models of an emerging lunar economy
- Accelerating economic access to space for business, science, and exploration

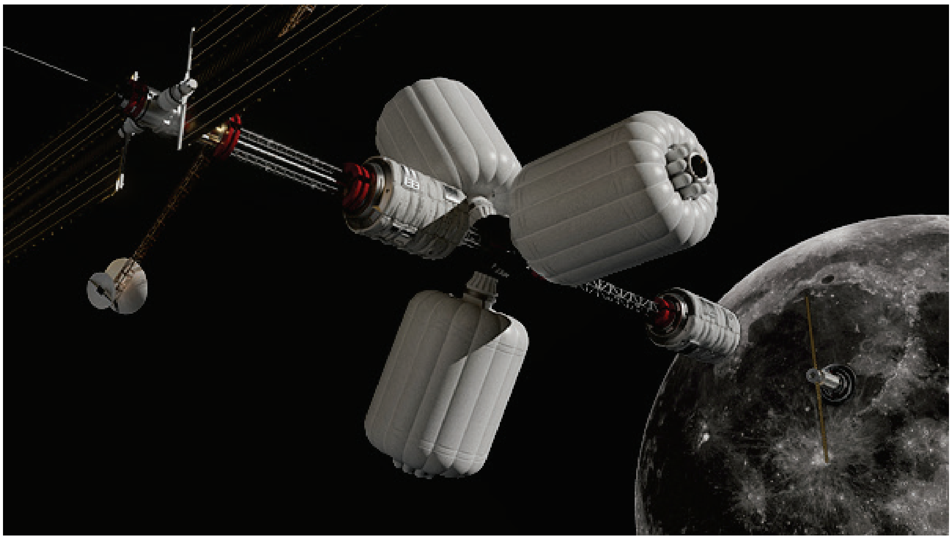

Figure 9: Lunar Space Elevator with a crawler on the right. (Credit: Astrostrom)

According to LSE researchers Radley, Eubanks, Penoyre and Sandford, a significant aspect of this proposal is the fact is that a GE⨁-LSE could be built today with existing materials such as Dyneema and Zylon which are already commercially available in large quantities. Additionally, lunar sourced basalt fibre may be sufficient for reinforcing and extending the elevator once it has become operational.

6.2.9. Robotic Assembly Operations

The robotic assembly is planned to happen at EM-L1 and later also directly at GEO. A construction robot will assemble the GE⨁-LPS trusses and will use the truss as fixation point. This robot will have four arms as shown in Figure 11. Inside its cylindrical shape it will have solar panels for energy and a toolbox. It has a main ionic drive for moving longer distances, and attitude control thrusters. In front, behind a dome, visual and non-visual sensors are located. Additionally, sensors are located at the ends of the robotic arms.

A different robot will deploy the hybrid PV-antenna panels. This robot also will have an ionic drive and solar panels. It can retrieve the packets of folded hybrid PV-antenna elements and deploy them from the main longitudinal axis towards the ring truss as shown in Figure 12.

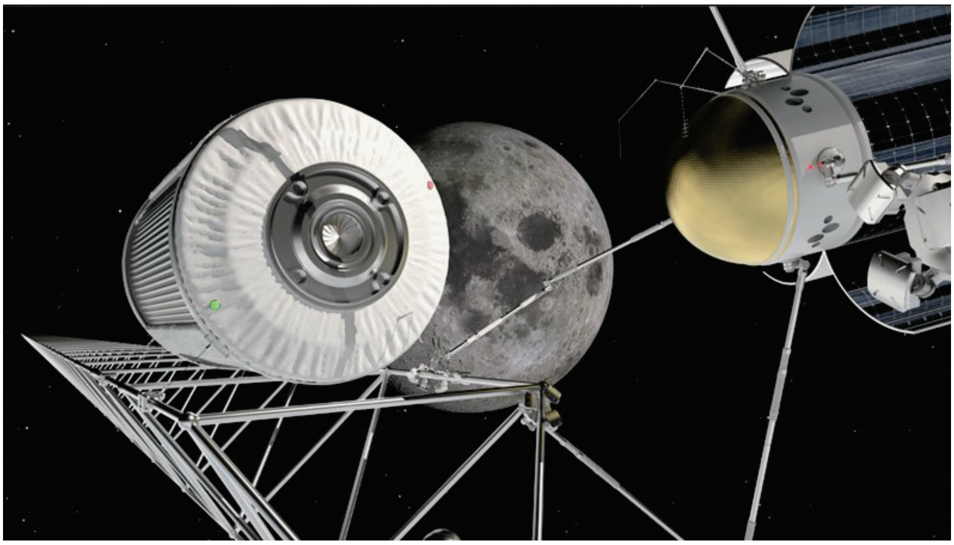

Figure 10: Construction robot assembling the rim truss of the GE⊕-LPS. Microgravity tube container on the left. (Credit: Astrostrom)

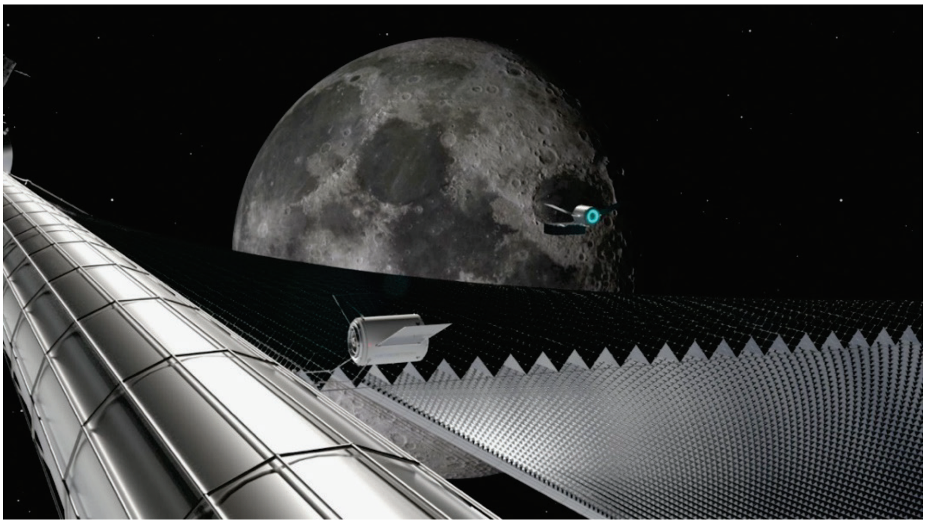

Figure 11: Small robot with ionic drive deploying the hybrid PV-antenna modules. (Credit: Astrostrom)

6.2.10. The Greater Earth Cislunar Transportation System

The development and implementation of the GE⊕-LPS infrastructure will require the establishment of an Earth-Moon transportation infrastructure called the Greater Earth Cislunar Transportation System (GE⊕-CTS). Not only will this be necessary for the implementation of the GE⊕-LPS, but this will have many significant benefits for cislunar space development such as lowering costs through standardization and modularity and increasing flexibility. The GE⊕-CTS is divided into different segments which are designed to correlate with the GE⊕-LPS development plan taking place in cislunar space. The first segment of the GE⊕-CTS will be deployed in LEO and, in the initial phases, will rely on existing launch technology. Once the core infrastructure of the GE⊕-CTS is established, crew and cargo flow can be handled with economical small reusable rockets.

The need for a **European reusable heavy-lift launcher (ERHLS)** is obvious for future independent space capabilities, particularly when planning human and cargo missions to the Moon. It will also be useful for setting up the GE⊕-CTS. Setting up initial mining and processing operations on the surface of the Moon will require the involvement of a human crew to supervise, manage and troubleshoot the deployment of the initial facilities. Thus, a **crew version of the ERHLS** will become necessary. Building infrastructure in LEO is an important first step in the GE⊕-CTS.

The **LEO Cargo Relay Station (LEO-CRS)** will be an orbital platform that serves to decouple the logistical differences of flying through Earth atmosphere and flying through space. Placed in an equatorial orbit, it is easily accessible from the European spaceport at Kourou, French Guiana. The equatorial orbit would allow a launch window every 1.5 hours, which would further increase flexibility of space access. In the first instance, the **LEO-CRS will be an orbital platform for developing and testing the various technologies essential to the GE⊕-LPS concept.** Initially, the structure will be a testbed for robotic and telerobotic assembly technologies as well to test the various construction materials such as basalt truss elements and fixation techniques that will be needed to construct the GE⊕-LPS.

A Cislunar Cargo Shuttle (CCS) is a spaceship which picks up cargo containers stored on the LEO Cargo Relay Station and transports these to the EM-L1 Hub Station and vice versa. Standardized cargo containers should be developed for the GE⊕-CTS, which can provide intermodal freight transportation in reusable rockets, ion drive transporters, space elevators and surface transportation elements.

EM-L1 will be the location of the main hub, cargo storage, habitat, construction, and satellite assembly site. It will also be arrival point of the of the Cislunar Cargo Shuttle and the Lunar Landing Gantry and later of the Lunar Space Elevator GE⊕-LSE. **The EM-L1 Hub**, with its cargo and supply storage docks which allow the interchange of goods to different transportation modes, will probably become the busiest location in cislunar space, similar to a sea harbour on Earth.

To shuttle large and heavy cargo from EM-L1 to the lunar surface and back a **Lunar Landing Gantry (LLG)** capable of soft landing 10-12 tons on the lunar surface is proposed.

As mentioned, the **Greater Earth Lunar Space Elevator (GE⊕-LSE)** will use cables or tethers to move materials from an anchor point on the surface of the Moon to a docking station at EM-L1 and eventually beyond towards a High Earth Orbit near GEO.

6.3. Economic Considerations

Due to the high-costs and logistical launch bottleneck confronting any future Earth-launched Solar Power Satellite system, a business case was made for a GE⨁-SPS - the lunar approach to SPS procurement once the infrastructure on the Moon has been installed and is operational.

6.3.1. Initial Infrastructure Investment

The implementation of the GE⨁-LPS concept would require an infrastructure investment estimated to cost less than €100 billion, which according to BloombergNEF's European Energy Transition Outlook 2022, would be less than 2% of the anticipated European energy transition budget of 5 trillion Euros. This amount is comparable to other major space projects, but with the fundamental difference that GE⨁-LPS will result in a very significant commercial return on the initial investment.

Figure 12: GE⨁-LPS System Initial Infrastructure Investment. (Credit: Astrostrom)

However, the overall implementation cost of the GE⨁-LPS includes the research and development of a SPS system (€15 billion), a European Reusable Heavy Launch System (€10 billion) with a similar design and capacity as the Starship heavy launch System and a Lunar Space Elevator (€11 billion). These three items constitute €36 billion of the proposed infrastructure budget and could be developed independently of the GE⨁-LPS concept's initial investment, in which case the incremental cost of GE⨁-LPS would be reduced to €63 billion. This infrastructure budget anticipates 467 heavy lift launches delivering 5,500 metric tonnes of material to EM-L1 or to the surface of Moon and a crew of 6 to supervise and manage operations.

The resulting advantage for lunar manufactured and launched SPS components is quite robust with respect to development costs, in the sense that, even if the initial development costs were 100% higher than estimated here, the economic and environmental advantage of delivering SPS components from the lunar surface instead of the Earth's surface is so large that, while the time to reach break-even would be longer, the cost of lunar-manufactured components in GEO would still become cheaper than terrestrial components as the scale of SPS power supply to Earth increases.

6.3.2. Lunar produced SPS compared with terrestrially produced SPS

Once GE⊕-LPS concept was operational on the Moon, the study used the proposed 1.44 GW GE⊕-SPS described in the Frazer Nash/London Economics Cost/Benefit Analysis to make a system and a Levelised Cost of Electricity (LCoE) comparison. The results were:

Frazer-Nash *(FNC/LE, (2022)*:

- €7.6 billion per deployed 1.44-GW CASSIOPeiA (10th system)
- 54 SPSs = €418 billion delivering 70 GWe
- 2,491 MT per SPS = 134,514 MT launched to GEO
- **LCoE: €156/MWh**

GE⊕-SPS:

- €3.6 billion per deployed 1.44-GW GE⊕-SPS (10th system)
- 54 GE⊕-SPSs = €192 billion delivering 70 GWe
- 400 MT* per GE⊕-SPS launched to EM-L1 = 21,600 MT
- **LCoE: €74/MWh**

** Assuming 20% of the mass of the GE⊕-SPS will be launched from Earth*

6.3.3. Profit/Loss Estimate of a GE⊕-SPS

The **total cost per GE⊕-SPS of was estimated at €5,600 million** which includes €3.6 billion for the hardware and launch and €2 billion for financing, operations, and maintenance. Supplying 11,352,960 MWh of electricity per year, the profit/loss calculations indicated a yearly net profit of €589,829,524 or a net profit of €17,694,885,729 over the 30-year operational lifetime of the system. This profit was based on a reference **Wholesale Price of Electricity (WPoE) of €150/MWh** and the difference between this and a **Levelised Cost of Electricity (LCoE) of €74/MWh**. (Figure 14)

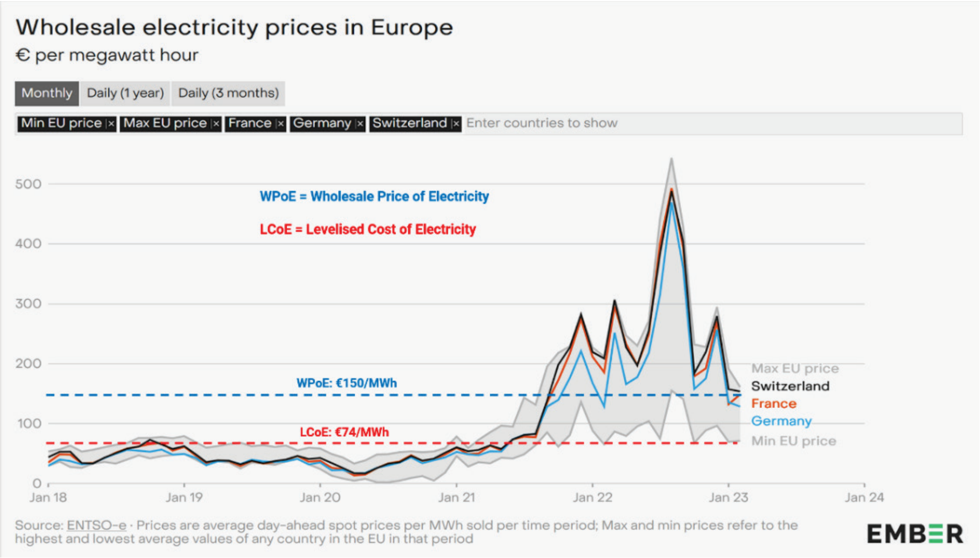

Figure 13: Wholesale Electricity Prices in Europe and the GE⊕-SPS (Image credit: ember-climate.org)

Delivering the same amount of baseload power that was supplied by nuclear energy in 2021 (882.8 TWh) would cover 11% of Europe's projected electricity needs in 2050 with 101 GWe of baseload power and provide 886 TWh of clean electricity per year. This scenario could generate a **potential net profit of approximately €1.4 trillion over a 30-year period** with 78 GE⊕-SPS systems in operation.

6.3.4. Economic Synergies and Flywheel Effects

Implementing the GE⊕-LPS will have a catalytic pull-effect on other cislunar technological and industrial developments and will thereby create new business opportunities which will become economically self-sustaining. These include:

- Reusable Launcher Development
- Cislunar Space Elevator
- EM-L1 Economic Hub
- Greater Earth International Energy Consortium
- Mining Industry
- Construction Industry
- Energy Industry
- Lunar Industrial Development
- Common Utilization of In-situ Resources
- Rocket Propellent Production
  Life Support Systems
- In-Situ Energy Production and Storage
- Space Tourism

The development and growth of the GE⊕-LPS system will build upon several "flywheel effects", which accelerate each other, build greater momentum, and maintain growth over a long time. As shown in Figure 15, the initial driver is the need for a green baseload energy source supplying the growing terrestrial electricity market, which is worth trillions.

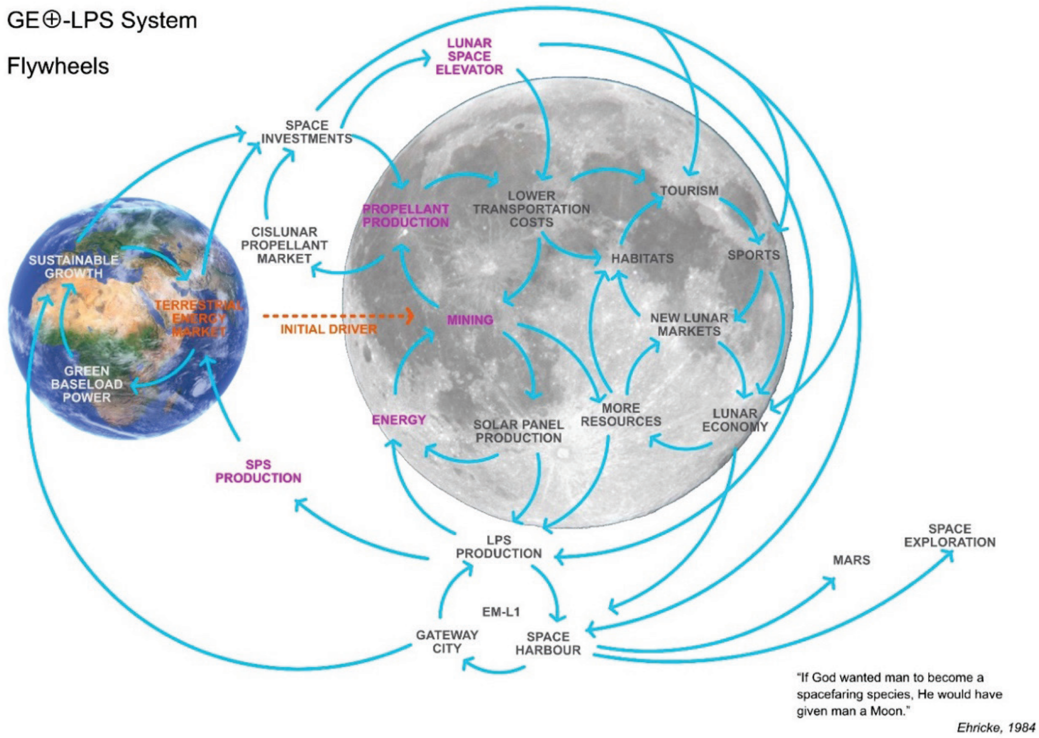

Figure 14: The GE⊕-LPS System Flywheel Effects. (Credit: Astrostrom)

6.3.5. Greater Earth Energy Organization - GEEO

With the projected implementation costs on the order of one hundred billion Euros to help achieve Europe's energy goals, a multi-national approach was deemed likely and necessary. The study proposes the incorporation of a **Greater Earth Energy Organisation (GEEO)** based on existing and established organizational examples, such as Intelsat and ESA, as an approach to implementing the *Space Energy Option* and, by doing so, taking a first step in creating a new space energy industry. The primary goal of the GEEO would be to provide Europe and eventually the entire world with an inexhaustible supply of environmentally clean energy in an equitable, economical, and socially just manner.

Ideally, the GEEO would be set up as a democratic organization composed of national entities independent of any other international organization or influence. A multi-national collaborative consortium working together would also allow expediency in addressing the regulatory issues of spectrum allocation, orbital positioning, and energy distribution. As an international consortium of nations, the GEEO should be incorporated as a not-for-profit organization with the means to provide the necessary initial development capital. The main advantage to having such a structure would be to avoid conflict between nations over space resources and infrastructure while providing a transparent process for the development and eventual distribution of this new and vital space energy resource.

6.4. Cultural Impact

Despite all the technological innovation and economic growth that enabled humanity to reach the threshold of becoming a spacefaring species, the 21st century has become a period of the Mega-Crisis. Multiple crises: economic, energy dilemma, climate emergency, environmental degradation, water scarcity, pandemics, leading to imposed restrictions on freedom, travel and thought and always accompanied by the ever-present threat of a new global war are impacting the human spirit. **The human spirit needs to believe in a future full of expectations, excitement, challenge, inspiration, and hope.** Expanding our civilization to the Moon and using lunar resources to address one of the most pressing issues on Earth may be the best way to ensure humanity's future. This would provide humanity with a purpose, and a motivation to achieve something transformative. It could unite the entire world in a shared mission with an enduring vision.

6.4.1. Enhancing the Overview Effect

More than 30 years ago, author Frank White used the term "Overview Effect" to describe the new awareness that is born in the psyche after viewing the Earth from orbit or from the Moon. White found that this experience profoundly affects astronauts' perceptions of themselves, of Earth, and of the future. Fundamentally, the Overview Effect is seeing the Earth as a whole system without borders or boundaries. Human expansion to the Moon will greatly increase the number of individuals who are able to experience or witness the Overview Effect, which will produce incalculable cultural benefits on Earth, including a stronger impetus for peace. At the very least, GE⊕-LPS operations on the Moon supplying clean energy to Earth will be **a powerful impetus for future space development.**

6.4.2. Choosing a Space Age or a Stone Age

The means to implement GE⊕-LPS exist today, and it is surely reasonable to assume that the technologies which need to be developed to implement the GE⊕-LPS project will continue to improve over coming years, making the project easier to complete. However, the same is surely not true of the energy situation on Earth. With international tensions arising from the inadequacy of energy supplies having already led in 2022 to the deliberate destruction of major pieces of energy supply infrastructure, it seems more likely that further delay in developing such a potentially major new energy source as SBSP would dangerously aggravate already increasing international frictions related to military spending, climate effects, migration, energy insecurity, inflation, water and food supplies, semiconductor production, etc.

Humanity has a choice to make. This study has shown that the GE⊕-LPS is both technically feasible and affordable. Its implementation would represent **choosing the *Space Option*.** Of all the options currently available to our species at this critical moment in its history, the *Space Option* offers humanity surely the most promising path to its long-term sustainability and survival. If implemented in time and with sufficient commitment, the ultimate reward would be a prosperous and dynamic planetary civilization living in a healthy environment as well as the creation of an infrastructure in space upon which the expansion of the human species throughout the solar system and beyond could be realistically anticipated.

However, if our species does not soon embrace this unique opportunity with sufficient commitment, it may miss this present chance to do so. Humanity may soon be overwhelmed by one or more of the many crises it now faces, and the window of opportunity may already be closing. The main challenge is to inform and convince the public and its leaders of the implications and viability of the GE⊕-LPS concept, and by so doing choosing the *Space Option* as the most optimistic alternative to the other current approaches to human destiny, of which our future will be either **"A Space Age or a Stone Age".**

7. Outstanding Challenges and Recommendations

Addressing each of the 'Outstanding Challenges' results in a specific recommendation. What is important is that all of the challenges need to be addressed as soon as possible and with commitment.

7.1. Technical Challenges

While the technical challenges are not trivial, it appears most can be solved with additional research and dedicated development programs. No major technological breakthroughs are necessary which is not the case for fusion energy technology. The approach taken to establish the feasibility of the GE⊕-LPS concept has been to identify the simplest technologies that have existing industrial precursors and engineer these to become compatible for the lunar environment. Indeed, the core technologies mentioned above can be deployed and tested on Earth and then packaged as modules for lunar operations.

The main technological challenges in need of immediate follow-up are:

- **Lunar Space Elevator**
  The Lunar Space Elevator (LSE) could be be made with existing materials available today such as: T1000 ™, Dyneema ™, Magellan-M5 ™, and Zylon ™ . These

materials need special attention for how they can be produced and deployed in the required mass and dimensions.

- **Lunar in-situ PV Fabrication**
  Dedicated research should be applied to enhance the efficiency level of Monograin Layer (MGL) photovoltaic production with the aim to develop a functioning modular factory that could be transported to the Moon and deployed in an operational state.
- **Lunar Materials Processing**
  Industrial-scale lunar material processing will require a considerable amount of solar heated furnaces, piping, cryo-chillers, insulated tanks, etc. At first, precursor demonstrators and experimental ISRU facilities on Earth will be needed to better understand the processing of regolith on the Moon.
- **Electronics and Semiconductors**
  Semi-conducting materials such as silicon, ilmenite and pyrite are available on the Moon. The focus will be to use these materials for electronic component production.
- **Thin Film Technologies**
  Given the fact that up to 80% of the mass of a SPS can be the solar panels, it is important to develop a glass-free thin film technology such as MGL to be manufactured on the Moon.
- **Lunar Propellant Production**
  Lunar propellant production is a priority for all proposed lunar operations and will be important in the first phase of establishing the GE⊕-LPS system especially for refuelling the Lunar Landing Gantry.
- **European Reusable Heavy Lift Launch System**
  Accelerated development of a European reusable heavy-lift launcher (ERHLS) is an obvious priority for future independent space capabilities, particularly when planning human and cargo missions to the Moon.

7.2. Financial Challenges

An initial investment of €99 billion may seem daunting when compared to the yearly budget of the European Space Agency which was €6.5 billion 2021 or even NASA's $24 billion budget in 2022. However, this large sum is realistic when seen in the context of what is necessary to achieve the clean energy goals being pursued by various countries. The study **proposes a 3-step financial development path for GE⊕-LPS development** shown in Figure 16. Once this study is approved and published, €5 million should be dedicated to solidifying the results through additional feasibility studies addressing the core technological challenges. €5 million should be invested in fundraising, investor acquisition and marketing research focused on the energy market and potential stakeholder investors. The goal would be to create a momentum for initiating Step 2 to establish a stakeholder consortium such as the proposed GEEO with a yearly annual budget of €100 million.

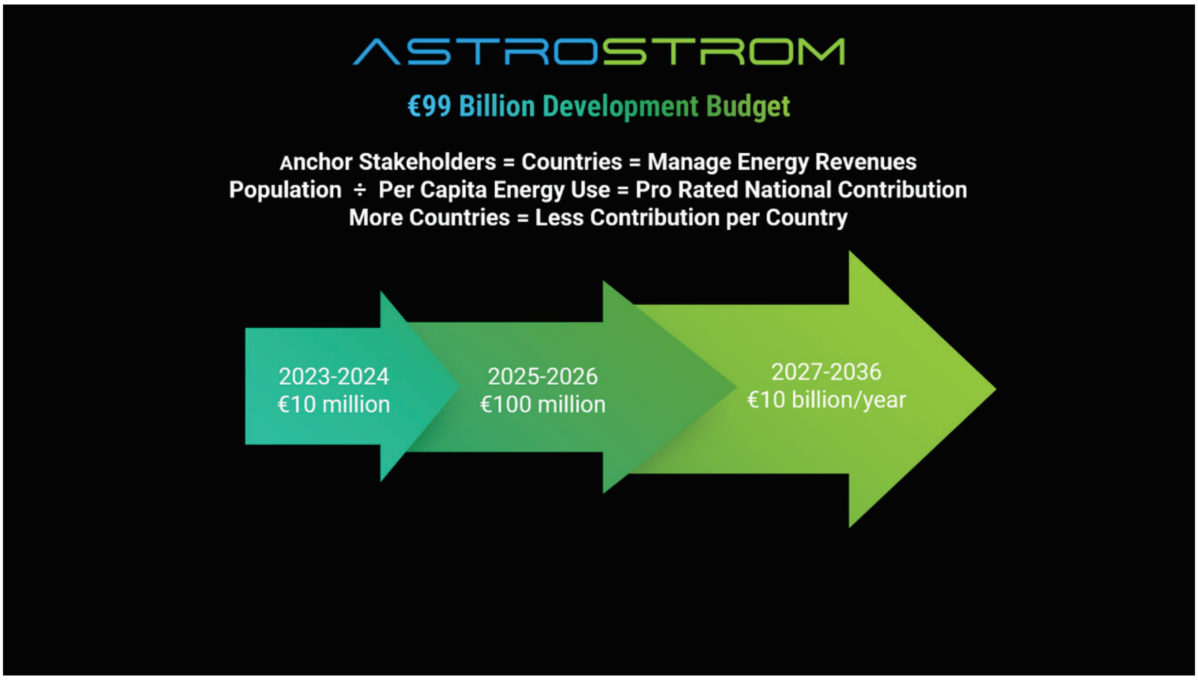

Figure 15: 3-Step approach for financing the GE⊕-LPS concept. (Credit: Astrostrom)

On the technical side, enhanced R&D, followed by successful demonstrations and prototyping, as well as societal analysis, should lead to a convincing rationale sufficient to create the broad international consensus needed to attract more stakeholders and inaugurate implementation. Once the stakeholder consortium is established and operational, the necessary yearly budget needed to implement the GE⊕-LPS concept can be evaluated, implemented, and shared by the members of the consortium and distributed to their local industries. **As such, 10 years would be needed to fund and implement initial GE⊕-LPS operations.**

7.3. Geopolitical Challenges

While the technological and financial challenges are large but not insurmountable, **the geopolitical challenges may be the most difficult to overcome**. Recent geopolitical events related to the Ukraine conflict have again highlighted that fact that the control of fossil fuels has been and will continue to be a major factor in geopolitical conflicts, which also directly impacts the energy market and the economies of the nations most dependent on importing a reliable supply of energy. Therefore, a large multi-national consortium of nations dedicated to jointly developing the *Space Energy Option* as described in this study would seem to be the best way forward. As the GE⊕-LPS concept represents a significant industrial development program that spans cislunar space to service the terrestrial energy market, **international legal cooperative arrangements and agreements will be a prerequisite for its eventual success**. The creation of a cislunar transportation infrastructure and the ability to supply Earth with an inexhaustible source of clean energy will surely be disputed if only one nation or even if a small group of politically aligned nations takes the initiative. Ideally, a large multi-national organization such as the proposed GEEO will secure the necessary collaboration and legal authority to implement and manage such an operation. In many ways this could significantly contribute to easing many of the geopolitical tensions currently associated with control of resources on Earth.

8. Path Forward

The study describes the path forward as a series of successive time-specific developmental milestones.

8.1. 2023-2024

- €10 million funding milestone
- Establish the GEEO
- Conduct comprehensive LSE feasibility study
- MW-scale ground WPT demonstration
- Investment in MGL PV technology to increase efficiency
- Investment in basalt fabrication technology to make it lunar compatible
- PR and marketing activities directed at national energy departments and industries
- LEO-CRS technical and engineering study
- ERHLS development kick-off

8.2. 2025-2026

- €100 million funding milestone
- GEEO organizational development and staffing
- Recruit additional member nations to join stakeholder consortium
- Consolidate the legal parameters for cislunar transportation and energy operations
- Distribution of Phase A/B development contracts for LSE and lunar manufacturing
- Orbital demonstration of WPT

8.3. 2027-2036

- €100 billion funding milestone (€10 billion yearly)
- Deploy first segment of the LEO-CRS platform via robotic assembly operations
- Deploy tether experiments from the LEO-CRS
- Deploy Space-to-space and space-to-Earth WPT demonstrations from the LEO-CRS
- Launch ERHLS prototypes
- €11 billion earmarked for LSE development and deployment
- €10 billion earmarked for development of the ERHLS

- €15 billion earmarked for GE⊕-SPS technology development
- €40 billion earmarked for delivery of initial lunar facilities to the Moon
- €5 billion earmarked for human crew and surface habitat
- €9 billion earmarked for initial GE⊕-LPS operations
- €5 billion earmarked for scaling lunar production facilities
- €5 billion earmarked for delivery of first GE⊕-SPS to Earth orbit

8.4. 2037-2050

- Goal 1: Production of one GE⊕-SPS per year for the terrestrial energy market
- Goal 2: Produce 20 GE⊕-SPSs to repay initial investment and finance future GE⊕-SPS production.

8.5. 2050 and beyond

- Install 100 GWe GE⊕-SPS capacity providing 886 TWh/year to Europe, i.e. 78 GE⊕-SPS @ 1.44 GW
- Invest profits in the production of additional GE⊕-SPS systems.

8.6. Roadmap

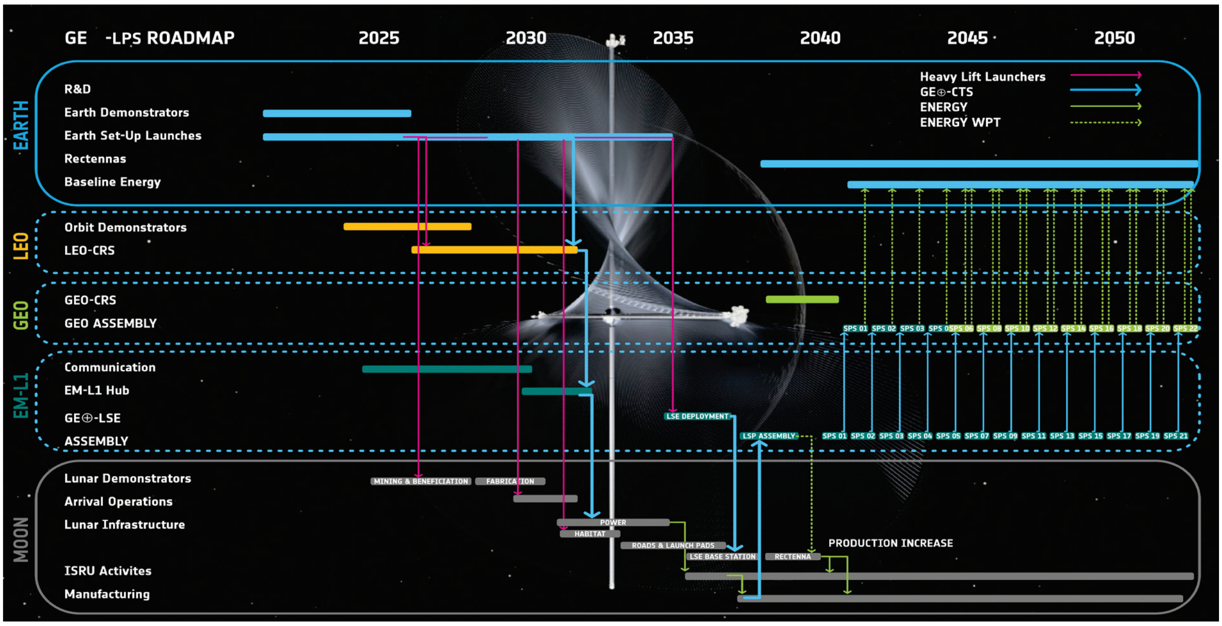

Figure 16: Proposed roadmap for the GE⊕-LPS deployment and GE⊕-SPS development.

9. Afterword

In the last two decades the technical, financial and socio-cultural conditions on Earth have changed to the extent where the ***"Space Energy Option"*** - to mine the Moon and fabricate Solar Power Satellites to supply the Earth's energy needs - has not only become realistically feasible but may become a near-term necessity.

The GE⊕-LPS study presented here has cast a new light on this energy from space dream, which emerged with the beginning of the space age around 50 years ago. Since then, the reliance on fossil fuels to power civilization has increased exponentially with all the accompanying negative consequences for the biosphere.

As a result, **all current outlooks for further growth and well-being on our planet are tagged with question marks**. Historically, in situations like this people chose to migrate to find a better future elsewhere on the planet. Today, as the planet is nearly completely occupied, extending human activities out into space is the only viable option. However, we do not propose to emigrate people to the Moon or elsewhere, but rather to begin using the resources located beyond the atmosphere to deliver green baseload energy to Earth and thus helping the biosphere to recover and stabilise by accelerating the elimination of fossil fuels.

The literature we studied and the proposals we make in this report show that, with the right commitment, **the "giant step" for humankind to become a spacefaring species**, with all its economic and cultural implications is indeed possible, and surely has never been so close to being within our reach as today. The window of opportunity is open as we submit this study.

The task is big: mining, beneficiation and fabrication processes must be fully automated and adapted for the lunar environment. However, human's experience on Earth in these fields is vast. A cislunar transportation infrastructure must be set up, and for the first time ever a lunar space elevator will need to be developed and deployed. However, **none of this is more complicated than 'rocket science**' and providing space engineers with new challenges.

Thus, if the GE⊕-LPS is considered feasible by the space community, its task will be to inform and convince the non-space community to seriously consider the Space Energy Option and **the choice which still needs to be made**. The path forward and the proposals made in this study may not be without problems, but the promise for humankind is no less than a sustainable clean energy future and starting a whole **new two-planet economy** without further exploitation of the home planet. And last but not least, it would give **future generations an outlook towards a more positive future**, based on successful human characteristics of exploration, innovation, and economical skills, which has brought us from a Stone Age to a Space Age, where we stand today. We can look back and we can look forward, but if human history teaches us one thing, it is: *Fortes fortuna adiuvat,* ***"Fortune favours the bold".***