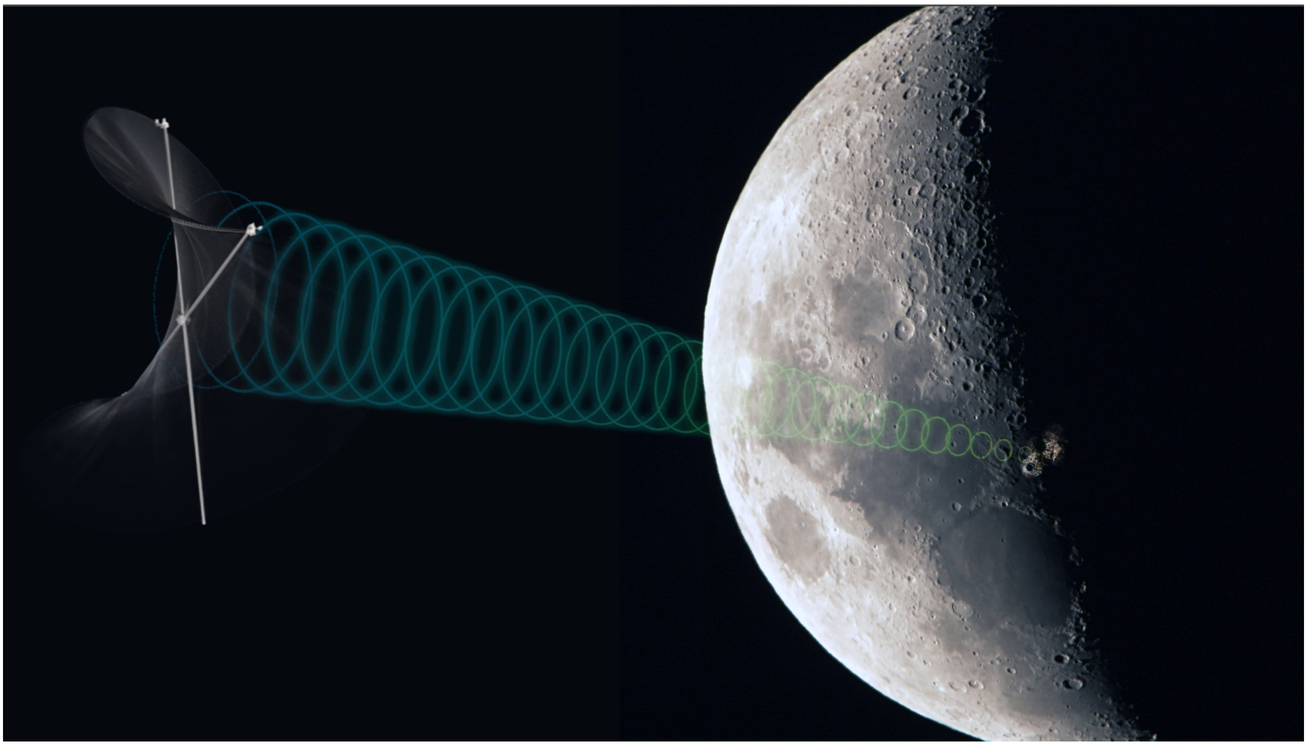
Greater Earth Lunar Power Station (GE⊕-LPS)



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

– FINAL REPORT –

Astrostrom GmbH

June 2023

Prepared by:
Arthur Woods – Team Leader, Project Manager, Cultural and Economic Analyst
Andreas Vogler – Chief Architect and System Designer
Dr. Patrick Collins – SBSP, Space Tourism and Economics Expert
Dmitrijis Gasperovics – Visualizer and Animator

ESA Contract No: 4000136309/21/NL/GLC/ov

Table of Contents

1. Acronyms

BP	British Petroleum
AM0	Air Mass Zero
BAU	Business as Usual
BIS	Bank for International Settlements
CAA	Civil Aviation Authority (UK)
CASSIOPeiA	Constant Aperture, Solid-State, Integrated, Orbital Phased Array
CCS	Cislunar Cargo Shuttle
CH	Confoederatio Helvetica (Switzerland)
CIO	Comité International Olympique
CLLSS	Closed Loop Life Support System
COPUOS	Committee on the Peaceful Uses of Outer Space
DoE	US Department of Energy
EEEC	European Electronic Communications Code
EIA	U.S. Energy Information Agency
EM-L1	Earth Moon Lagrange point 1
EM-L2	Earth Moon Lagrange point 2
ERHLS	European Reusable Heavy Lift System
ERML	European Reusable Medium-Size Launcher
ESA	European Space Agency
FAA	Federal Aviation Administration (US)
FCC	US Federal Communications Commission
FIFA	Fédération Internationale de Football Association
GAP	General Assembly of Parties
GE⊕	Greater Earth
GE⊕-CTS	Greater Earth Cislunar Transportation System
GE⊕-LPS	Greater Earth Lunar Power Station
GE⊕-LSE	Greater Earth Lunar Space Elevator
GE⊕-SPS	Greater Earth Solar Power Satellite
GEEO	Greater Earth Energy Organization
GEO	Geostationary Orbit
GSO	Geosynchronous Orbit
GTO	Geostationary Transit Orbit
GW	Gigawatt
GWe	Gigawatt electric
He-3	Helium-3
HEO	High Earth Orbit
HLS	Human Landing System
IAA	International Academy of Astronautics
IAASS	International Association for the Advancement of Space Safety
IATA	International Air Transport Association
IEA	International Energy Agency
IOC	International Olympic Committee
ISS	International Space Station
ITT	Invitation to Tender
ITU	International Telecommunications Union

kW	Kilowatt
kWh	Kilowatt hour
LCoE	Levelized Cost of Electricity
LEO	Low Earth Orbit
LEO-CRS	Low Earth Orbit Cargo Relay Station
LLG	Lunar Landing Gantry
LOX	Liquid Oxygen
LRO	Lunar Reconnaissance Orbiter
LSE	Lunar Space Elevator
LSP	Lunar Solar Power
MEO	Middle Earth Orbit
MGL	Monograin Layer
MPM	Mining Processing Manufacturing
MR-SPS	Multi-Rotary Joints Solar Power Satellite
MT	Metric Tonnes
Mtoe	Millions of tonnes of oil equivalent
MW	Megawatt
NASA	National Aeronautics and Space Administration
NZ	Net-Zero
OSIP	Open Space Innovation Platform
OST	Outer Space Treaty
OTV	Orbital Transfer Vehicle
PCA	Power Conversion Array
PMAD	Power Management and Distribution
PSB	Platform Structural Backbone
PV	Photovoltaic
R2R	Roll-to-Roll
RASSOR	Regolith Advanced Surface Systems Operations Robot
RF	Radio Frequency
SBSP	Space-Based Solar Power
SDG	Sustainable Development Goal
SEP	Solar Electric Propulsion
SPS	Solar Power Satellite
SPS-ALPHA	Solar Power Satellite by means of Arbitrarily Large Phased Array
SRA	Solar Reflector Array
SSP	Space Solar Power
TES	Total Energy Supply
TFT	Thin Film Transistor
TW	Terawatt
TWe	Terawatt electric
TWh	Terawatt hour
UNOOSA	United Nations Office for Outer Space Affairs
WHO	World Health Organization
WPoE	Wholesale Price of Electricity
WPT	Wireless Power Transmission

2. Energy Measurements

- A kilowatt (kW) is a unit of power equal to one thousand watts.
- A megawatt (MW) is a unit of power equal to one million watts.
- A gigawatt (GW) is a unit of power equal to one billion watts.
- A terawatt (TW) is a unit of power equal to one trillion watts.
- A gigawatt hour (GWh) is a measure of energy.
- One GWh is the electrical energy consumption rate equivalent to a billion watts consumed in one hour.
- One TWh is the electrical energy consumption rate equivalent to a trillion watts consumed in one hour.
- One GWh is equivalent to 3,600 gigajoules = 3.6 terajoules (TJ).
- One GWh = 3,600,000,000,000 Joules.
- One TWh = 3,600,000,000,000,000 Joules.
- One TWh is equivalent to 3,600 terajoules (TJ) = 3.6 Petajoules (PJ).

How Much Power is 1 Gigawatt?
(Source: Energy.gov, 2022)

1. One gigawatt (GW) = 1 million kilowatts (kW) = 1 thousand megawatts (MW)
2. One GW = 3,125,000 Photovoltaic (PV) panels
   One PV panel = 320 watts.
3. One GW = 333 Utility-Scale Wind Turbines
   An average utility-scale wind turbine size of 3 megawatts (MW) installed.
4. One GW = 100 million LEDs
   A light-emitting diode (LED) A19 lamp is roughly 92 lumens per watt and consumes about 10 watts.
5. One GW = 1 million microwave ovens
   One microwave oven = 1,000 watts.
6. One GW = about 1.3 million horses
   Based on horsepower to watts conversion: 746 watts = 1 horsepower.
7. One GW = 2,000 Corvette sport cars
   The Chevrolet Corvette Z06 engine delivers 670 horsepower. 2,000 of those engines would equal 1.34 million horsepower, or 1 GW.
8. One GW = 9,090 Nissan Leaf electric cars
   The Nissan Leaf has a 110-kilowatt (kW) motor. 1 million kW divided by 110 kW = 9,090 Nissan Leaf electric vehicles.

3. The Study Team

3.1. Astrostrom GmbH

This study has been managed under the auspices of Astrostrom GmbH.

Astrostrom GmbH
Talacker 12
8259 Kaltenbach
Switzerland

CEO: Arthur Woods
Tel. +41 (0) 52 742 37 40
E-mail Contact: admin@astrostrom.ch
Website: astrostrom.ch

VAT/Firm Number UID: CHE-107.353.894
Commercial Registry Office: Canton of Thurgau
District Court: City of Frauenfeld

ESA Bidder code: 1000007938

The primary purpose of Astrostrom is to introduce, promote and expand upon the economic, technological and cultural dimensions of harvesting of clean and plentiful energy from space. The company was incorporated in 1996 under the name Swissart GmbH and changed its name to Astrostrom GmbH in 2021 to reflect its new orientation. Astrostrom GmbH functions as a think-tank of industries, institutions, organizations, and individuals dedicated to developing and providing clean and inexhaustible energy from space to Europe and the world.

In 2021 Astrostrom's proposal "S.O.S. – Space Option Star" (Idea: I-2020-05263) submitted to the OSIP campaign "What's next? New space mission ideas and concepts" was selected from the 201 submitted ideas. The Space Option Star (SOS) is a Space Solar Power (SSP) demonstrator and represents a logical early step for any Space-Based Solar Power (SBSP) development program. The SOS mission has a dual purpose: first, its technical mission represents an in-situ demonstration of SBSP technologies and, secondly, its communication mission is to raise public awareness about the potential of the Space Energy Option to address the Energy Dilemma and the Climate Emergency facing the world population.

The current study called "GE⊕-LPS Greater Earth Lunar Power Station" (Idea: I-2020-05847) submitted to the OSIP campaign 'Clean Energy – New Ideas for Solar Power from Space' was selected from the 85 submitted proposals and was awarded a one-year study contract (ESA STAR 2-1789/21/NL/GLC/ov - GE⊕-LPS).

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.

3.2. Overall Team Composition

1. Arthur Woods – Team Leader, Study Manager, Cultural and Economic Analyst
2. Andreas Vogler – Chief Architect and System Designer
3. Dr. Patrick Collins – SBSP, Space Tourism and Economics Expert
4. Dmitrijis Gasperovics – Visualizer and Animator

3.2.1. Arthur Woods

Arthur R. Woods is a Swiss independent researcher and astronautical artist with two art-in-space projects successfully flown on the Russian Mir space station: the Cosmic Dancer sculpture in 1993 and Ars Ad Astra: The First Art Exhibition in Earth Orbit in 1995 during the EuroMir95 mission. He studied at Mercer University from 1966-1970. His astronautical artwork has been exhibited in a number of international space and art exhibitions. He grew up in the vicinity of the Kennedy Space Center in Florida between 1959 and 1970 and worked at the space center in the summers of 1967 & 1968 during the Apollo program. He began his astronautical art career in the mid-1980s with the introduction of the Orbiting Unification Ring Satellite project to celebrate the new millennium with 'a circle in the sky'. In its development program, in 1988 he signed an agreement with Glavkosmos of the USSR to deploy a prototype sculpture called OUR-SPS during a spacewalk from the Mir station during the 1992 International Space Year. The inflatable sculpture was first planned to be built with European space technology but, when this became unavailable, a full-size inflatable object was built by NPO Energia in 1990. In the development of these projects, he negotiated directly with NASA, ESA and the Russian space agency. In 1990 he founded the OURS Foundation, a cultural and astronautical organization dedicated to identifying and developing a cultural dimension to humanity's space endeavours. Together with Dr. Marco C. Bernasconi, he is co-author of the Space Option concept – an evolutionary plan to meet the basic and anticipated needs of humanity with the addition of adding near Earth resources - especially energy - for use on Earth to meet humanity's growing needs. He and Bernasconi were also the originators of the Greater Earth concept – a new perception of our planet which extends its true dimension into cislunar and geolunar space. He has co-managed several studies for the European Space Agency and the International Academy of Astronautics (IAA). He is a full member of the IAA and member of the IAA Permanent Committee on Space Solar Power. Currently, he is co-chair of the Moon Village Association's Cultural Considerations Working Group.

3.2.2. Andreas Vogler

Andreas Vogler is a Swiss architect working in the fields of aerospace, art and architecture. His speciality is design-driven system innovation in various fields of technology. His work encompasses architecture, transportation design and robotics and, specific to space, includes designs for habitats and manned rovers for Moon and Mars as well as inflatables. As scientific assistant at the Technological University Munich in 1999, he participated zero-gravity flights with NASA Houston with his students, testing equipment for the International Space Station ISS. He is one of the very few pioneering artists to have successfully realized an artwork specifically designed for the micro-gravity environment of a space habitat. His extensive portfolio of architectural projects includes many concepts related human habitation in space including 'Moon Capital' (2010) a design proposal for a Second-Generation Habitation on the Moon located on the rim of Shackleton crater at the Lunar South Pole based on current technology and scientific knowledge. 'Project Enterprise' to bring tourists into suborbital space from Germany, 'MoonVille' a design of a permanent lunar settlement in the year 2050 providing living and workspace for 100 inhabitants and visiting tourists and 'MoonRolly' (2009) a PLR (Pressurized Lunar Rover) that was phase 0/A study for the European Space Agency's Aurora Core Exploration Programme, conducted with Thales Alenia as main contractor. The six-wheeled, pressurized rover is powered by solar arrays and fuel cells. Together with DLR German Aerospace Center, Institute of Vehicle Concepts DLR he developed an advanced high-speed double-deck train concept for the UK. He was co-director for the Astrostrom produced SOLARIS video commissioned by ESA.

3.2.3. Dr. Patrick Collins

Dr. Patrick Collins is a British expert on space solar power and space tourism currently residing in Japan. He is chairman of the Society for Space Tourism of Japan (SSTJ) and Emeritus Professor of Azabu University, where he taught economics for 19 years. Earlier he was a Guest Researcher at the Research Center for Advanced Science and Technology of Tokyo University (RCAST), the National Space Development Agency (NASDA), the National Aerospace Laboratory (NAL) and the Institute for Space and Astronautical Science (ISAS) in Japan. Before that he was Senior Lecturer at Imperial College in London, where he wrote his doctoral thesis on the economics of solar power satellites, while also working as a part-time researcher at ESTEC. Currently, he is a Vice-President of Space Renaissance International. The focus of Dr. Collins' research for the past 40 years has been how to stimulate growth of commercial space activities, the two most important opportunities being tourism and solar power satellites, including their use as snow melting satellites (SMS) – topic he has co-authored with Marco Bernasconi. He has written some 200 publications.

3.2.4. Dmitrijis Gasperovics

Dmitrijis Gasperovics resides in Latvia and is a specialist in computer 3D animation and video realization using Blender 3D, Unreal Engine and Houdini for Fluid Simulations with a dedicated interest in space technology visualizations. He is a freelance CGI developer whose work in the form of pre-rendered animations and After Effect templates are available on the VideoHive platform. Many of his products depict spacecraft, space stations, rocket launches and astronauts. Since 2017 Gasperovics has worked for Arthur Woods to produce custom project specific CGI animations and 3D illustrations. In addition to many animations for the Greater Earth project, he made the renderings for this GE⊕-LPS proposal and the launch and deployment sequences for the Space Option Star project, both selected by ESA for further development. As a member of the study he regularly contributes visualizations and video animations of the concepts being developed. He was the chief animator for the Astrostrom produced SOLARIS video commissioned by ESA.

3.3. External Experts

Various external experts were consulted over the course of the study:

- Dr. Marco C. Bernasconi, Astronautical Engineer
- Dr. Taavi Raadik, Talllin Technical University, MGL PV Technology
- Prof. Dr. Dieter Meissner, crystalsol GmbH, MGL PV Technology
- Dr. Matthias Krieger, Thin-film PV space technology
- Tim Cash, RF and WPT engineering specialist
- Dr. Charles Radley, Lunar space Elevator
- Dr. Marshall Eubanks, Lunar Space Elevator
- Georgi Gogoladze, Deutsche Basalt Faser GmbH, Basalt technology
- Dr. Alexander Niecke, RWTH Aachen University, MoonFibre Basalt technology

4. Introduction

"*If God wanted man to become a spacefaring species, he would have given man a Moon." (Krafft A. Ehricke*, 1984)

"The share of the world's population with access to electricity rose from 83 percent in 2010 to 91 percent in 2020. The number without access declined from 1.2 billion people in 2010 to 733 million in 2020. At current rates of progress, the world will reach only 92 percent electrification by 2030. To meet the target of Sustainable Development Goal (SDG) 7 and to achieve universal electricity access by 2030, the pace of electrification needs to accelerate significantly." (Tracking SDG 7, 2022)

"Over the second half of the 20th century, with living standards in the West and other advanced economies rising, the growth in energy demand accelerated even more. Those dynamics have continued into this century, as China has helped power global GDP to a median rise of 3.7 percent per year since 2000, with global energy demand continuing to rise as well. And 21st-century economies will continue their ascent. The world population will continue to grow, potentially reaching ten billion by mid-century; the plateauing of Chinese and Organisation for Economic Co-operation and Development (OECD) populations will be more than offset by significant increases in India, other parts of Asia, and, especially, Africa, where more than 50 percent of the world's projected population increases will occur through 2050." (McKinsey & Company, 2019)

"World electricity demand remained resilient in 2022 amid the global energy crisis triggered by Russia's invasion of Ukraine. Demand rose by almost 2% compared with the 2.4% average growth rate seen over the period 2015-2019. The electrification of the transport and heating sectors continued to accelerate globally, with record numbers of electric vehicles and heat pumps sold in 2022 contributing to growth. Nevertheless, economies around the world, in the midst of recovering from the impacts of Covid-19, were battered by record-high energy prices. Soaring prices for energy commodities, including natural gas and coal, sharply escalated power generation costs and contributed to a rapid rise in inflation. Economic slowdowns and high electricity prices stifled electricity demand growth in most regions around the world." (IEA, Electricity Market Report, 2023)

"Energy conversions are the very basis of life and evolution. Modern history can be seen as an unusually rapid sequence of transitions to new energy sources, and the modern world is the cumulative result of their conversions." (Smil, Vaclav, 2022)

"According to the Intergovernmental Panel on Climate Change (IPCC), limiting global warming to 1.5°C requires net human-caused carbon dioxide (CO_2) emissions to fall by 45% by 2030 and to reach net-zero by 2050. Even limiting the temperature rise to 2°C will require CO_2 emissions to fall by 25% by 2030, requiring a turnaround of the present trend." (WEF, 2020)

"Clean energy transitions offer major opportunities for growth and employment in new and expanding industries. There is a global market opportunity for key mass-manufactured clean energy technologies worth around USD 650 billion a year by 2030 – more than three times today's level." (IEA, January 12, 2023)

Humanity is at a crossroads. After more than 200 years of using fossil fuels to power modern civilization, it must soon decide if it prefers to live and prosper in an energy rich world or attempt to survive in an energy poor one. Approaches to finding a viable solution to the imminent climate and energy crises which are confronting humanity and an analysis of the energy options currently available are urgently necessary. The fundamental causes of these interrelated crises are the many environmental and geopolitical issues associated with the continued use of fossil fuels added to the fact that continued reliance on fossil fuels is projected to become problematic and conflict prone in the coming decades. Thus, a sensible transition to reliable, sufficient, and environmentally neutral alternative sources of energy is imperative in order to preserve and sustain present civilization and to provide future generations with adequate energy and a realistic hope for future prosperity and peace.

The GE⊕ 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 MW 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 help 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.**

Space-Based Solar Power (SBSP) and space tourism could become synergistic economic drivers for future space development. The GE⊕-LPS concept incorporates both of these aspects. The elements of the GE⊕-LPS would be constructed primarily from lunar resources using a highly automatized manufacturing process which are then transported to the Earth-Moon Lagrange point 1 (EM-L1) for robotic assembly. The GE⊕-LPS design allows for the central placement of a habitat and control centre that uses water and regolith for radiation shielding. The GE⊕-LPS incorporates an ion electric propulsion system to enable artificial gravity for crew and guests as well as to provide manoeuvrability and attitude control. If shown to be technically feasible, the lunar manufacturing operations could be scaled to any dimension, and SPSs assembled in lunar orbit could provide much needed clean solar energy for terrestrial purposes.

The GE⊕-LPS study has three main objectives:

1. To describe an optimized technological approach to develop a realistic Space-Based Solar Power concept using lunar resources to address the energy dilemma and climate emergency crises on Earth by mitigating the launch logistical challenge of SBSP,
2. to explore the economic parameters that would justify and enable its implementation, and,
3. to provide an inspiring and pragmatic approach for developing humanity's cislunar aspirations.

The present study commenced in late 2021. It 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 is consolidating its position as an emerging space nation with competing economic and geopolitical agendas.

The goals for obtaining a net-zero society by 2050 have put many governments under intense pressure. However, when the study started, there was no anticipated limitation of inexpensive Russian natural gas and consequently, only very few seemed seriously concerned about the impending energy dilemma facing European and other societies. The fallout from the Ukraine conflict is hitting generations of Europeans which never experienced the ravages of war nor a decrease in wealth during their lifetimes. 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.

With this study we present an exciting 'space option' to mitigate both the green energy dilemma and the de-industrialization resulting from an energy poor world by initiating a new cislunar economy. The available resources, the know-how, the technological development, which have all accelerated in the last 25 years, have never been in a better constellation than today, to make such a bold and innovative step towards the Moon - not as much for science and exploration - but for fulfilling human energy needs on Earth and with an unparalleled business case for doing so.

4.1. Background to the Study

In recent years the need and demand for new sources of reliable and clean energy has become one of the dominating topics in international discourse. Measurable effects of human-induced global warming have been widely accepted and major industrial states are committed to reduce global warming to 1.5° C above the preindustrial state. The "Paris Agreement" sometimes referred to as the Paris Accords or the Paris Climate Accords, was adopted in December 2015, , which set the long-term goal of keeping global warming "well below" 2 degrees Celsius above pre-industrial levels, and ideally to 1.5 degrees Celsius. The Agreement is a legally binding international treaty. It entered into force on 4 November 2016. Today, 194 Parties (193 States plus the European Union) have joined the Paris Agreement.

The continued use of carbon fossil fuels to power human activities is no longer considered tenable nor desirable while, at the same time the easy access to harnessing these fuels diminishes. Alternative terrestrial energy sources are being developed and deployed at an increasing pace, yet these represent only a small percentage of the current global energy mix which is still overwhelmingly dominated by fossil fuels. To accelerate the transition to new energy sources, policies and measures are being implemented to restrict the use of fossil fuels even though current energy alternatives cannot be deployed on a sufficient scale to reliably power modern civilization in the developed countries and to provide adequate energy for developing countries to escape poverty. With the planned conversion from a fossil energy dependency to (green) electrical energy, the resource race has got a new dimension. The race for lithium is just one example.

Furthermore, many governments and organisations fail to address the real causes of the worsening energy situation and discourage useful discourse. This has resulted in creating much uncertainty and insecurity with regards to how energy use will be sustained in the immediate future and how civilization will continue to maintain living standards and even to prosper.

Additionally, geopolitical events with energy related consequences have led to a contraction of energy use and restricted access to fossil fuels sources in the western societies. The need to urgently develop new sources of energy that are reliable, sustainable, and capable of growing to very large scale worldwide has very recently become even clearer due to the geopolitical fallout from the conflict in Ukraine. This has been very sudden and shows the need for sufficiently abundant and secure energy supplies to provide countries the flexibility needed to adapt to such disruptions. In this situation, there is surely no sound reason not to invest in at least studying the feasibility of SBSP as one potentially major contributor to solving this problem, in view of the many benefits it offers over existing energy options.

This developing and complex situation has stimulated a renewed interest in the feasibility of 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 while becoming ever more sophisticated and capable. Consequently, new SBSP initiatives have appeared in various parts of the world. Thus, a 'Window of Opportunity' appears to have opened if SBSP development plans can be introduced with sufficient urgency and commitment. However, in addition to the substantial up-front costs of SBSP development, a major obstacle to realizing clean energy from space at scale remains the logistical challenge of launching thousands of rockets from the surface of Earth to deploy 100's of gigawatt-scale power satellites that are each several kilometres in diameter. This logistical challenge is further compounded by the present lack of available heavy lift launchers and the potential environmental impact on the ozone layer resulting from the high launch cadence required to support the realization of SBSP on a significant scale *(Nolan, TWP, 2023).*

The focus of this study is to detail a potential mitigating solution to this daunting and limiting logistics problem facing SBSP development and deployment by examining the feasibility of fabricating much of the Solar Power Satellites (SPS) components on the Moon from lunar materials and assembling these at the Earth-Moon Lagrange point 1 (EM-L1). The first objective is to supply sufficient electrical power for a lunar mining and fabrication operation. If shown to be technically and economically feasible, then this approach would be scaled to produce SPSs for servicing the terrestrial energy market. This approach would greatly reduce the number of launches from the surface of the Earth required to deploy large numbers of SPSs in geostationary orbit (GEO) that would be needed to significantly contribute to supplying clean energy to power civilization by mid-century. At the same time it would establish mining and production facilities on the Moon which will consequently generate more business models and use-cases for a growing lunar industry, thereby also contributing greatly to economic growth on Earth.

4.2. 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 breadth 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 was 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 for various outreach products.
- Work Package 5 was dedicated to study management, coordination, and reporting.

This approach has led to a broader understanding of both the challenges and the possible solutions which has resulted in a novel system architecture that has many implications for the future of a sustainable planetary civilisation and a future space program that would contribute as much as possible to economic growth worldwide.

Assumptions

The following assumptions directed the focus of the study:

1. Energy use is directly correlated with prosperity.
2. Demand for clean energy solutions will continue to grow in proportion to increases in population and demand for economic growth and climate mitigation (e.g. carbon drawdown from the atmosphere).
3. 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.
4. As opposed to nuclear fusion energy supply, SBSP does not need any major scientific breakthroughs to be realized.
5. The launch bottleneck for massive SBSP deployment remains unsolved in the foreseeable future.
6. The accelerated developments in the last decade in PV technology, robotics and automation will continue, fed by strong world demand.
7. Energy markets have sufficient financial means to develop and deploy new and innovative sources of clean and sustainable energy such as SBSP.
8. The geopolitical competition for energy and other strategic resources will continue to intensify.

5. Global Energy Assessment

Humanity is facing an imminent *Energy Dilemma* in that the proven reserves of extractable fossil fuels suitable for energy production could reach depletion levels at mid-century and none of the alternative terrestrial energy options – nuclear – wind – ground solar (PV) – hydroelectricity - can be sufficiently scaled in time to achieve the goal of divesting from fossil fuels by the year 2050. Additionally, these finite resources are needed as chemical resources for many other aspects of modern civilization and, as such, are too valuable to be used for energy production. Harvesting solar energy uninterrupted and directly in space, is probably the most promising, technically feasible and scalable near-term additional energy source currently available to humanity to help complete the transition away from using fossil fuels for energy production, while meeting its future energy needs and achieving the net-zero targets.

5.1. The Climate Emergency

Due to the many assessments and reports issued since 1990 by the United Nation's IPCC – Intergovernmental Panel on Climate Change - the world population has become increasingly alarmed that a period of global warming has commenced which may lead to an environmental catastrophe by the end of this century. Numerous scientific studies indicate that this warming is caused by rising levels of CO_2 in the atmosphere which is attributed to the continued dependence on the use of fossil fuels to satisfy most of humanity's energy needs. A worldwide program to address the impending climate disruption has been incorporated into the United Nation's Agenda 2030 *(UN, Agenda 2030, 2023)* including the Paris Agreement and the 17 Sustainable Development Goals as well as through a number of international conferences (*UN News, 2019)* sub-organizations and public-private partnerships. Similar measures are being promoted, developed, and adopted by environmental and scientific organizations worldwide to meet the net-zero targets *(ClimateEmergency.com, 2023).*

Not only is global warming a significant concern but also global cooling should be recognized as a potential threat to society. As the Sun warms the surface of Earth and drives the hydrologic cycle, it is the primary source of energy for the climate system which keeps Earth suitable for life. The sunspot cycle of the Sun also influences the changes in the climate and scientists report that the current long period of low sunspot activity may indicate that the Sun is entering a Solar Minimum which could lead to a severe cooling effect similar to the last Little Ice Age, which especially affected Europe and North America between the 14th and 19th centuries *(SpaceWeather.com, 2019).* Solar activity which modulates the influx of galactic cosmic rays (high-speed particles that strike the Earth from space), has been shown to have a direct influence on cloud formation and has been correlated with warmer periods during high solar activity and cooling periods during low levels of solar activity *(GWPF, Svensmark, 2019).* Severe global cooling would probably be much worse for humanity than the predicted rise in global temperatures as this would directly affect food production and require additional energy for heating and maintaining all aspects of society. In either case, addressing the Climate Emergency will require massive amounts of clean energy production for a growing population to adapt and survive a severe warming or cooling situation *(Collins, Bernasconi, 2019).*

5.2. The Energy Dilemma

In addition to the impact on the environment related to fossil fuel use, energy security emerged as a major concern in 2022. This was especially relevant for Europe as geopolitical developments drastically reduced the imports of fossil fuels from its largest supplier Russia. Thus, the limited nature of these resources also needs consideration. For instance, in Figure 1 the "BP: World Reserves of Fossil Fuel" report shows that the remaining proven extractable reserves of fossil fuels are critically finite. Accordingly, at current rates of consumption – over 35 billion barrels of oil per year - humanity will exhaust said reserves of:

- crude oil by the year 2066,
- natural gas by 2068
- and coal by 2169

BP: World Reserves of Fossil Fuels

Published: Monday, July 30, 2018

Data Driven

Subscribe Export View Archive Bookmark Follow

According to the latest BP Statistical Review of World Energy, total global reserves, by fossil fuel, are now:

Coal - 1,139 billion tonnes

Natural Gas - 187 trillion cubic meters

Crude Oil - 1,707 billion barrels

While these volumes may seem large at a glance, at today's level of extraction and production rates, BP's estimated proved reserves*, by fossil fuel, would be exhausted as follows:

Coal - year 2169

Natural Gas - year 2068

Crude Oil - year 2066

BP dutifully acknowledges the abundance of factors that could *easily* alter these projections, but these factors do not alter the global policy imperitive to support sustainable fossil fuel extraction and development. All we need now is to define "sustainable" against ever changing market, political, and social conditions.

* *Estimated years of extraction-remaining are estimated as the ratio of proved reserves to production per year.*

Sources: Crude Oil Reservs, Natural Gas Reservs, Coal Reservs, Crude oil prices, Natural Gas prices, Coal prices, Historical Energy Statistics.

Figure 1: World Reserves of Fossil Fuels (Knoema, 2018)

A similar estimate is found in Figure 2 *(Our World in Data, 2020).*

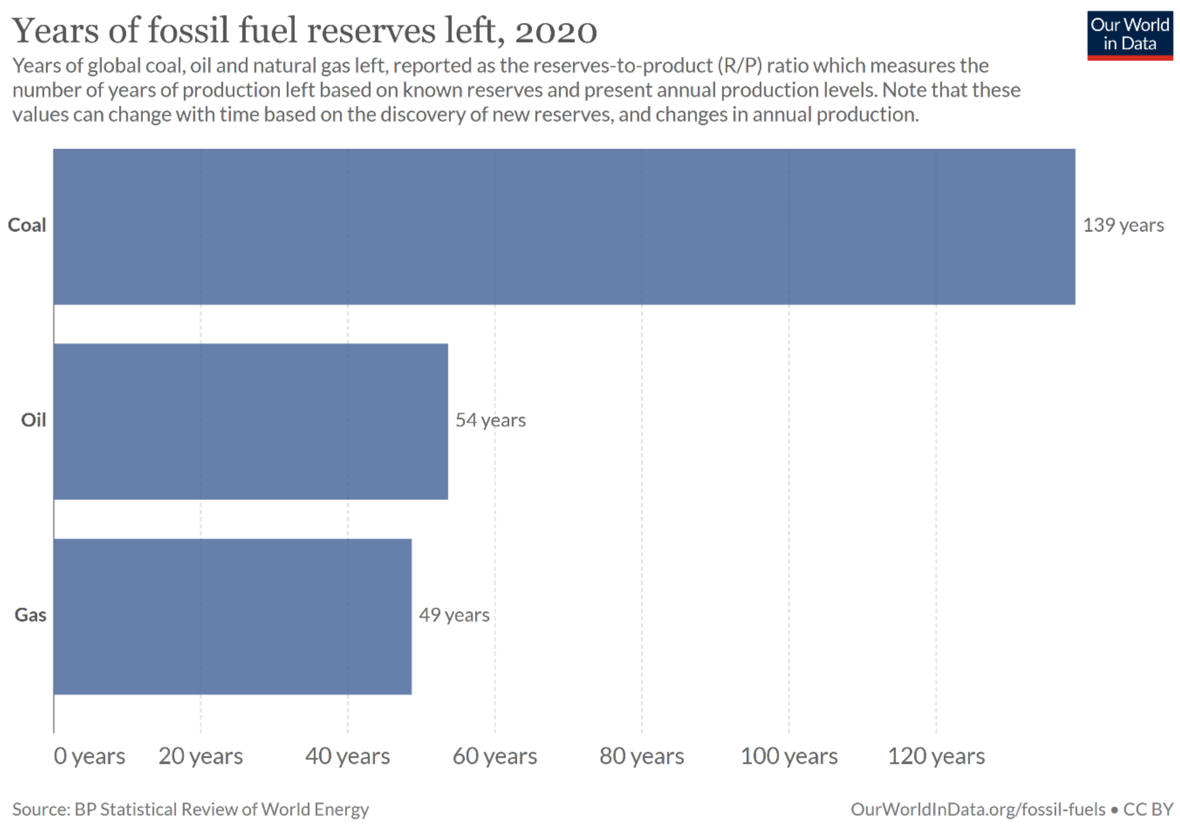


Figure 2: Years of fossil fuel reserves left (Our World in Data, 2020)

Furthermore, EROI – Energy Return on Investment – is also a critical issue for future production predictions as this will influence the price of fossil fuels as they become more difficult to extract and thus less economical to produce. This aspect also significantly adds to the urgency of finding a viable and sustainable alternative energy solution and underscores the imminent energy dilemma that the energy intensive societies are facing in the coming decades. For the lesser developed nations and regions, the energy situation is even more dire.

The United Nations Sustainable Development Goal 7 is intended to ensure access to affordable, reliable, sustainable, and modern energy for all. The SDG 7 website indicates that in the year 2020 over 733 million people - almost 1/10 of the world population - had no access to electricity and 2.4 billion people still use inefficient and polluting cooking systems such as biomass and dung (UN: SDG 7, 2020). In the year 2022, world population surpassed 8 billion people and 2 billion more are expected to be added by the year 2050. This will require an increase of at least 50% more available energy. This means that global power capacity will have to grow from 18.5 TW currently to more than 28 TW by the year 2050. Under these circumstances it is necessary to examine the dimensions of world and European energy consumption to comprehend the full scope of the energy dilemma facing humanity.

5.3. World Energy Consumption

There are several sources of energy data available in order to have a picture of the world energy demands now and in the future. One source commonly used is the annual BP Statistical Review of World Energy which in its 71st edition published in 2022 (BP: 2022). For 2019, it shows the World Total Primary Energy consumption was: 587.43 EJ, in 2020 it was 564.01 EJ, and for 2021 595.15 EJ (Exajoule = 10^{18} Joule) Figure 4.

Converted into Terawatt Hours (TWh): 2019: 163,175 TWh, 2020: 156,670 TWh and 2021: 165,320 TWh. The average for the three years was 161,722 TWh indicating the equivalent of 18.5 TW of continuous energy production capacity currently needed to power civilization.

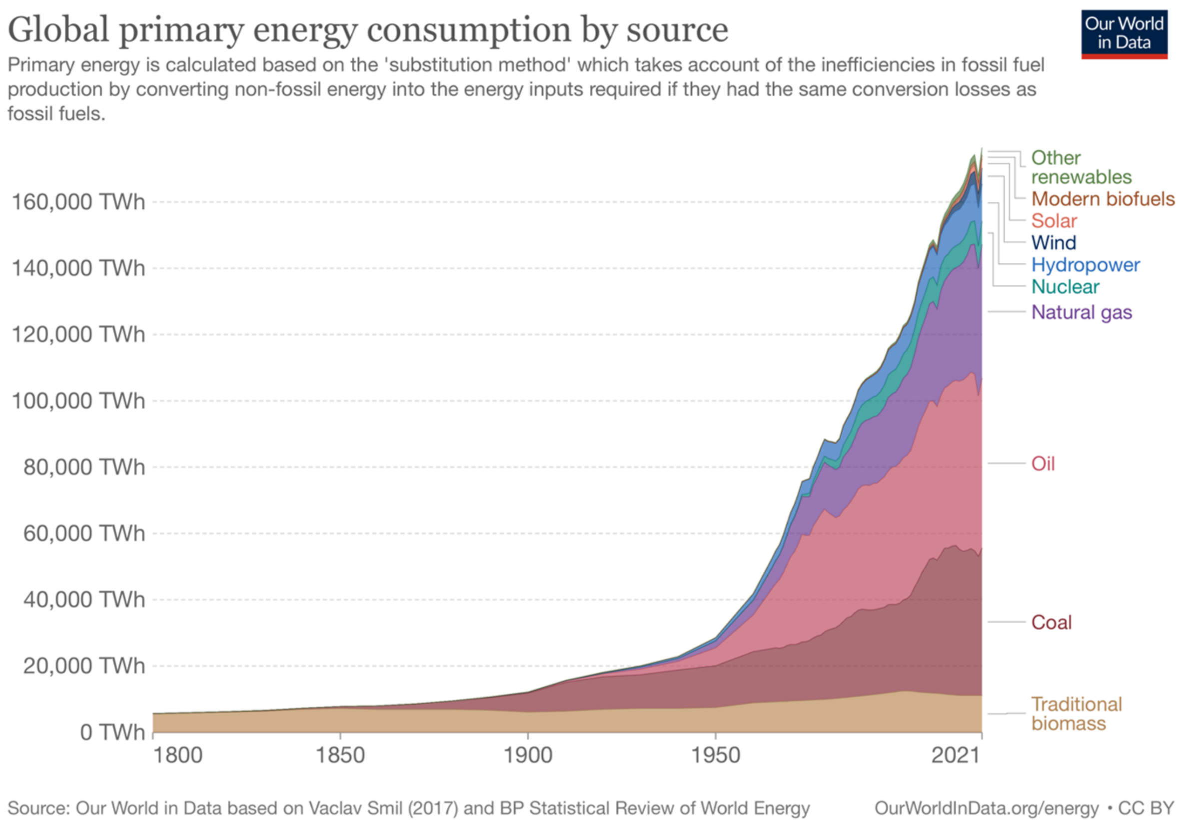
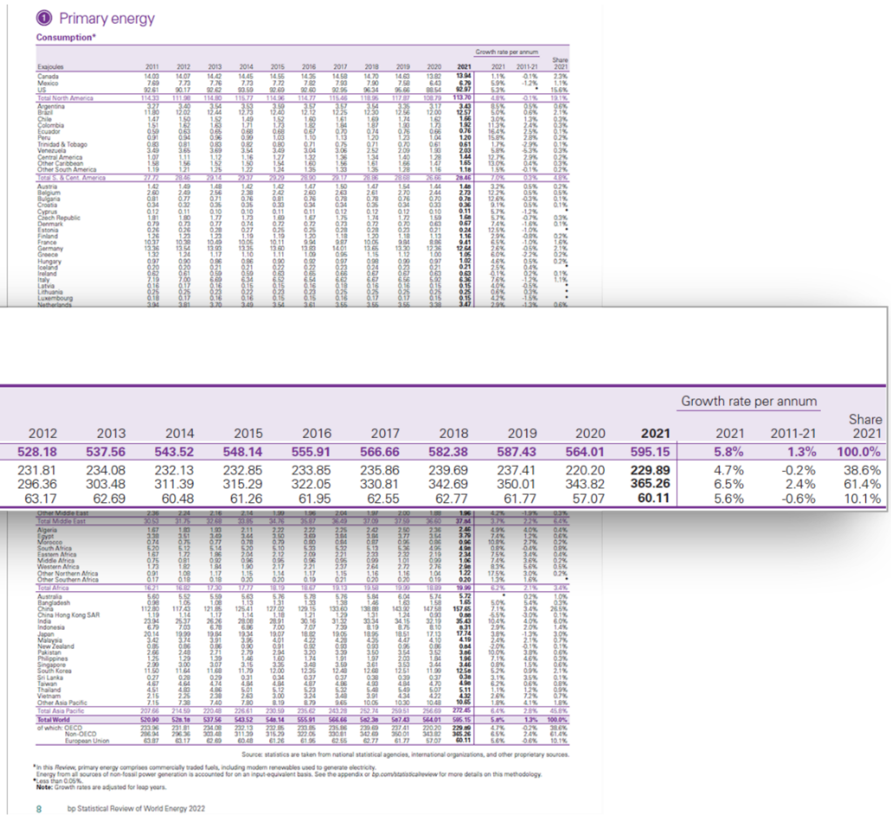


Figure 3: Energy Production and Consumption (Our World in Data, 2021)

The above chart presents primary energy consumption via the 'substitution method'. The 'substitution method' – in comparison to the 'direct method' – attempts to correct for the inefficiencies (energy wasted as heat during combustion) in fossil fuel and biomass conversion. It does this by correcting nuclear and modern renewable technologies to their 'primary input equivalents' if the same quantity of energy were to be produced from fossil fuels. Most sources, including the annual BP Statistical Review of World Energy, tend to prefer and report on the substitution method rather than the direct method. The substitution method is also the preferred approach of the *Intergovernmental Panel on Climate Change (IPCC)*. The substitution method provides a more accurate understanding of how low-carbon energy is competing with fossil fuels *(Our World in Data, 2021).*



Primary energy

Consumption*

Exajoules	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	Growth rate per annum 2021	Growth rate per annum 2011-21	Share 2021
Total World	**520.90**	**528.18**	**537.56**	**543.52**	**548.14**	**555.91**	**566.66**	**582.38**	**587.43**	**564.01**	**595.15**	**5.8%**	**1.3%**	**100.0%**
of which: OECD	233.96	231.81	234.08	232.13	232.85	233.85	235.86	239.69	237.41	220.20	**229.89**	4.7%	-0.2%	38.6%
Non-OECD	286.94	296.36	303.48	311.39	315.29	322.05	330.81	342.69	350.01	343.82	**365.26**	6.5%	2.4%	61.4%
European Union	63.87	63.17	62.69	60.48	61.26	61.95	62.55	62.77	61.77	57.07	**60.11**	5.6%	-0.6%	10.1%

Figure 4: 2022 BP Statistical Review of World Energy 71st edition (BP: page 8)

5.3.1. Replacing Fossil Fuels in the World

The long-term target is for humanity to opt out of using fossil fuels for energy production and use the 'black gold' as a resource for more valuable products like plastics and pharmaceuticals. Hopefully by switching to electric cars, heat pumps, and other technologies, efficiencies for energy production can be considerably increased. However, these may be counterbalanced by growing wealth and population worldwide.

To put this into context, replacing the 133,858 TWh/year currently generated by fossil fuels with a terrestrial energy alternative such as nuclear power by the year 2050 would require about 16,978 new 1-GW nuclear reactors (assuming a 90% availability). This represents 17 TW of power generating capacity. If this could be achieved, it would mean that for the next 27 years, 628 nuclear power plants would have to go online each year. In the years 2019-2021, fossil fuels accounted for ca. 83% (133,858 TWh) of the total energy use world-wide whereas nuclear power systems accounted for only 4.3% (6,914 TWh) of the total energy use. Currently, building one nuclear power plant takes about 10-15 years and only 57 are currently under construction, mostly in China. Thus, nuclear energy - including fusion which has been in a research state for several decades - is not likely to be the main energy solution.

Likewise, renewables would have to scale up in the same dimension. As wind and solar photovoltaic (PV) generators have significantly lower availability: the inherent intermittency and storage aspects, makes it necessary to deploy multiples of their equivalent rated (peak) power levels to equal the output, e.g., of nuclear power systems. For wind, the generating capacity needs to be some 3.35 times higher *(NEI, 2015)* and for PV, 6-7 times higher. Thus, to replace 2019-2021 average use of fossil fuels with wind and solar, no less than 70 TW (depending on the assumed wind/ PV mix) of power generating capacity from these two renewable sources would need to be installed. Again, this translates into 2.6 TW of electrical generating capacity from wind and solar that would need to be installed every year from now until the year 2050 – i.e., ca. 7 GW per day – and this would have to start immediately. The net addition of all renewables in the year 2021 was only 286 GW, just one-tenth of what is needed *(IEA, Renewables, 2022).*

Looking further ahead, studies such as the one by the U.S Energy Information Agency *[EIA,2019]*, projects a nearly 50% increase in world energy use by 2050 due to the needs of an increasing world population and energy demand. In this case, global energy consumption would increase by 50% from 161,394 TWh/year (2019-2021) to 242,091 TWh/year (2050). This level of world energy consumption would require approximately 28 TW (28,000 GW) of power generation capacity.

In contrast to this projection, in their World Energy Outlook 2022, the International Energy Agency (IEA) projects three scenarios for future energy use: *(IEA, (2022) WEO)*

1. In **Stated Policies Scenario (STEPS)** IEA assesses the likely effects of 2022 policy settings. The share of fossil fuels will fall from 80% to about 60% in 2050. This would lead to global average temperatures still rising when they hit 2.5 °C above pre-industrial levels in 2100. A reduction of only 13% in CO2 emissions is far from enough to avoid severe impacts from changing climate.
2. The **Announced Pledges Scenario (APS)** assumes that all government targets will be met in full and on time. Average temperature will rise by around 1.7 °C by 2100. The APS scenario is not designed to achieve a particular outcome. Emissions do not reach net zero and the rise in average temperatures associated with the STEPS is around 2.5 °C in 2100 (with a 50% probability).
3. The **Net Zero Emissions by 2050 Scenario (NZE)** is a way to achieve a 1.5 °C stabilisation in the rise in global average temperatures. The NZE scenario also meets the key energy-related UN Sustainable Development Goals, achieving universal access to energy by 2030 and securing major improvements in air quality. Electricity demand is 150% higher than today. The share of nuclear in the generation mix remains broadly where it is today, around 10%. Oil use for passenger cars falls by 98% between today and 2050. By 2050, unabated fossil fuels for energy uses account for just 5% of total energy supply: adding fossil fuels used with CCUS and for non-energy uses raises this to slightly less than 20%. The share of fossil fuels will fall from 80% in 2020 to just over 20% in 2050.

The report provides the following energy data for 2021 with projections to the year 2050:

1. **Stated Polices Scenario** World Energy Supply (Table A. 1a)
   2021: total: 624 EJ = 173,333 TWh
   2030: 673 EJ = 186,944 TWH
   2050: 740 EJ = 205,556 TWh

2. **Announced Pledges Scenario** World Energy Supply (Table A. 1b)
   2021: total: 624 EJ = 173,333 TWh

2030: 636 EJ = 176,667 TWH
2050: 629 EJ = 174,722 TWh

3. **Net Zero Emissions by 2050 Scenario** World Energy Supply (Table A. 1c)
2021: total: 624 EJ = 173,333 TWh
2030: 561 EJ = 155,833 TWH
2050: 532 EJ = 147,778 TWh

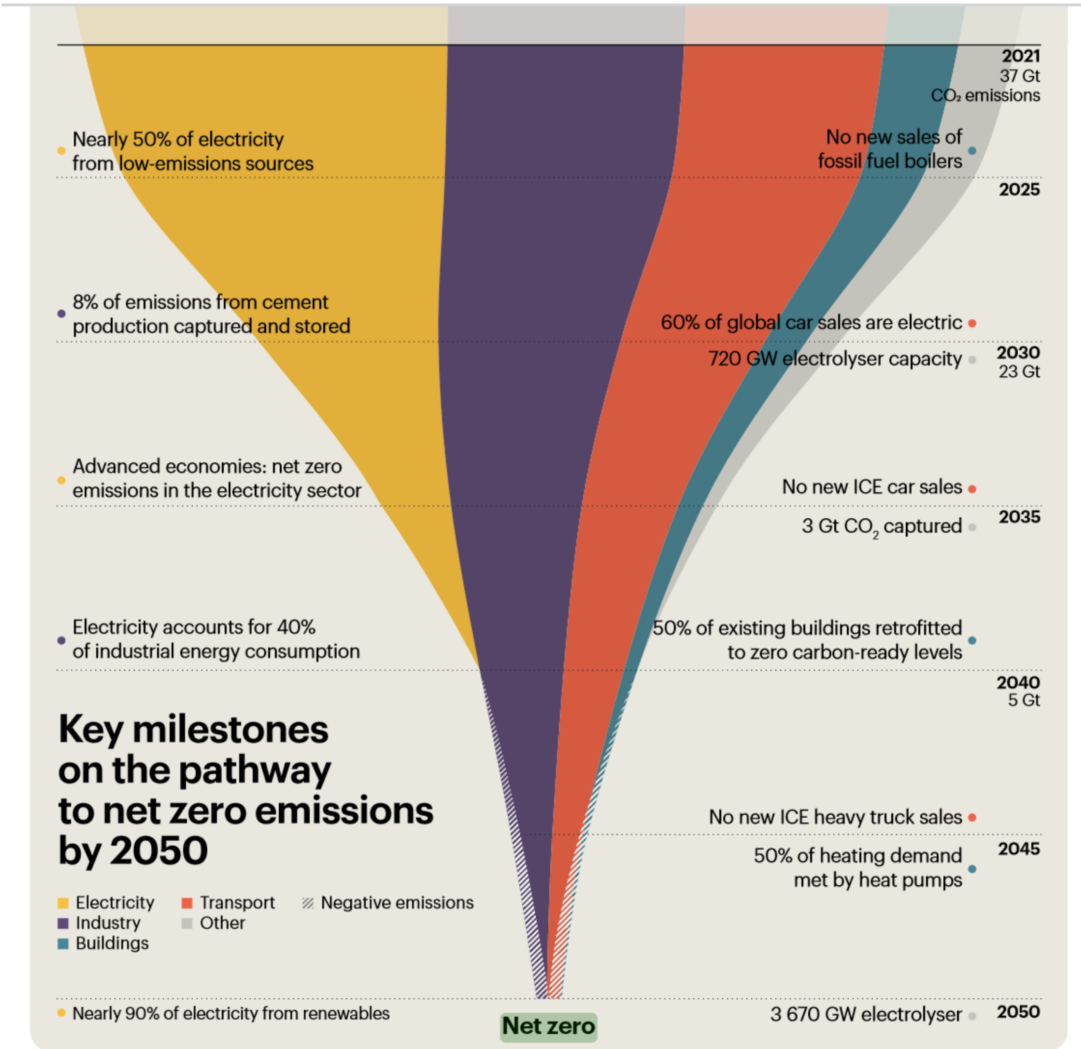


Figure 5: IEA Pathway to Net-Zero Emissions in 2050 (Source: IEA, WEO, 2022)

The Net Zero 2050 scenario represents ca. 15% decrease in the world energy supply and ca. 30% less in world final consumption. The NZE scenario would require a more than USD 4 trillion clean energy investment by 2030. *(Wikipedia, 2023, World Energy Supply and consumption)*

5.4. Europe's Energy Consumption

As mentioned, the BP Statistical Review of World Energy reports on total energy consumption in the world on a yearly basis by region and by country. For Europe the following figures have been extracted.

In 2019 total energy use in Europe was 83.82 EJ or 23,283 TWh @ power level: 2,658 GW
Oil, Natural Gas, Coal (61.7 EJ) = 73.6% *(BP, 2020)*

In 2020 total energy use in Europe was: 78.93 EJ or 19,703 TWh @ power level: 2,249 GW
Oil, Natural Gas, Coal (54.88 EJ) = 69.53% *(BP, 2021)*

In 2021 total energy use in Europe was: 82.38 EJ or 22,883 TWh @ power level: 2,612 GW
Oil, Natural Gas, Coal (55.84 EJ) = 67.78% *(BP, 2022)*

Average energy consumption for the years 2019, 2020, 2021: 22,533 TWh/year

Average power level for the years 2019, 2020, 2021: 2,506 GW
Average percentage of Oil, Natural Gas, Coal for years 2019,2020,2021: 70.3%
Average amount of fossil fuel use for years 2019,2020,2021: 16,183 TWh/year

As a comparison to the BP report, the International Energy Agency (IEA) listed Total Energy Supply (TES) for Europe in 2019 at 81,561,587 TJ (81.56 EJ) which converts to 22,656 TWh indicating a power level of 2,586 GW which is close to the BP report (83.82 EJ) for the same year *(IEA, Energy Statistics, 2022).*

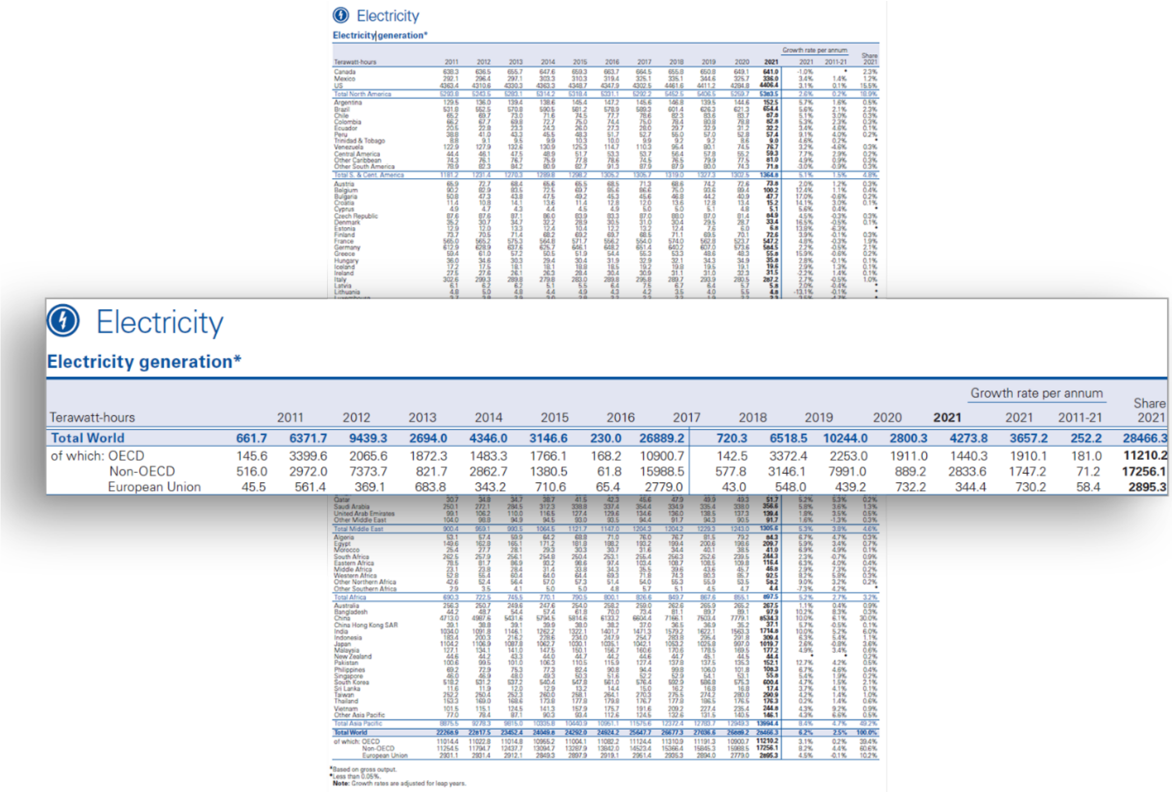
5.4.1. Replacing Fossil Fuels in Europe

As in the above example of global energy consumption, to replace current European fossil fuel use of 16,183 TWh/year with baseload nuclear power, Europe would need approximately 2,053 new 1-GW nuclear reactors providing 1.8 TW of power. To replace fossil fuel use with terrestrial renewables would require approximately 4-5 times this much power generating capacity (7 TW to 9 TW) to be equivalent to nuclear power.

Decarbonization of Europe means replacing 80% of fossil fuel use by 2050 as proposed in the IEA net-zero scenario. Currently this would require the equivalent of 1,642 new nuclear power plants providing 1.3 TW of power. To achieve this level of power production with wind and solar power would require 4-5 times as much, or 5 TW to 6.5 TW of equivalent nuclear power generating capacity. Total installed solar power in Europe in 2022 was 41.4 GW *(Solar Power Europe, 2022)* and total installed wind power in 2022 was 236 GW *(Wind Europe, 2022).* Together this is 270 GW of installed power or just 0.27 TW. Scaling this to 5 or 6.5 TW (5,000 GW / 6,500 GW) will be a real challenge for Europe.

5.5. Global Electricity Demand

As SBSP is intended to supply electricity to the energy market it is useful to analyze the current world and European electrical generation data. According to the 2022 BP Statistical Review of World Energy 71st edition, total world primary energy consumption in 2021 was 595.15 exajoules which when converted into terawatt hours equals 165,320 TWh *(BP, 2022).* This amount is predicted to increase by at least 50% to more than 247,980 TWh by the year 2050.



Electricity

Electricity generation*

Terawatt-hours	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	Growth rate per annum 2021	Growth rate per annum 2011-21	Share 2021
Total World	**661.7**	**6371.7**	**9439.3**	**2694.0**	**4346.0**	**3146.6**	**230.0**	**26889.2**	**720.3**	**6518.5**	**10244.0**	**2800.3**	**4273.8**	**3657.2**	**252.2**	**28466.3**
of which: OECD	145.6	3399.6	2065.6	1872.3	1483.3	1766.1	168.2	10900.7	142.5	3372.4	2253.0	1911.0	1440.3	1910.1	181.0	**11210.2**
Non-OECD	516.0	2972.0	7373.7	821.7	2862.7	1380.5	61.8	15988.5	577.8	3146.1	7991.0	889.2	2833.6	1747.2	71.2	**17256.1**
European Union	45.5	561.4	369.1	683.8	343.2	710.6	65.4	2779.0	43.0	548.0	439.2	732.2	344.4	730.2	58.4	**2895.3**

Figure 6: Electricity Generation: 2022 BP Statistical Review of World Energy 71st edition (page 51)

In terms of electrical generation, world production in 2021 was 28,446 TWh which could increase by 150% to 71,115 TWh by the year 2050 (or in the in the IEA NZE scenario below to 73,231 TWh) due to the growing electrification of transport, industry, and heating, combined with the increase of data usage. It is interesting to compare this projection with the data from the IEA World Energy Report 2022, where the World Electricity Sector data is detailed in the same three scenarios as energy.

1. **Stated Polices Scenario:** Total Electricity Generation (Table A. 3a)
   2021: 28,334 TWh
   2030: 34,834 TWH
   2050: 49,485 TWh

   Stated Polices Scenario: Total Electricity Capacity (Table A. 3a)
   2021: 8,185 GW
   2030: 11,954 GW
   2050: 19,792 GW

2. **Announced Pledges Scenario** Total Electricity Generation (Table A. 3b)
   2021: 28,334 TWh
   2030: 35,878 TWh
   2050: 61,268 TWh

   Announced Pledges Scenario: Total Electricity Capacity (Table A. 3b)
   2021: 8,185 GW
   2030: 12,932 GW
   2050: 26,541 GW

3. **Net Zero Emissions by 2050 Scenario** Total Electricity Generation (Table A. 3c)
   2021: 28,334 TWh
   2030: 37,723 TWH
   2050: 73,231 TWh

   Net Zero Emissions by 2050 Scenario: Total Electricity Capacity (Table A. 3c)
   2021: 8,185 GW
   2030: 15,306 GW
   2050: 33,878 GW

5.6. European Electricity Demand in 2050

Considering the projected electrical power market in Europe, the annual BP Statistical Review of World Energy report for the year 2021 *(BP, 2022)* indicates total electricity generation in Europe was 4032.5 TWh (Figure 7).

Of this total, nuclear energy provided 882.8 TWh in 2021 or approximately 22%. The other sources of electricity for 2021 were: Fossil Fuels 1,479 TWh (37%), Hydroelectric 650 TWh (16%), Renewables 946.5 TWh (23.5%) and Other 74.2 TWh (1.5%).

Electricity generation by fuel*

	2020								2021							
Terawatt-hours	Oil	Natural Gas	Coal	Nuclear energy	Hydro electric	Renew-ables	Other‡	Total	Oil	Natural Gas	Coal	Nuclear energy	Hydro electric	Renew-ables	Other‡	**Total**
Canada	2.9	73.6	38.6	97.5	386.5	49.3	0.6	649.1	2.9	75.9	38.7	92.0	380.8	50.0	0.7	**641.0**
Mexico	32.4	200.1	18.9	11.2	26.9	36.2	–	325.7	32.8	203.3	13.6	11.9	34.7	39.7	–	**336.0**
US	18.6	1746.4	844.3	831.5	282.8	547.7	13.5	4284.8	20.2	1693.8	978.5	819.1	257.7	624.5	12.7	**4406.4**
Total North America	54.0	2020.1	901.9	940.1	696.3	633.2	14.1	5259.7	55.9	1973.0	1030.7	923.0	673.3	714.1	13.5	**5383.5**
Argentina	7.1	88.0	1.6	10.7	23.7	13.0	0.6	144.6	7.9	93.3	2.9	10.8	19.6	17.2	0.6	**152.5**
Brazil	10.5	53.5	20.3	14.1	396.4	126.5	–	621.3	21.9	86.9	24.1	14.7	362.8	144.0	–	**654.4**
Other S. & C. America	66.3	90.5	49.1	–	271.2	59.5	†	536.6	66.1	100.9	45.3	–	277.7	68.1	†	**558.0**
Total S. & C. America	83.9	231.9	71.1	24.7	691.2	199.1	0.6	1302.5	95.9	281.1	72.3	25.5	660.1	229.3	0.6	**1364.8**
Germany	4.7	95.0	134.6	64.4	18.3	231.8	24.8	573.6	4.8	89.0	162.6	69.0	19.1	217.6	22.4	**584.5**
Italy	11.4	133.7	15.1	–	45.7	68.8	5.8	280.5	8.3	146.4	14.5	–	43.1	71.4	3.5	**287.2**
Netherlands	1.4	72.6	7.6	4.1	†	33.0	4.9	123.6	1.4	56.3	17.8	3.8	0.1	40.1	2.1	**121.6**
Poland	1.7	17.3	109.4	–	2.1	25.3	1.3	157.1	1.5	15.5	131.7	–	2.3	27.8	1.3	**180.0**
Spain	10.7	69.7	6.1	58.3	30.5	83.2	4.7	263.4	10.3	69.2	6.1	56.5	29.6	95.8	4.7	**272.1**
Turkey	0.3	70.9	105.8	–	78.1	51.5	–	306.7	0.3	110.4	104.2	–	55.7	62.7	–	**333.3**
Ukraine	0.3	14.2	40.2	76.2	7.6	9.4	–	147.8	0.8	10.3	36.8	86.2	10.4	11.0	–	**155.5**
United Kingdom	0.8	111.4	5.5	50.3	6.8	127.8	9.3	312.0	1.5	124.2	6.5	45.9	5.0	116.9	9.9	**309.9**
Other Europe	17.4	180.5	145.4	580.0	468.8	291.8	30.3	1714.2	19.1	178.1	151.9	621.4	484.4	303.2	30.3	**1788.3**
Total Europe	48.9	765.4	569.7	833.2	657.9	922.7	81.1	3879.0	47.9	799.3	632.0	882.8	649.7	946.5	74.2	**4032.5**

Figure 7: BP Statistical Review of World Energy 2022 I 71st edition (page 9)

Electricity demand evolution is one of the biggest uncertainties for the electric power supply sector. This is due to the interplay of a multitude of drivers such as: electric vehicles, production of hydrogen via electrolysis, deployment of heat pumps and other electric heating solutions, most of which put upward pressure on electricity demand *(Deloitte Insights 2021).*

The IEA's NZE Scenario projects that electricity demand in 2050 could be up to 150% higher than today.

"There are many uncertainties in our Outlook, but one point which is common to all the scenarios is the rising share of electricity in global final energy consumption. From 20% today, this increases to 22% by 2030 in the STEPS, and 28% in 2050. In the APS, the share rises to 24% in 2030 and 39% in 2050. In the NZE Scenario, the share rises further to 28% by 2030 and 52% by 2050. This is associated with a huge overall increase in global electricity demand over the coming decades – by mid-century, electricity demand is 75% higher than today in the STEPS, 120% higher in APS and 150% in the NZE Scenario. Clean electricity and electrification are absolutely central to the shift to a net zero emissions system." (IEA, WEO, 2022, page 44)

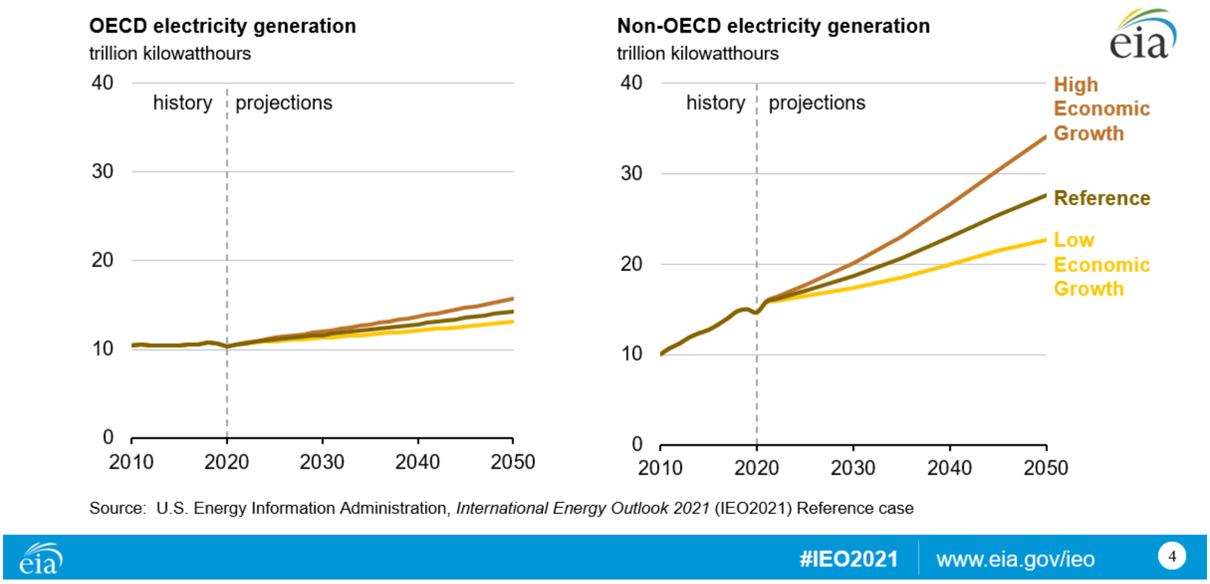


Figure 8: International Energy Outlook 2021 with projections to 2050, (EIA, IEO 2021)

Considering all this, the demand for electricity in Europe seems likely to increase by at least 75%, but more realistically by 120% - 150%. Thus, Europe's annual electricity demand could increase from 4032.5 TWh to between 7,057-10,081 TWh/year by 2050. This would require an overall electrical power-generation capacity between 806 GWe and 1,151 GWe.

The overall 2050 European electricity 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. If SBSP could supply the same amount in 2050, it would be approximately 101 GWe or approximately 10% of the electricity mix. The IEA WEO 2022 report projects that electricity generation from unabated fossil fuels in 2050 would be 26% in the STEPS scenario, 8% in the APS scenario, and less than 1% in the NZE scenario. *(IEA, WEO, 2022, Tables: A.3a, A3.b and A3.c)*

Therefore, a useful goal for SBSP could be to provide Europe with at least the same amount of baseload electrical power as nuclear power provided in 2021, i.e. 883 TWh. For an Earth-launched SBSP system as described in the Frazer-Nash study, this would mean that 78 SPS systems with a capacity of 1.44 GW each operating with an availability of 90% (1.30 GW/SPS) would be needed to provide the 101 GWe of power, requiring between 6,708 (86 per SPS) and 9,282 launches (119 per SPS) respectively. In terms of mass-to-orbit, between now and the year 2050, and with a launch mass of 2,491 MT each, 78 SPSs would have a total launch mass of 194,298 MT to Geostationary Orbit (GEO). However, the demand for electricity from SBSP could be much higher if the Net-Zero Emission goals are implemented.

Plans to achieve "Zero CO_2 Emissions" are still politically uncertain, being dependent on many assumptions, future technologies and on partially unclear or controversial scenarios. Carbon neutrality refers only to CO_2 emissions, whereas net-zero relates to all greenhouse gases (carbon dioxide, methane, nitrous oxide, etc.). Net-Zero is a scenario in which human-generated greenhouse gas emissions are reduced as much as possible, with those that remain being balanced out by the removal of greenhouse gas emissions from the atmosphere. Whereas Absolute-Zero describes a state where one does not emit any greenhouse gases at all. It refers to an absence of emissions. Indeed, some "Net-Zero" scenarios may actually intend to achieve 'Absolute-Zero" results. Yet, some major uses of energy such as aviation, shipping and the military have been politically excluded from the binding agreements.

One example is the "FIRES" report commissioned by the UK government in 2019 *(UK FIRES, 2019)*. This report was prepared by researchers from Oxford University, Imperial College, and other universities. Among the conditions needed in order for the UK to reach the stated goal of Zero CO_2 Emissions by 2050, the reports' authors include the need to close all airports; stop all shipping; end the production and consumption of beef and mutton; and end new building construction! How acceptable such radical reductions in the general public's standard of living might be is unknown.

It seems likely that, instead of this scenario, developing SBSP to make a major net addition to the availability of environmentally clean energy would be widely popular. Clean electricity supplied by SPS units could be used in many different ways to reduce other environmental harms. For example, some rectennas could be used to produce hydrogen (and oxygen) by electrolysis, some of which could be used as fuel for airliners, shipping, and other transport systems - thereby preserving international trade as well as the very popular air travel industry and enabling it to continue to grow and create employment. The large-scale development and implementation of SBSP starting now has a great potential to mitigate these radical consequences of a net zero emission scenario.

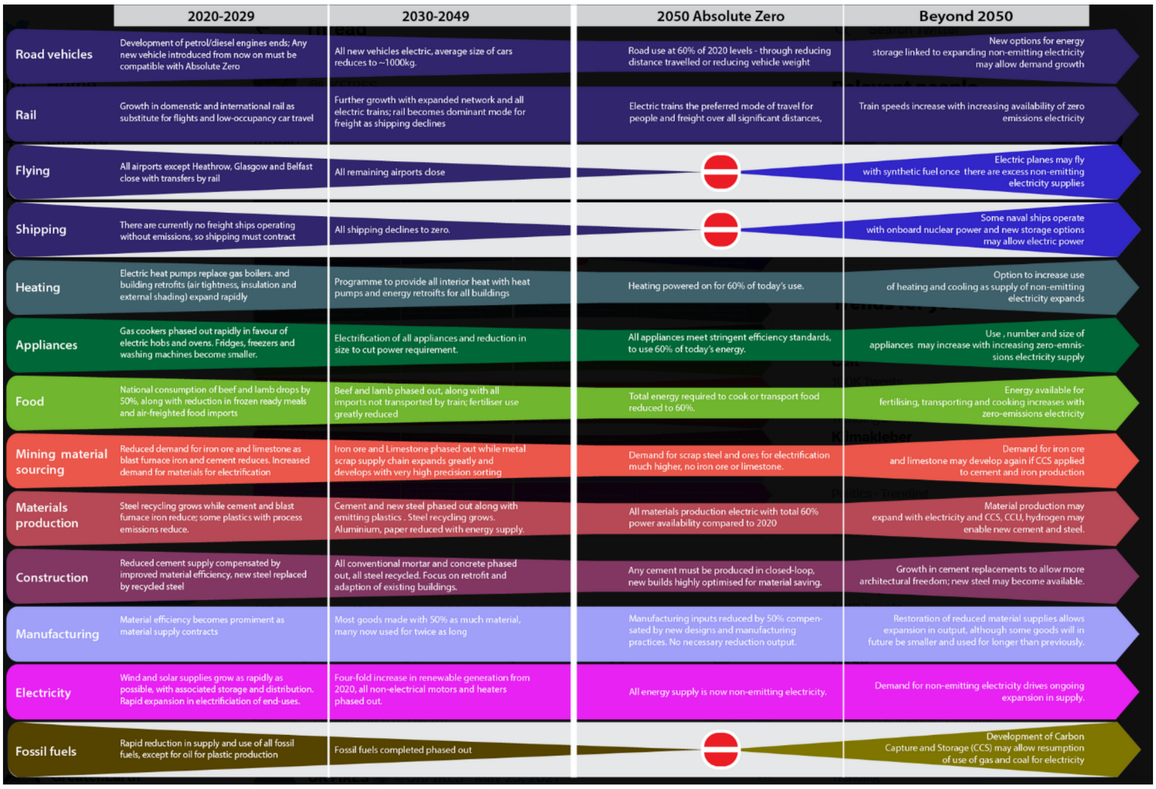


Figure 9: FIRES report the path to net-zero. (UK FIRES, 2019)

Major points in the 2019 FIRES report are summarised in the above chart. FIRES claims to be more realistic than other scenarios which assume rapid progress in developing such novel systems as "carbon capture", but which have not yet been demonstrated at an industrial scale - thereby greatly limiting the maximum scale which such new technologies could reach by 2050.

However, a recent update claiming that experience from 2019 to the present supports their argument is quite thought-provoking. *"There is no possibility of this level of energy infrastructure being built by 2035…"* and *"we don't want to think about a future in which we don't have all the energy we want." (UK FIRES, 2023).*

It seems possible that the FIRES report had some influence in persuading the British government to give some preliminary support to SBSP research and development, in order to make a realistic scenario towards Zero CO_2 Emissions by 2050 without requiring severe reduction in British living standards.

5.7. Energy Conclusions

Global fossil fuel use has risen alongside GDP since the start of the Industrial Revolution in the 18th century: putting this rise into reverse while continuing to expand the global economy will be a pivotal moment in energy history. The share of fossil fuels in the global energy mix has been stubbornly high, at around 80%, for decades. To bring it down anywhere near the 20% needed to achieve a net-zero scenario, a considerable amount of electricity generated from alternative energy sources will be needed. Additionally, the 2 billion people who have little or no access to reliable energy today, need to have some reassurance that there will be sufficient clean energy for them as well.

Combustion technologies used for transportation, industrial production, and agriculture will have to be converted into more efficient electrical technologies, which significantly increases the need for electricity in the energy mix. Even though electricity generation from wind and solar is very effective, these energy sources are very intermittent as well. Deploying these at scale will be a major challenge, even if sufficient storage plants could be realized in future. Nuclear power with all its implications remains the only scalable baseload energy technology currently available. Relying only on this technology will undoubtedly massively increase the number of nuclear power plants needed with all the consequences related to geopolitics, risk, regulatory delays, public acceptance, and waste storage.

As an alternative, in this study we emphasize the development of SBSP at scale as a green baseload and dispatchable energy source. To mitigate the launch bottleneck and the environmental impact of launching many SPS systems from the surface of Earth into orbit, we are proposing to build much of the components of the Solar Power Satellites from lunar materials by setting up a robotic industrial operation on the Moon.

6. The Space Energy Option

Currently approximately 83% of world energy consumption comes from fossil fuels. The United Nations, many governments, scientific and environmental organizations are calling for net-zero CO_2 emissions targets by the year 2050 to lessen the effects of CO_2 induced global warming by divesting from the use of fossil fuels. This process assumes that terrestrial solutions will be adequate for addressing this crisis if intergovernmental measures can be implemented in time. The International Energy Agency (IEA) has detailed the essential conditions for the global energy sector to reach net-zero CO_2 emissions by 2050 in its 'Net Zero by 2050: Roadmap for the Global Energy Sector' *(IEA, Net-Zero, 2021).*

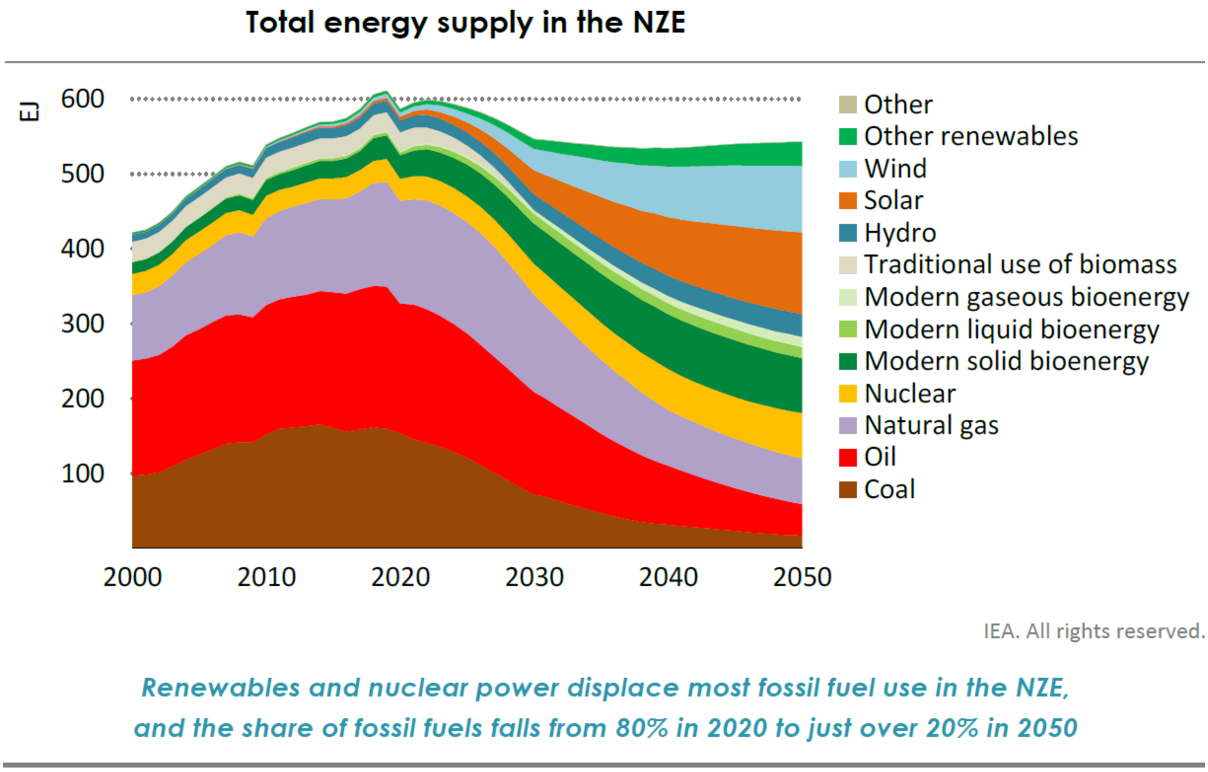


Figure 10: IEA Net-Zero Scenario (Source: Net Zero by 2050 A Roadmap for the Global Energy Sector, 2021)

As seen in the above chart, the IEA's path to net-zero emissions requires immediate and massive deployment of all available clean and efficient energy technologies. They predict the world economy will grow by 40% by the year 2030 but will use 7% less energy. They call for scaling up solar and wind rapidly this decade, reaching annual additions of 630 gigawatts (GW) of solar photovoltaics (PV) and 390 GW of wind by 2030. Then, to reach net-zero by 2050 will require further rapid deployment of available technologies as well as widespread use of technologies that are not on the market yet. Major innovation efforts must occur over this decade in order to bring these new technologies to market in time. Most of the global reductions in CO_2 emissions through 2030 in their pathway to net-zero will come from technologies readily available today. But in 2050, almost half the reductions must come from technologies that are currently at the demonstration or prototype phase *(IEA Net-Zero, 2021).*

However, upon close examination, any mix of currently available terrestrial energy options – nuclear, hydroelectric, biogas, wind, and solar photovoltaic – is unlikely to realistically provide the necessary baseload power. Solar and wind are intermittent - nuclear, biogas and hydro face substantial opposition in democratic systems for their risk, land use and are all facing increasing risk of extreme heat and extended drought periods. Additionally, as shown in the chart below, enormous battery storage capacity – 3,100 GW – would have to be added by the year 2050. The resources needed for batteries (lithium, cobalt, etc.) have many unresolved environmental, geopolitical, and social implications.

Category	2020	2030	2050
Total electricity generation (TWh)	26 800	37 300	71 200
Renewables			
Installed capacity (GW)	2 990	10 300	26 600
Share in total generation	29%	61%	88%
Share of solar PV and wind in total generation	9%	40%	68%
Carbon capture, utilisation and storage (CCUS) generation (TWh)			
Coal and gas plants equipped with CCUS	4	460	1 330
Bioenergy plants with CCUS	0	130	840
Hydrogen and ammonia			
Average blending in global coal-fired generation (without CCUS)	0%	3%	100%
Average blending in global gas-fired generation (without CCUS)	0%	9%	85%
Unabated fossil fuels			
Share of unabated coal in total electricity generation	35%	8%	0.0%
Share of unabated natural gas in total electricity generation	23%	17%	0.4%
Nuclear power	*2016-20*	*2021-30*	*2031-50*
Average annual capacity additions (GW)	7	17	24
Infrastructure			
Electricity networks investment in USD billion (2019)	260	820	800
Substations capacity (GVA)	55 900	113 000	290 400
Battery storage (GW)	18	590	3 100
Public EV charging (GW)	46	1 780	12 400

Note: GW = gigawatts; GVA = gigavolt amperes.

Figure 11: Key milestones in transforming global electricity generation (Source: IEA Net Zero by 2050 A Roadmap for the Global Energy Sector, 2021, Table 3.2)

In current discussions about transiting from fossil fuels to some other alternative energy source, it is surprising that, until recently in Europe, clean energy from space, or Space-Based Solar Power (SBSP), a technologically feasible idea that was introduced as the Solar Power Satellite by Peter Glaser in 1968 *(Glaser, 1968)* and patented in 1973, has been rarely considered or even seriously discussed as a possible alternative to terrestrial energy sources. This is because neither economic launch capabilities nor sufficiently advanced PV and power-semiconductors were available. Also, there was no robotic option to replace hundreds of astronaut construction workers in orbit, who would need to be supplied with oxygen, food, and water, and rest periods for at least 50% of the time.

Today, this *Space Energy Option* is a technically feasible, medium-term energy solution currently available to humanity for addressing all these issues. The standard criticism of SBSP since it was first introduced has been its large scale and the initial costs. While these factors were showstoppers for economic feasibility in the past, launch costs have been reduced by approximately 90% and space hardware costs by almost 99% in the past decade. In addition, innovative modular approaches to development and deployment of space power satellites based on mass-produced components have emerged as well as digital technologies and robotic construction.

However, due to the very large scale of space power systems, initial financing for their practical development and implementation is still a major challenge that will most likely require public-private partnerships and international collaboration beyond the scope and means of any one nation. Spectrum allocation and orbital positioning issues will also require international collaboration. In addition, security guarantees for such space systems must be assured before sufficient investments will be made. Thus, an international organization with the mandate and authority to provide clean energy from space may be an imperative.

In parallel to current approaches to SBSP being implemented by a few countries, a comparable international initiative to achieve clean energy and terrestrial energy security through the implementation of the *Space Energy Option* may be the optimal approach. Due to the global scope and magnitude of the energy and climate issues, such an initiative would likely be more effective under the auspices of a global multi-national organization. The mandate of this organization would be to provide participating member nations with a plentiful supply of environmentally clean energy in a scalable, economically viable and socially equitable manner that would eventually reduce humanity's dependence on terrestrial energy sources for powering civilization.

The standard objection to SBSP has been the initial cost to implement such a space solar power system *(Nanalyze.com, 2020)* compared to ground solar and wind. While costs will remain considerable, studies have shown that the LCoE of SBSP when deployed at scale in 2050 could be comparable with nuclear power and potentially even terrestrial renewables *(ESA SBSP Cost vs. benefit studies, 2022).* A fairer comparison should be considered in the context of the increasing demand for CO_2-neutral energy and the size and value of the global energy market between now and by the year 2050. Thus, the initial cost of implementation should have lesser relevance as terrestrial energy alternatives prove to be insufficient, impractical, too expensive, or undesirable and the magnitude of the issues facing humanity in relation to its use of energy overwhelm its abilities to find and implement viable terrestrial solutions.

6.1. Space-Based Solar Power Overview

The idea of harnessing energy in space originated with the Russian and Soviet rocket scientist and astronautical pioneer Konstantin Eduardovich Tsiolkovsky *(Tsiolkovsky, 1929).* Peter Glaser described the basic Solar Power Satellite (SPS) concept in terms of actual technological capabilities. Intriguingly, several science-fiction authors had presented related schemes since the 1940's. In particular, Isaac Asimov described a space station near the Sun collecting energy and transmitting it to various planets using microwave beams in his short story "Reason" *(Asimov, 1941).*

The basic SBSP concept consists of an exceptionally large satellite carrying solar cells in Earth orbit which would capture solar energy and convert it into electrical power and use wireless power transmission (WPT) to send this energy to a ground station on Earth via a microwave or laser beam where it would be captured by a large receiving and rectifying antenna called a rectenna. This rectenna converts the energy into AC electrical current that is then fed into the existing electrical grid. Solar photovoltaics installed in space are not affected by the atmosphere, clouds, water, dust, snow, or sand as are PVs installed on Earth. Furthermore, they are illuminated by the Sun in Geostationary Earth orbit (GEO) 99.94% of the time – 8,755 hours/year. Sunlight in space has an energy density of roughly 1,350 W/m^2, whereas sunlight at midday near the equator on Earth has an energy density of roughly 1,000 W/m^2. Converting sunlight into electrical power, then converting this into electromagnetic waves, beaming this to Earth and then converting the beam into electricity has an end-to-end efficiency of approximately 10-15% *(ESA, SBSP FAQ, 2022).* The highest loss is in the solar cell technology.

		Efficiency Range	Power (MW)
Collect	Incident solar power		8,800
	Reflector efficiency	94.0% to 96.0%	
	HCPV Input Power		8,400
Convert	HCPV Efficiency	27.0% to 36.0%	
	DC Power		2,600
	Satellite housekeeping	3.0% to 5.0%	
	Housekeeping Power		105
Transmit	DC to RF efficiency	74.1% to 84.4%	
	Transmitted RF Power		2,100
	Atmospheric loss	98.8% to 100.0%	
Receive	RF Power received at ground		2,080
	Airy Disc	84.0% to 84.0%	
Distribute	Rectenna input power		1,750
&	RF to DC efficiency	82.0% to 88.0%	
Connect	DC to AC efficiency	95.0% to 98.5%	
	Power to grid		1,440

Figure 12: Typical Power Flow Estimate for 1.44 GW System (Frazer-Nash TN3, 2022, Table 2-2)

In the above table, which is based on the CASSIOPeiA SPS concept, roughly 8.8 GW of raw sunlight yields about 2.08 GW of baseload electrical power transmitted to the rectenna which then outputs 1.44 GWe of electrical power to the grid – an end-to-end efficiency of 16.36% and a DC-AC efficiency of 56% (1,440-2,100). Conversion after PV and beaming it to Earth has a DC-to-RF transmission efficiency of approximately 69% (1,440-2,600).

At local midnight near the spring and fall equinoxes, a space solar power platform in geostationary orbit (GEO) will enter the Earth's shadow and temporarily stop collecting sunlight. This lasts for about one hour. When this occurs, other flexible energy sources must provide electricity during this period. The total period of outage will be about 0.5% of the year, yielding a theoretical capacity factor of about 99.5% compared to 90% availability for a typical nuclear power plant and 13% for solar PV in northern Europe.

There are a number of technological approaches to building the optimal SPS. These range from very large structures placed in geostationary orbit (GEO) to smaller satellites in Middle Earth Orbit (MEO) and in Low Earth Orbit (LEO). The size and mass of the satellite and the choice of orbit will have much impact on the overall efficiency and cost of an eventual SPS system. Significantly, all the technological components of this concept already exist and have been tested and verified – although not yet in space at the performance scale and distances necessary to make it economically competitive.

For comparison with terrestrial energy alternatives, one may build on the 5-GW power level used e.g., in the DoE/NASA reference study mentioned below. The power generated by the orbital plant must cover the losses in the transmission chain:

1. in the conversion from DC electrical to microwave power,
2. in relation with the beam's space and absorption losses, and,
3. with the microwave capture and conversion to AC power at the ground "rectenna" (rectifying antenna).

To provide 1 TWe of continuous power, some 202 solar power satellites would be necessary. Scaling this to meet humanity's energy needs, about 3,434 of such solar power plants would be necessary to deliver 17 TWe, which is approximately what would be needed to replace fossil fuel use today.

6.1.1. SBSP before 2011

Following Glaser's publication, several technical studies assessed the feasibility of supplying Earth with solar power from space. To date, the most extensive study remains the "Satellite Power System Concept Development and Evaluation Program," conducted from 1977 to 1981 by the US Department of Energy (DoE) and NASA, with a $19.7 million budget *(DoE, 1978).* Ralph Nansen, at the time with the Boeing Corporation, participated in this study. In his book: Sun Power: The Global Solution for the Coming Energy Crises *(Nansen, 1995/2012),* he writes that the study had concluded that Space Solar Power relying on large reusable rockets and automated assembly systems in orbit was technically feasible and, had the project gone forward, an investment of $2 trillion would have saved the United States $22 trillion by 2050. This would have adverted the energy crises we are now facing forty years later.

In addition to the aforementioned study by DoE/NASA study, various approaches to SPS are discussed in detail in these books about Space-Based Solar Power:

- Frank P. Davidson, L.J. Giacoletto, & Robert Salked, Eds. (1978) Macro-Engineering and the Infrastructure of Tomorrow. AAAS Selected Symposium 23, Westview Press, Boulder (CO), 131-137

- P Glaser, F Davidson, & K Csigi, (1998) Solar Power Satellites, Wiley
- Ralph Nansen, (1995, 2012) Sun Power: The Global Solution for the Coming Energy Crisis, Ocean Press 1995, Nansen Partners 2012

In 2004 ESA conducted a study of SBSP with the title: *Earth & Space-Based Power Generation Systems: A Comparison Study (ESA: LBST, 2005*). One of the conclusions of this study was that SBSP systems would require a multi-national alliance for research, development and operation and that this alliance must be embedded into a strong legal framework which is both transparent and internationally accepted by third-party states. Our study has reached a similar conclusion.

6.1.2. SBSP from 2011

From 2008 until 2011, a comprehensive study on Space-Based Solar Power was carried out by the International Academy of Astronautics *(IAA, 2011)* which realistically describes how a SPS located in Earth orbit would use the latest technologies and be built by robots out of modular components – a concept that has both economic and maintenance advantages.

In 2011-2012 an international team, working under the auspices of NASA's Innovative Advanced Concepts (NIAC) program examined a novel, more practical hyper-modular approach to realizing SSP: "SPS-ALPHA" (Solar Power Satellite by means of Arbitrarily Large Phased Array), invented by John Mankins the team leader of the IAA study. Together, the IAA and NIAC studies provided the foundation of an integrated treatment of the topic, "The Case for Space Solar Power" *(Mankins, 2014);* this book presented the first single-volume, integrated and detailed discussion of the topic in some 20 years.

In its most recent iteration SPS-Alpha Mark III would have a launch mass of approximately 7,600 MT and provide 2 GWe of power *(RB-OHB, TN-003, 2022).* In Mankins' concept, sunlight first intercepts numerous thin-film reflectors (each an individually pointed "heliostat") organized on an extremely large, tiered / conical structural frame. Together, the reflecting heliostats and the frame that supports them comprise the "Solar Reflector Array" (SRA). These very low-mass mirrors redirect incoming sunlight either directly to photovoltaic (PV) cells that cover the upper-side of the base of the platform, or to another mirror in the SRA and thence to the photovoltaics. This is the top surface of the "Power Conversion Array" (PCA). On the opposite, Earth-facing side of the PCA WPT transmitters are connected by local power management and distribution (PMAD) to the PV modules. Connecting the PCA and the SRA is a "Platform Structural Backbone" (PSB). These three elements comprise the majority of the SPS-ALPHA MK III concept *(Mankins, 2022).*

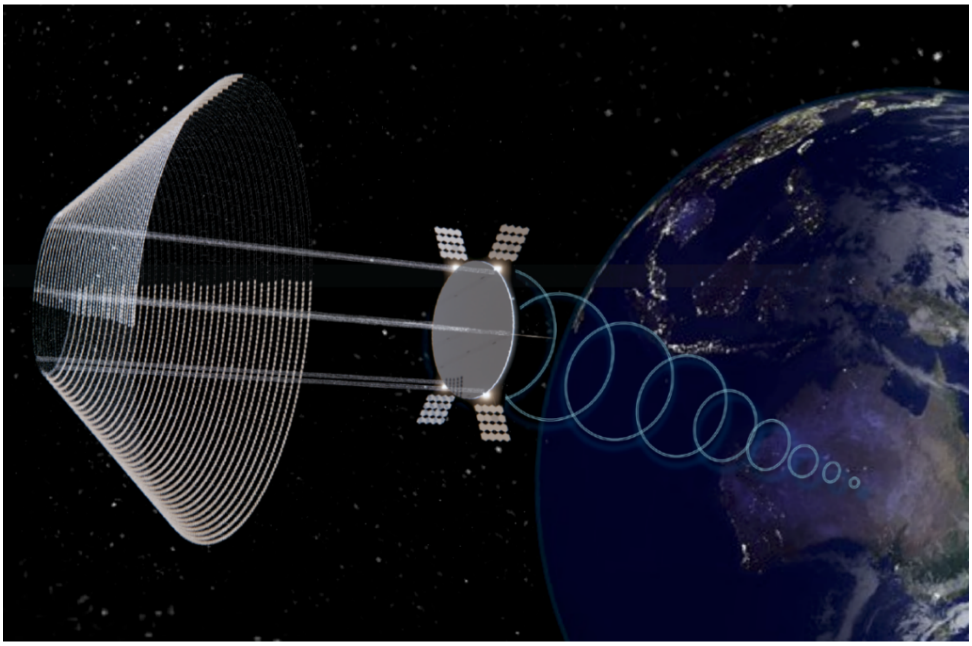


Figure 13: SPS-ALPHA MK III (Credit: John Mankins)

In China, a SPS concept called the Multi-Rotary Joints Solar Power Satellite (MR-SPS), was invented in 2015 by Xinbin Hou and others at the China Academy of Space Technology in Beijing. The MR-SPS would have a mass of 10,000 metric tonnes(MT) and provide 1-GW of power. The large solar array is sub-divided into many small solar sub-arrays, and each solar sub-array has two middle-power rotary joints. The extreme technical difficulty of high-power rotary joints in previous SPS concepts is simplified by many middle-power rotary joints. Thus, the single-point failure problem existing in traditional SPS concept is also solved. The MR-SPS concept does not incorporate mirrors to enhance power generation *(Hou, 2018).*

Figure 14: Multi-Rotary Joints Solar Power Satellite (MR-SPS) (Credit: Xinbin Hou)

In 2017, Ian Cash working in the U.K. introduced his SPS design concept called CASSIOPeiA (Constant Aperture, Solid-State, Integrated, Orbital Phased Array) as a new format microwave antenna suitable, amongst other applications, for wireless power transfer in a space environment. When integrated with high efficiency photovoltaics, CASSIOPeiA may form the basis of a utility-scale Solar Power Satellite having unprecedented specific power *(Cash, 2020).* Ian Cash has proposed several configurations for CASSIOPeiA for GEO with his 1.44 GW version having a launch mass of 2,491 MT and a 2-GW version with a launch mass of ca. 2,700 MT both versions including the mass of an Orbital Transfer Vehicle (OTV) and propellant. The introduction of digital beam-steering allows for no movable parts and the entire satellite only has to rotate around its own axis. This is a major step in SPS conceptual design. The development of the CASSIOPeiA concept has led to the formation of the UK Space Energy Initiative with wide governmental and corporate support *(SEI, 2022).*

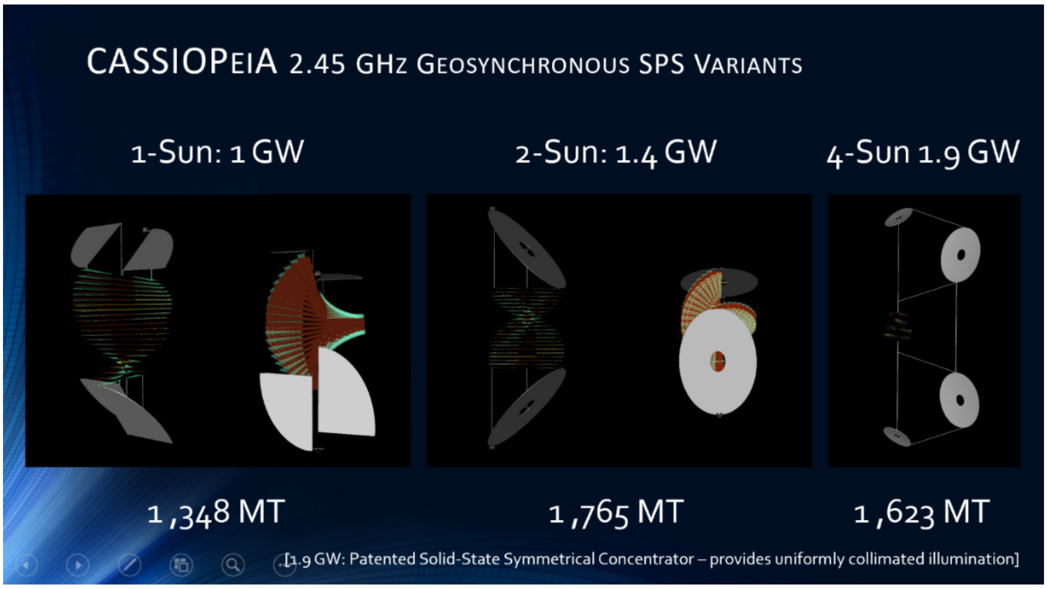


Figure 15: CASSIOPeiA Configurations (Credit: Ian Cash)

The US company Virtus Solis yet has another interesting approach. Instead of building one large satellite, they propose to send up many smaller ones, which allows a low-level start with easy scalability and a good economy of scale. Satellites are grouped into massive arrays--100,000 satellites for 100MW--allowing for a highly scalable energy platform. *(Virtus Solis, 2022)*.

Space-Based Mirrors (Sunlight Reflected to Earth) is not, properly speaking, a solar power satellite of the same type as that invented by Dr. Peter Glaser in the 1960s. Rather, this is the idea of placing large, lightweight mirrors in Earth orbit that would directly reflect sunlight down to solar arrays positioned on Earth. The idea of using mirrors in space to beam sunlight down to Earth for terrestrial solar electric power generation was first proposed by Dr. Krafft Ehricke in 1978 under the title Powersoletta *(Ehricke, 1978).*

The concept of an Earth orbiting reflector has the following advantages:

1. no requirement for energy conversion systems on the spacecraft (i.e., no PV arrays);

2. no need for electronic wireless power transmission systems (i.e., no microwave phased array or laser systems);
3. no requirement for either power management and distribution or thermal management systems on the spacecraft.

However, there are a number of significant technical challenges that make this concept far less promising than it might otherwise appear. Reflected sunlight is subject to the effects of weather, such as haze, overcast and atmospheric refraction. Reflecting the light of the Sun spreads out with the distance from the mirror. And to be useful, it would require the construction of an optically flat (to a fraction of wavelength of light) over the very large surface area of a mirror in orbit. In order to deliver solar energy at the intensity of about 'one-Sun' which is approximately 1,000W/m^2 at Earth, a flat space mirror in GEO would need to be hundreds of kilometers in diameter *(Mankins, 2014).*

Also, the effect of cloud cover needs to be examined as it is one of the major unknowns of climate modelling. Generally speaking, daytime cloud cover cools the Earth, while night-time cloud cover warms it - although different types of clouds at different altitudes also have different effects. One well predicted effect is that as Earth's atmosphere warms, increased evaporation from the oceans will increase cloud-cover *(Vandette, 2019).* However, whether this increases or reduces global warming, it could greatly reduce the output of terrestrial solar electricity generation systems around the world. This is an important systemic risk for all terrestrial solar electricity generation systems, for which alternative, back-up electricity generation systems need to be prepared. The slowly declining strength of the Earth's magnetic field will also lead to increased radiation reaching the lower atmosphere which may increase cloud cover due to the "Svensmark effect" *(GWPF, Svensmark, 2019)*, and so to an additional decline in output of all terrestrial solar generation. Earth's magnetic field is being investigated by ESA *(ESA, Swarm, 2020).*

6.1.3. ESA SBSP: 2020-2022

In 2020 the European Space Agency (ESA) signalled its interest in SBSP via its future-oriented Discovery programme by issuing 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. With this call, ESA addressed a variety of organisations to gather around a common theme. The aim was to answer the following question in as much detail as possible: how do you convert a large amount of solar energy into a useful form and beam it down to Earth or another planetary surface, as efficiently as possible?

These activities were launched to explore a diverse range of SBSP technologies, including how to more efficiently collect sunlight and how to safely transmit this power to Earth, as well as how to manufacture and assemble these huge solar power satellites, control them and keep them in the right location.

In addition to the 13 studies that were funded as a result of 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, 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 reported that, *"In 2020, the total energy supply of Europe was around 1,500 million tonnes of oil equivalent (Mtoe), which, in terms of electrical power, is equivalent to 17,445 TWh. Although, the use of all fossil fuels has declined somewhat over the past decades, especially the use of coal, nevertheless, Europe is still heavily reliant on fossil fuels for its energy needs. More than two thirds of Europe's total energy supply in 2020 was provided by fossil fuels, including oil and petroleum, natural gas, and coal. Low carbon energy sources made up smaller proportions, with renewables and biofuels accounting for 18% of the total energy supply and nuclear for around 13%. Of the total 3,000 TWh of electricity generated in 2020, renewables contributed around 40% and nuclear 25%." (LE-SBSP-TN4, 2022)*

Frazer Nash's report predicts that electricity demand in 2050 will be about 4,000 TWh/year under their Net-Zero (NZ) scenario, and 8,000 TWh/year and 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 (which corresponds to 1.296 GW at 90% availability) could provide 70 GWe of power or ca. 610 TWh/yr (15.25% of 4,000 TWh/yr or 7.6% of 8,000 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. This is equal to the satellite mass of 1,816 metric tons plus 675 MT for station keeping propellant, assembly robots, and an Orbital Transfer Vehicle (OTV) *(FNC, 2022).*

The 54 SPSs for the year 2050 mentioned above would need between 4,644 and 6,426 launches. An 86-launch scenario per satellite would place 29 tonnes into GTO using a Starship refilling concept. A 119-launch scenario would place 21 tonnes of mass per launch directly in GTO. In terms of mass-to-orbit, between now and the year 2050, 54 SPSs with a launch mass of 2,491 MT each equal 136,514 MT of payload needed to be sent to 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. The 54 SPS systems would cost approximately €418 billion.

Based on the EU Reference Scenario 2020, *(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 (314 TWh = 9% and 390 TWh = 11.1% of 3,500 TWh). In their analysis the total cost per SPS unit varies between €8.07 billion and €33.41 billion per SPS system. 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.

In the summer of 2022, ESA announced its proposed SOLARIS programme with the goal to prepare the ground for a possible decision in 2025 on a full development programme by establishing the technical, political and programmatic viability of Space-Based Solar Power for terrestrial needs (ESA, Solaris, 2022). 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 decarbonisation.

The SOLARIS initiative will also address potential environmental, health and safety issues and challenges related to regulation and international space policy coordination *(ESA: Solaris RFI, 2022).* Through SOLARIS, Europe may extend the technological state-of-art in a diverse set of key technologies relevant to applications both on Earth and in space, such as high-efficiency solar cells, wireless power transmission and robotic in-orbit assembly. It would ensure that Europe becomes a key player – and potential leader – in the international race towards scalable clean energy solutions for mitigating climate change and providing energy security.

Since its introduction in August 2022, over 100 press articles have appeared in the international press *(Astrostrom, Solaris, 2023)* and its promotional video has been viewed over 31 thousand times on YouTube *(ESA: Solaris, YouTube, 2022).* Through this proposed new programme ESA has taken the next step in pursuit of space contributions to provide Europe and Earth with clean energy from space.

6.2. The GE⊕-LPS Approach to SBSP

As seen in the above analysis and examples, a major challenge to implementing the *Space Energy Option* is not only the substantial cost and technical complexity of the system but also the enormous manufacturing and logistical effort and the substantial environmental cost needed to launch the many gigawatt-scale SPSs from the surface of Earth into orbit. As early SPS systems will most likely be developed with an Earth-launched approach, demand for launch services to implement a large scale SBSP program would become a market driver for the development of reusable heavy lift launch capacity. However, opportunities for reducing the environmental impact of SBSP deployment are 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.

The GE⊕-LPS concept proposes to address both the logistical and environmental challenges 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 for providing energy to Earth at a significant level. As such, this approach could also significantly lower the costs of realizing SBSP. If implemented on the scale needed, 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 real spacefaring civilization.

While this would become a true macro-engineering project, even larger projects to generate solar power on the lunar surface have been proposed, such as the Lunar Solar Power (LSP) system advocated and analysed in detail by Criswell *(D. Criswell, (2000, 2010).* Criswell's concept would use approximately 200,000 square km of solar panels on the lunar surface to supply 20 TWe of electrical power to Earth via microwave beams and Earth-orbiting reflector satellites. The scale of 20 TWe is based on Criswell's argument that 2 kW of electric power per capita would enable a comfortable standard of living worldwide. This matches an environmental vision of a "2000-watt society" by 2050, first introduced in 1998 by the Swiss Federal Institute of Technology in Zürich *(ETH Zurich, 1998).* An even more gigantic proposal is that by construction company Shimizu corporation to build a 400 km wide" belt" of photovoltaic panels around the entire lunar equator and transmit microwave power continuously to rectennas on Earth *(Shimizu Corporation, 2009).*

7. The GE⊕-LPS Proposed Concept

The proposed GE⊕ Lunar Power Station (GE⊕-LPS) is a multi-purpose concept that addresses several critical issues related to lunar development and terrestrial energy production. Briefly stated the Greater Earth Lunar Power Station is a habitable space station in lunar orbit that is also a solar power satellite. The GE⊕-LPS is designed to be constructed primarily from lunar resources and materials using lunar based automatized manufacturing processes. As such, the GE⊕-LPS is intended to provide needed electrical power for lunar surface 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. Last, but not least, if the GE⊕-LPS concept and its energy production functions can be shown to be technically feasible, the concept may be scaled to any dimension. Thus, larger versions could be manufactured from mostly lunar materials and then positioned in Earth orbit to provide clean solar energy for terrestrial purposes.

As per the Technical Proposal, the GE⊕-LPS proposal pictured in Figure 16 represents a "different power station" approach to provide power from space and large-scale space applications. In its initial iteration, it proposes an area-redundant, solar collecting element, crossed by four tubular rays that position a spherical body at the center. As such, the GE⊕-LPS was not intended to point to the Earth, but to be oriented towards the Moon, returning electrical energy to the surface whence (most of) its constituent materials came.

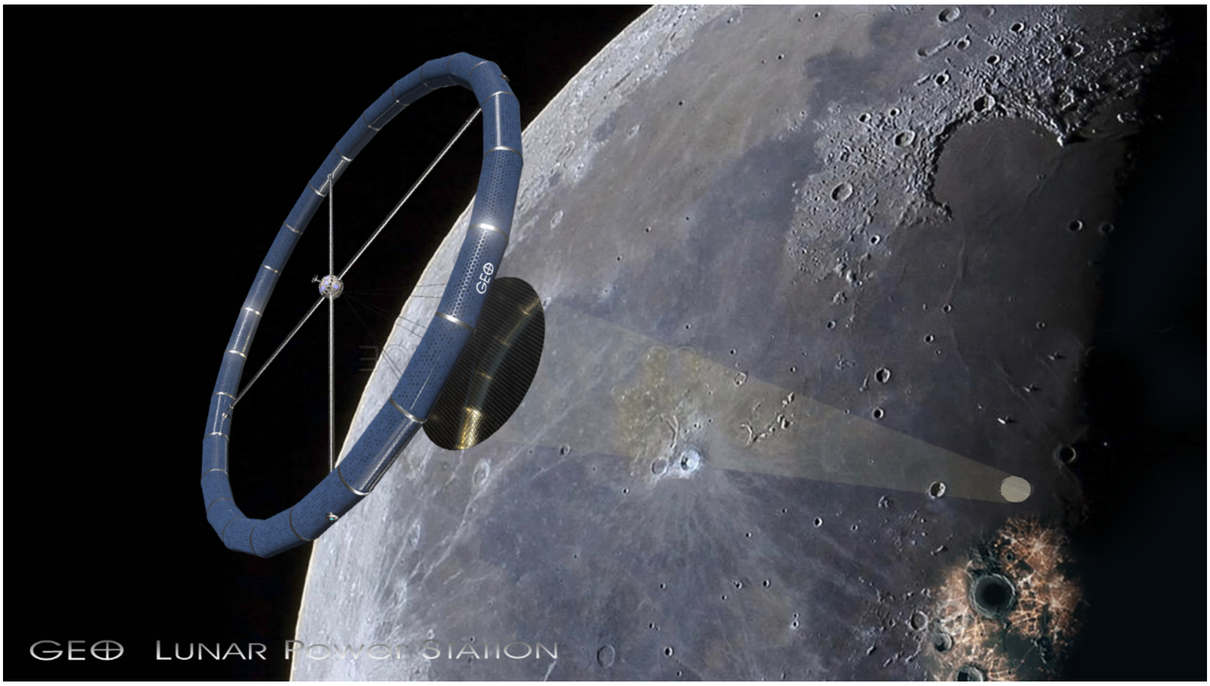


Figure 16: The initial proposed design of the GE⊕-LPS providing power to lunar operations. (Credit: Astrostrom)

Accordingly, its realization requires a number of mining, processing and manufacturing facilities on the surface of the Moon. Excavated, transported, and beneficiated lunar regolith, would be delivered to the processing machines that will yield identified raw materials (e.g., aluminium, oxygen, silica and various other metal silicates, glasses and basalts, geopolymers (lunar polymers) components. These materials would then be processed into power producing (photovoltaics) and structural elements that will be integrated into the GE⊕-LPS structure via robotic assembly procedures in a lunar halo orbit at the Earth-Moon Lagrange point 1 (EM-L1). An efficient means of economical transport from the lunar surface to the assembly location at EM-L1 such as via a lunar space elevator or a mass driver will be necessary.

At EM-L1, the photovoltaic elements, the struts, the modules, the structural components for the supporting structure and the habitat sphere as well as those elements needed for the antenna will be assembled. 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. On the lunar surface, a rectenna to receive the power from the GE⊕-LPS will be constructed from the appropriate lunar-sourced and manufactured materials.

Thus, GE⊕-LPS proposal can be characterized on three levels:

1. The power generation level is intentionally limited and modest, giving to the program a predefined target point; however, the system's capability must be sufficiently large to require the evolutionary introduction of the mentioned spaceborne facilities; the different adopted processors will be developed, tested operationally, then improved, replicated and used for significant product volumes; the project's (however modest) complexity will define processors acting in parallel to obtain different products; after the project's formal conclusion, machinery and accumulated know-how will define an industrial basis that can grow, adapt, or expand to enable further productions.

2. The initial power station does not supply terrestrial receivers; this orientation will help to dispel unfounded fears from people opposing the power-from-space concept -- both directly (the microwave radiation goes on the Moon) and indirectly (the system's workings can be observed, measured, etc); although the precious power delivered will not serve the terrestrial societies directly, any similarly-sized prototype's practical contributions would remain negligible in any case, but an efficient advancement of technology and demonstrator could speed the regular operation of space power stations; in parallel, the production processes employed are those that would serve to build systems for Earth-directed use, greatly advancing their potential realization;

3. The design of the orbiting complex includes a degree of aesthetic freedom that underlines its difference from conventional power-from-space concepts; one may hazard, however, that the real differences consist in the project's dimension, the associated relatively wide usage of extra-terrestrial materials, its multiple functions (e.g. the creation of a tourist facility) could be gradually transformed into volumes for habitation and/or enclosed laboratories.

As such, the proposed Greater Earth Lunar Power Station - GE⊕-LPS - concept includes a habitable space solar power station orbiting the Moon, at least one rectenna (reception & rectification antenna) station on the lunar surface, surface mining, processing and manufacturing operations and a lunar surface-to-EM-L1 transportation system.

However, beyond these physical characteristics and specific objectives, the GE⊕-LPS concept will create spaces, venues, experiences, and narratives to support a widespread cultural involvement in astronautics, science, space exploration and development while simultaneously addressing critical energy needs on Earth.

8. Study Objectives

The main objective of the study is to explore the technological feasibility of implementing the GE⊕-LPS concept that would lead to a serious discussion of its applicability to proposed cislunar scenarios. 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.

An equally important objective is 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 to ensure its implementation. Therefore, the study has analyzed the GE⊕-LPS concept into a macro-economic context that considers competing approaches to terrestrial and space-based power producing systems.

8.1. Technical Objectives

The technical objectives of the GE⊕-LPS study have been broken-down into the following categories:

8.1.1. ISRU Identification

Identification of the necessary materials that are known and/or are assumed to be available in sufficient and obtainable quantities from the lunar regolith that would enable the realization of the GE⊕-LPS concept. The primary focus has been on photovoltaic production from lunar materials, structural elements for the LPS supporting framework and manufacturing facilities, rectenna and habitat construction, and radiation protection.

8.1.2. Production Operations

Terrestrial mining, processing and manufacturing (MPM) operations are established and well understood technologies. Automation of production processes is steadily increasing. Extrapolating these known technologies to the lunar environment wherever possible will ensure the most reliable approach to implementing feasible production operations.

8.1.3. Infrastructure Facilities

As the GE⊕-LPS concept spans the cislunar system, facilities located at the various waypoints distributed throughout the region will become necessary. These locations include Low Earth Orbit for demonstration, technology certification and cargo transition, the Earth-Moon Lagrange point 1 hub for cargo storage, assembly operations and lunar power delivery, the lunar surface for initial MPM operations, power generation, propellant production and storage, habitat and life support systems.

8.1.4. Habitats

Habitats will be located at each of the cislunar waypoints. Each of these will have unique requirements and characteristics yet may share life support elements which can be optimized for each situation.

8.1.5. Assembly Operations

Extrapolating from semi-autonomous mining and manufacturing operations on Earth, advanced robotic assembly scenarios will be developed and implemented requiring minimal human supervision and intervention.

8.1.6. Transportation Options

Due to their technological maturity, rocket based transportation systems will be necessary to implement the early phases of the GE⊕-LPS concept. Rocket transportation systems must become totally reusable and refuellable from either terrestrial or lunar propellants. Once production of lunar sourced elements for the GE⊕-LPS commences, the need for a more efficient transport of cargo from the lunar surface to EM-L1 and then from there to GEO will demand a more efficient cislunar transportation system such as the Lunar Space Elevator (LSE) or a mass driver.

8.1.7. Power Generation and Supply

Initial lunar surface operations will depend on an imported electrical power supply system that will be either photovoltaic or nuclear with sufficient capacity to supply initial operations. Due to international concerns and regulations on the deployment of nuclear power devices in space, the GE⊕-LPS concept will likely rely on pre-built, low-mass PV systems delivered from Earth as well as a storage system to compensate for the lunar night.

8.2. Economic Objectives

One of the objectives of the study was to identify and explore the economic parameters and dimensions of such an endeavour. As it was foreseen that the energy production functions of the GE⊕-LPS concept could be eventually scaled to any dimension, larger versions could be positioned in Earth orbit and help provide much needed clean continuous solar energy for terrestrial purposes. Consequently, another economic objective of the present study is to estimate the minimum cost needed to overcome the limitations to the growth of space-based solar power (SBSP) supply to Earth, so that its contribution to terrestrial electricity supply could grow beyond the approximately 100 GWe discussed in this report, to make a major contribution to world electricity supply, reaching perhaps 1,000 GWe or more.

8.3. Cultural Objectives

In addition to the technical and economic objectives, the GE⊕-LPS study has explored the cultural impact of such a technology and economy driven endeavor. For most people, the idea of harvesting energy in space and beaming it to Earth via Solar Power Satellites is already a step into the realm of science fiction and way beyond their awareness of humanity's steps into space. 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, defining the cultural dimensions of this project is a major objective of the study.

The Moon can be understood to be the ultimate global ambassador. Humans have been entranced and inspired by the Moon throughout history. Because it orbits our Earth, it is visible from all continents and latitudes, engages the awe and fascination of all Earth's peoples without reservation, and its dynamic phases attract everyone's attention each and every evening – and sometimes even during the day. The Moon is one of the first objects that children recognize and name as they train their eyes upon the night skies. Though our Sun is the giver of energy and life and dictates daily life around the globe, the Moon is an object of wonder that is imprinted on our psyche very early in our lives. The Moon, known as Selene in Greek mythology, shining bright through the darkness when the Sun has retreated, gives our planet and all who inhabit it new possibilities and potential. With the GE⊕-LPS concept, the Moon will not only reflect the light of the Sun to Earth during the night, but also will be the provider of the SPS built with lunar materials, which will send clean solar energy to our planet day and night. Thus, the eventual success of the GE⊕-LPS concept will build upon the fascination of the Moon and its role as a provider of resources for a growing technical culture and its role in determining the future destiny of our species as shown in this study.

In addition, as many engineers and writers of both fiction and non-fiction have described in detail, the surface of the Moon is capable of becoming a major centre of economic and industrial growth, if appropriate investment is made. Bringing this about will open a major new chapter in human history, becoming the stepping-stone for human populations to spread far out into the solar system.

8.4. Outreach Objectives

Due to the potential impact that the results of this study may have on the discussion related to Space-Based Solar Power, one of the key study objectives has also 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 results understandable and accessible to a large audience, different media approaches are being developed. These include online databases of relevant information, press releases, book publication and video production. In particular, the early visualisation of the technical concepts shall inspire engineers and economists and have a "pull-effect" towards the sooner rather than later realisation of the concept.

9. GE⊕-LPS System Concept

During the study development, a design concept has emerged based on the definition of the various key components of the GE⊕-LPS system. These 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 the 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 streets or tracks for base station transportation.

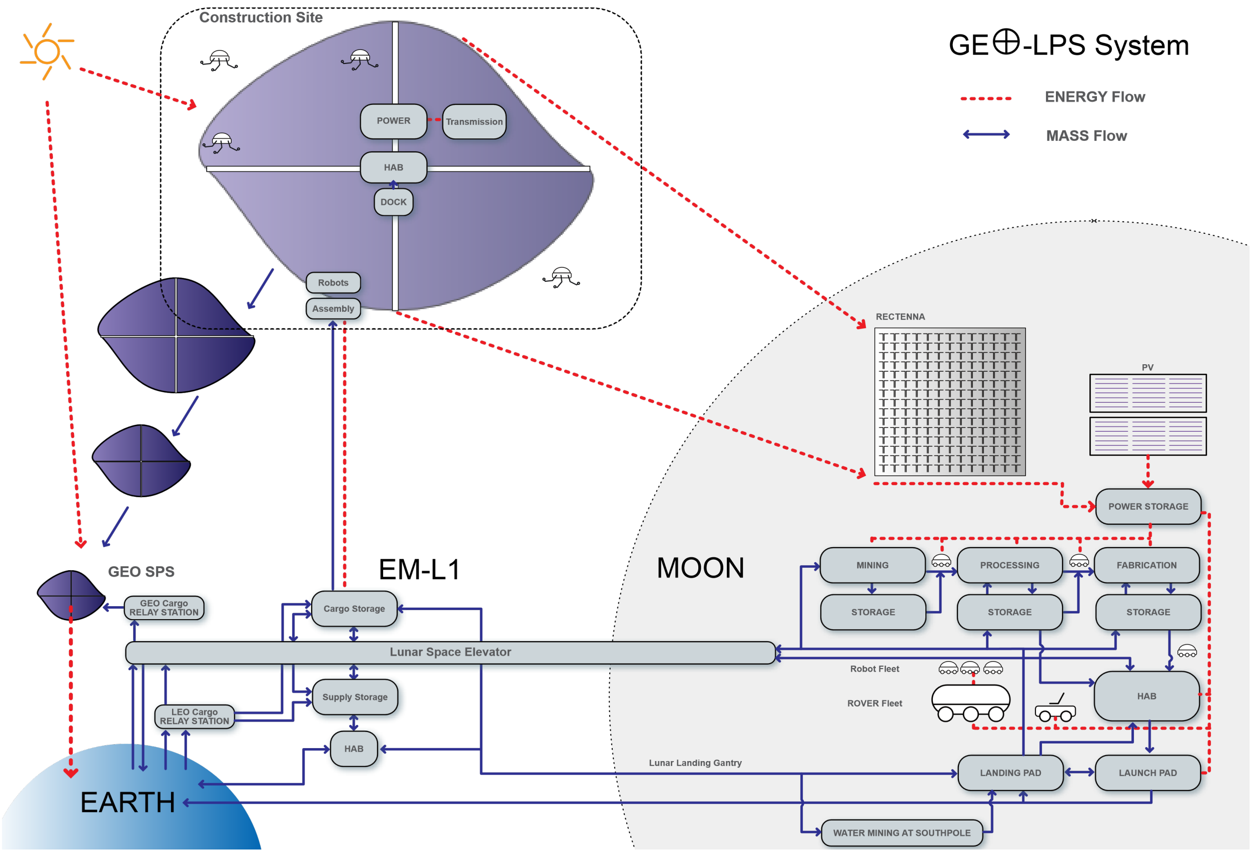


Figure 17: GE⊕-LPS System Diagram (Credit: Astrostrom)

Initially, transportation between the GE⊕-LPS and the lunar surface base station will rely on rocket powered vehicles. Reusable cargo landers could 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, and for bringing additional equipment down to the lunar surface at a greatly reduced cost.

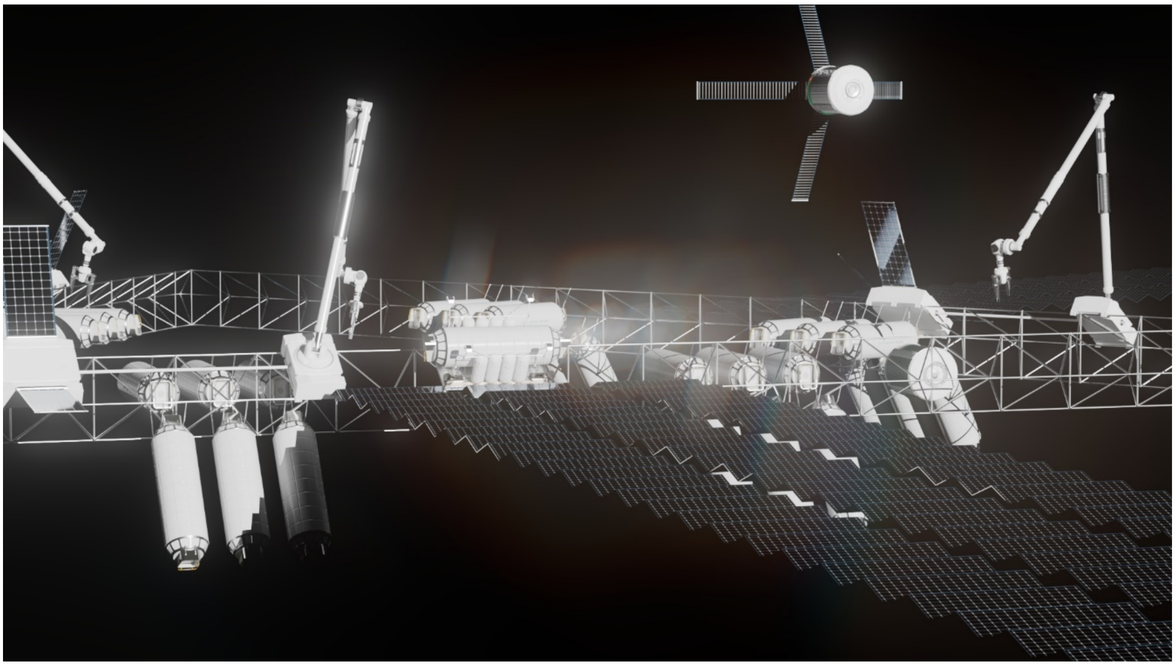


Figure 18: Lunar Space Elevator Hub at EM-L1 (Credit: Astrostrom)

Eventually, cargo transportation will be via a Lunar Space Elevator (LSE) which will be for delivery of the station 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 when transporting cargo in both directions. Together with the EM-L1 transportation hub this will create an interesting business case.

9.1. GE⊕-LPS Power Requirements

Roughly 300kW of power is assumed to be needed to run a single manufacturing facility *(Bergsrud, et al, 2013).* Selected data is shown in Table 1 below (*Gutowski, 2006).* It is also assumed that the mining and processing operations require the same amount of electrical power for operations. Thus, a total of about 1 MW of electrical power required by these three industries once these become fully operational. A lunar base with the equivalent power requirements as the ISS would require about 100 kW of electricity. Another 40 kW is needed for a rover that will be used for lunar exploration. The transportation industry including launch, cargo shipments in the Earth-Moon system and space tourism will also need amounts of electrical power. No number at this time can be reliably estimated for the power requirement of the transportation industry.

Process Name	Estimates		
	Power Required	Process Rate	Electricity Required
	kW	cm^3/s	J/cm^3
Injection Molding	35.76	1.40E+01	3.09E+03
Machining	75.16	4.01E-01	1.87E+05
Finish Machining	9.59	2.05E-03	4.68E+06
CVD	15.00	3.24E-03	4.63E+06
Sputtering	6.75	1.05E-05	6.45E+08
Grinding	7.50	2.85E-02	3.08E+05
Waterjet	16.00	1.04E-02	1.58E+06
Wire EDM	6.60	2.71E-03	2.44E+06
Drill EDM	2.63	1.70E-07	1.54E+10
Laser DMD	80.00	1.28E-03	6.24E+07
Oxidation	21.00	8.18E-07	2.57E+10
Total	275.99	----	----

Table 1: Power Requirements

Thus, initial GE⊕-LPS power generation baseline power requirements consist of 300 kW of power for each processing and manufacturing activity, and for life support and surface transportation:

1. Photovoltaic production – 300 kW
2. Basalt production – 300 kW
3. Metal production – 300 kW
4. Oxygen and Propellant production - 300 kW
5. Habitat operations – 100 kW
6. Surface transportation – 50 kW

Based on these estimates, baseline power requirements for lunar surface activities are approximately 1,350 kW. This implies that the GE⊕-LPS system should supply a minimum of 1.5 MWe of continuous power to the lunar surface once all systems are operational. Additional power may be needed for storage necessary for power in the lunar night period.

For lunar photovoltaic production we have selected Monograin Layer (MGL) solar cells due to their special ISRU properties which are described in detail in Section 9.2.2. For power transmission we are using the 5.8 GHz frequency as this is considered useful for power beaming to Earth as it is one of the frequencies reserved for non-communications applications; these are known as the Industrial, Scientific, and Medical (ISM) bands. Two of these ISM bands are of particular interest in prospective SPS and WPT applications: 2.45 GHz and 5.8 GHz. These two frequencies fall exactly within the range where the atmospheric attenuation of electromagnetic energy is the least *(Mankins, 2014).* The use of the electromagnetic spectrum (particularly, the RF) is managed by an organization known as the International Telecommunications Union (ITU). An alternative for lunar operations would be

24 GHz. The corresponding rectenna will be 3D printed from lunar materials, primarily basalt and aluminium.

9.2. The GE⊕-LPS Reference Design

The GE⊕-LPS concept has gone through a series of geometrical design iterations. After examining various geometric configurations for the GE⊕-LPS, we 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 do not need to be switched continuously.

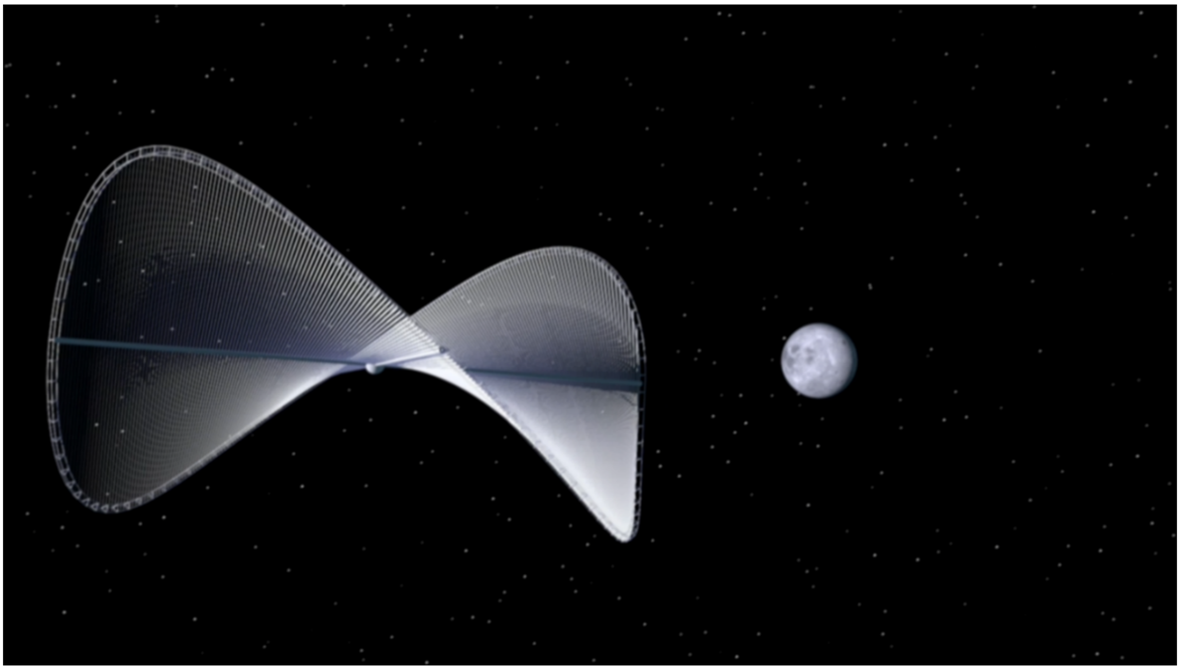


Figure 19: The GE⊕-LPS Butterfly Design Concept (Credit: Astrostrom)

As a baseline for power supply to the lunar surface we have established a requirement for the GE⊕-LPS of 1.5 MW of continuous power for initial 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 an efficiency of 91W/m^2 this would generate 3.6 MWe at the SPS and deliver 2.0 MWe at the rectenna. However, since a smaller antenna in space requires a much larger rectenna on the Moon, a larger SPS may be considered economically and technically advantageous, as more power can always be used to increase mining and production.

To provide power to the lunar surface from EM-L1 is 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 SPS with a diameter of 900-1,200 meters at EM-L1 will require a rectenna on the Moon with a diameter of 4-5 kilometers, assuming use of 5.8 GHz microwaves. With the rectenna located near the base station of the LSE at Sinus Medii, continuous power can be supplied for lunar beneficiation and fabrication operations. A GE⊕-LPS located near the EM-L1 hub would also benefit from station keeping and maintenance. Beaming power from lower lunar orbits would require more satellites.

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. Below are several power output calculations based on different Butterfly dimension configurations.

9.2.1. 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. The main difference compared to other metal oxide fibres, such as glass fibres or ceramic fibres, is the content of iron oxides in the basalt fibres. This gives the basalt fibres the dark coloration in contrast to white and transparent glass and ceramic fibres.

Basalt fibres will play a very important role in the GE⊕-LPS programme, as modern basalt technology enables very useful material properties:

The fibres can be individually oriented and placed in a structure for creating local variations in material properties:

- The use of continuous filament ensures a higher-fidelity manufacturing process due to better control over the placement of the material when compared to powders and liquids.
- Fibre based materials are suitable for both compression and tension structures, which extends the number of possible application areas.
- Fibrous materials are highly formable which allows production of complex shapes in response to unique performance criteria or site conditions.
- Fibres enable the production of lightweight and highly optimized structures.
- Fibrous materials may offer a better performance in response to thermal stresses.

Basalt fibre is a good candidate for use in lunar applications due to following reasons:

- Basalt-based materials are non-hazardous.
- Simpler manufacturing process than that of a glass fibre due to less complex composition, which can be produced in a single feed line because there is no need for secondary materials.
- High strength and high modulus with excellent shock resistance.
- Similar mechanical properties to glass fibres.
- High chemical durability against the impact of water, salts, alkalis and acids.

- High service temperature and fire resistance.
- Can be post-processed to change thermal and mechanical properties, e.g. via doping, plasma treatment or sol-gel technology for the application of metal oxide coatings

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 *(ESA - Advanced Concepts Team, 2019)*.

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.

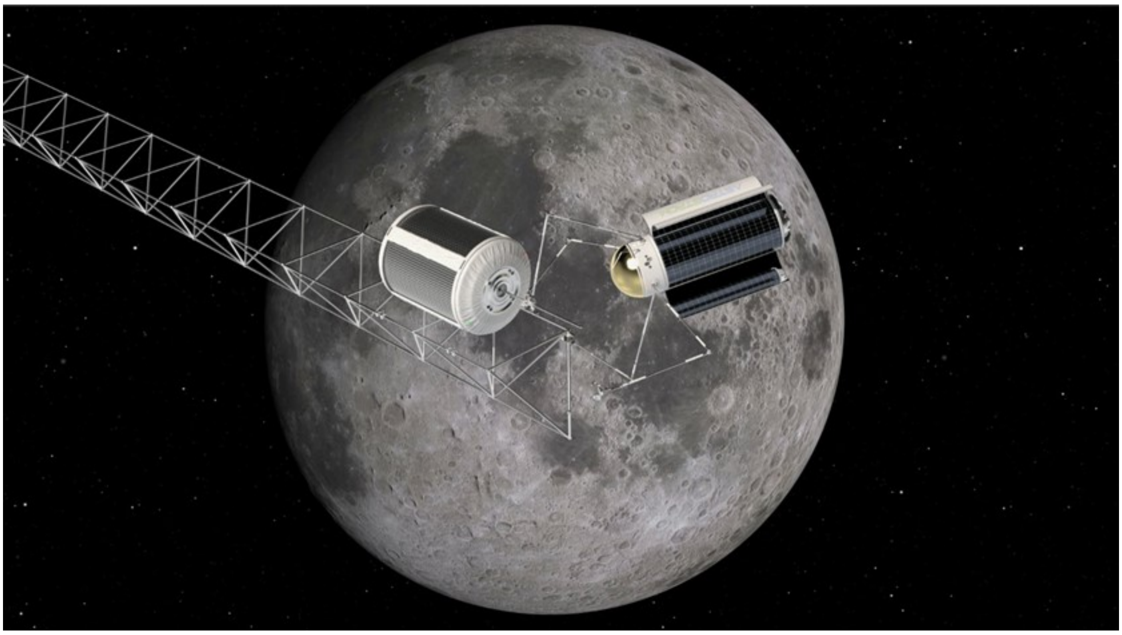


Figure 20: Robotic construction of the outer rim of LPS. (Credit: Astrostrom)

The GE⊕-LPS main structure consists of the two axes and the outer rim beam. The axes are conceived to be built with the GE⊕-LPS construction system and will be cladded with a 3mm aluminium sheet material. This is intended for a possible future pressurization of the axis to connect to further docks and equipment at the end of each axis. The diameter of the axis is 6 m. 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 robots. However, to reduce weight and complexity, a more promising approach would utilize a bonding system where the tubes are bonded in space directly, without the need for nodes. Both construction approaches need further research and development and ultimately in-space demonstrations. The robotic construction of the outer rims of the GE⊕-LPS in shown in Figure 20.

On the lunar surface, the GE⊕-LPS Construction System will allow the construction of similar masts for illumination and survey as well as for tramways, towers, bridges, cargo and maintenance hangars, cranes, supporting structures for machinery in mining, beneficiation and manufacturing.

9.2.2. Photovoltaics from Lunar Regolith

For lunar photovoltaic production we have selected Monograin Layer (MGL) solar cells with AM0 ratings of 3.7 %, 6.7%, 13% and (eventually) 21% with further development. MGL technology is completely different from traditional crystalline or thin film solar cell technologies. The lunar regolith holds several iron-bearing minerals and researchers at Tallinn University of Technology have identified pyrite FeS2 as one possible candidate for the solar cell material, as it has all the necessary electrical and optical properties, the power conversion efficiency of such solar cell could reach 25% *(Kristmann, et al, 2022).*

MGL lightweight solar panel technology combines the advantages of high-efficient single-crystalline material and low-cost roll-to-roll panel production, enabling to manufacture flexible, lightweight, and cost-efficient solar panels from powders of crystalline semiconductor absorber material. This type of cell has a lower efficiency than other material approaches, however these may be the easiest to produce in large quantities on the Moon from lunar ISRU as these do not require the complicated production of wafers which all other PV approaches do. Another advantage is that the monograin powder can be delivered from Earth in the initial phase of lunar PV production before ISRU operations for lunar sourced powders have commenced. Furthermore, MGL solar cell crystalline material can be recycled and reused when their end-of-life has been reached.

Monograin layer (MGL) solar cells are a single-crystalline type of solar cell. 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. Additional developments, modifications and patents were taken by the TalTech researchers and crystalsol GmbH in Vienna, Austria.

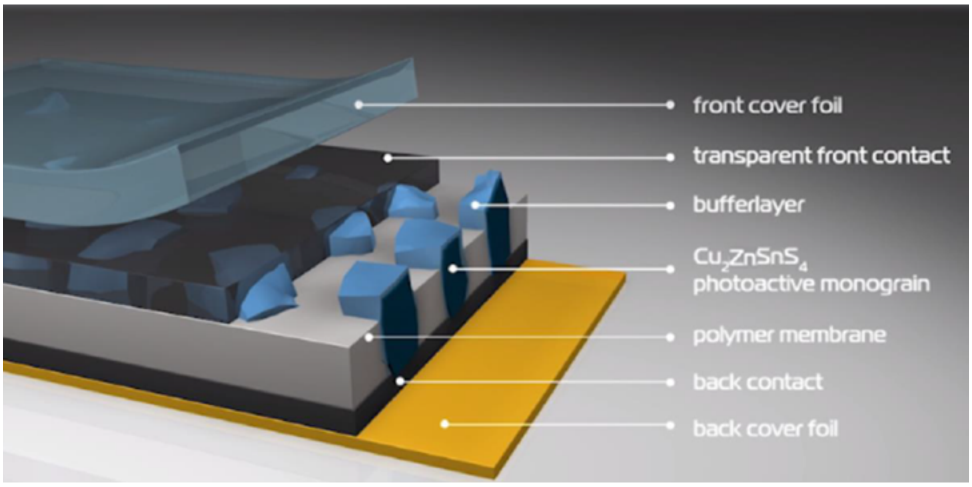


Figure 21: Monograin Layer Composition (Credit: Crystalsol GmbH)

MGL solar cell has a superstrate solar cell structure: back contact / absorber / buffer / transparent conductive oxide. The structure is glued on a supportive substrate (glass or polymer film). The MGL solar cell absorber is a monolayer of nearly unisize semiconductor powder crystals fixed with a thinner than crystal size layer of epoxy (or some other polymer).

MGL technology allows to cover vast areas with minimum cost. As 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 can be transported to the Moon or produced *in situ* from lunar regolith. To evaluate the suitability of MGL technology for space applications *(Raadik, et. al 2021)* have carried out preliminary environment 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. In addition, further development of this technology is expected to increase the AM0 to 13% and potentially to 20-21%. A 21% AM0 would equal ca. 286 W/m^2 which would be in the range of GaAs efficiency. According to press reports, *(Off Grid, 2021)* the theoretical efficiency of pyrite solar cells could reach 25% which mirrors the research from Kristmann et al mentioned above. Radiation tests on how pyrite will react to high energy particles have not yet been performed but may take place at CERN as part of future development.

The potential lunar material for MGL microcrystals would be pyrite FeS_2. Its elements, iron and sulphur, are quite abundant in the lunar regolith. Currently the use of pyrite for MGL is being investigated in Europe. Pyrite could be gained in the necessary quantities from the Troilite found in lunar soil. For the GE⊕-LPS hybrid PV-antenna elements it is proposed that the PV material as well as the semiconductors and integrated circuits for DC-RF conversion and the antennas are applied as thin-film printed electronics onto a transparent substrate.

9.2.3. Blue Alchemist Solar Cells from Regolith

In February 2023, Amazon founder Jeff Bezos' space firm, Blue Origin, announced it has developed a method for producing solar cells and transmission wire using only lunar regolith. The 'Blue Alchemist' method was developed over the past two years using regolith simulants that are chemically and mineralogically equivalent to lunar regolith, accounting for representative lunar variability in grain size and bulk chemistry. The process uses molten electrolysis to separate aluminium, iron, and silicon from bound oxygen in lunar regolith to extract the materials for solar cell construction. Their proprietary transport subsystem moves and separates molten material at temperatures above 1600 degrees Celsius in a controlled and power-efficient manner while withstanding the high-temperature, corrosive environment of the Moon. Molten regolith electrolysis then extracts iron, then silicon, and finally aluminium by passing a current through the molten regolith. The process purifies silicon to more than 99.999% without using toxic or explosive chemicals. *(Blue Origin, 2023)*

If shown to be produced at higher efficiencies, this could become an alternative to MGL technology for the GE⊕-LPS hybrid PV-antenna elements and having Blue Origin as a supplier of the PV technology would be an interesting option. However, as cosmic rays results in a degradation of the silicon cells, these will need to be covered with glass which takes substantial energy to produce on the Moon and adds significant weight to the solar panels to be used on a SPS. More in-situ research will be needed.

9.2.4. V-Shaped Photovoltaic Array

The idea to employ V-Shaped Photovoltaic Arrays with integrated beam steering antenna derives from several assumptions and challenges met during research and expert discussions. The proposal of GE⊕-LPS to manufacture solar cells on the Moon suggests avoiding highly complex industrial silicon PV production as known from Earth. A simpler system has to be found. Since PV-material is basically semiconductor material, and for DC-RF conversion and beam steering the need for electronics on a hybrid PV-RF element is given, the idea came up to look at 3D printed thin-film electronics, which allow an endless, automatic panel production and also the printing of antennas directly onto the panels. Flexible and printed electronics is a highly multidisciplinary research area with the potential for significant breakthroughs in developing new technologies for ubiquitous electronics. *(Bonnassieux et al., 2021)*

A roll-to-roll (R2R) gravure is the highest throughput printing method for printing magazines and packaging since it can reach the maximum printing speed of 600 m min^{-1}. The R2R gravure has been considered as a foundry to manufacture inexpensive, disposable and large-area electronic devices. Up to today, successfully printed Thin Film Transistor (TFT) based concept devices (logic gates and TFT active matrix) through all R2R gravure have been demonstrated (Figure 22). This emerging technology may allow a fully automatic, high-volume production of hybrid PV/Antenna panels on the Moon.

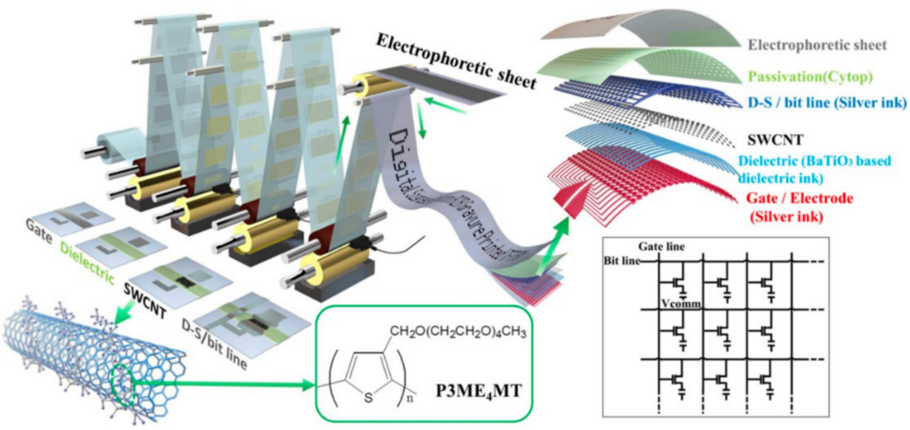


Figure 22: Schematic description of R2R gravure printing process to print TFT-active matrix using carbon nanotube as semiconducting material. (Copyright © 2020 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim).

We assume the PV efficiency initially will not be very high, but mass production is achievable. Figure 23 shows a concept design for such a hybrid panel. It can be flat-packed densely for delivery and be extended into a V-shaped structure on the construction site of the LPS. A transparent film could have several advantages, especially for the use of a single crystal layer technology, since the PV would be active on both sides. The fold out in an angle of 60 degree would bring the dipole antenna into position as described by Ian Cash in 2017 *(Cash, 2017)*. An additional PV panel in between would half that angle to 30 degrees, which is making use of a bionic approach guiding the light reflections like in butterfly wings.

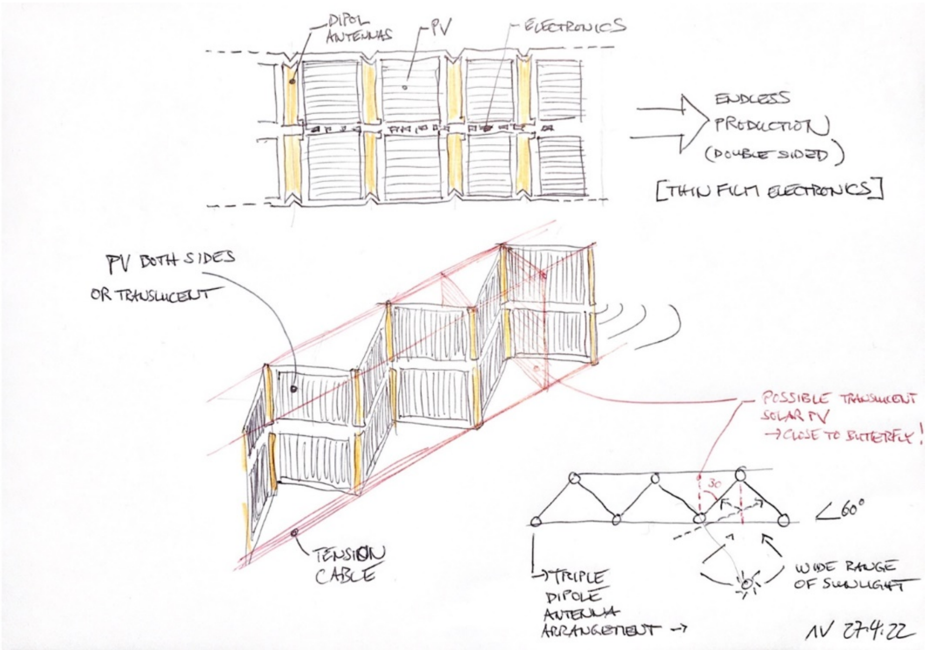


Figure 23: Concept design for a roll printed hybrid PV/Antenna element in V-shaped structure.

9.2.5. The Butterfly Hybrid Solid State Antenna

For hybrid modules also different antenna designs have been proposed. The test modules of Jaffe and the California Institute of Technology use patch antennas. Ian Cash's CASSIOPeiA proposes a triangular arrangement of dipole antennas, which can be switched to allow for a 360 degree electronic beam-forming *(Cash, 2017) (Cash, 2019) (Cash, 2020).*

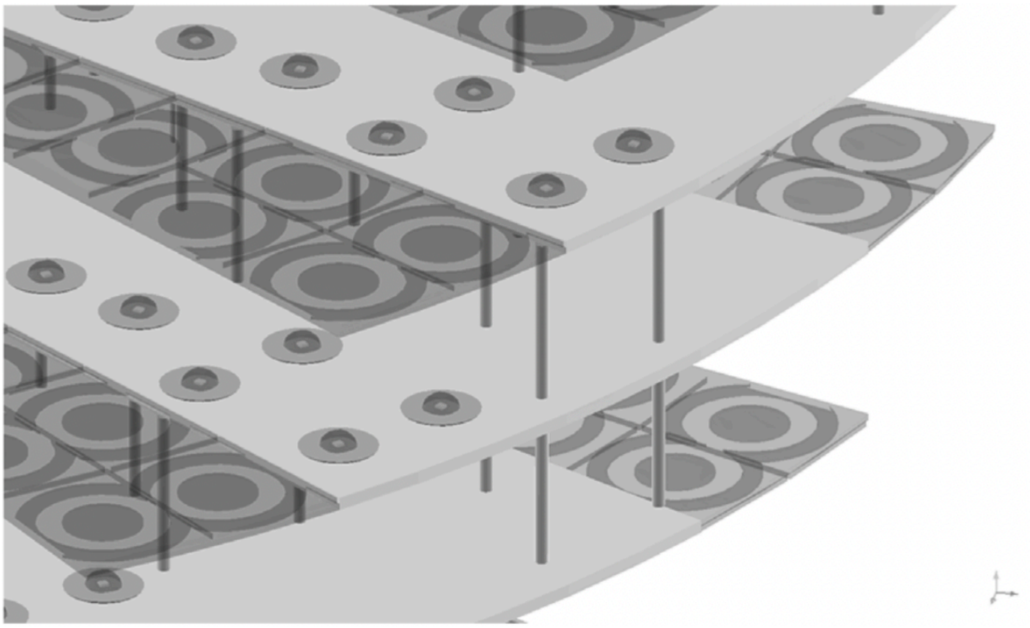


Figure 24: Helix elements of CASSIOPeiA, showing the solar concentrators, the high-efficiency PV cells and the triangular arrangement of the dipole antennas. (Credit: Ian Cash)

Beam steering limitations of planar phased arrays require other SPS concepts to have either physically rotating parts, redundant solar collector / RF transmitter area, or suffer cosine losses as the collector tilts away from the Sun. The novel phased array of CASSIOPeiA permits beam steering through a full 360 degrees without degradation. Thus, there are no moving parts and only the whole satellite must be rotated around its longitudinal axis to keep the mirrors directed towards the sun.

The Butterfly concept is making use of the same dipole antenna formation as in CASSIOPeiA but integrates the dipoles and its conversion electronics into the thin-film solar panel production. This has the benefit that the production of electricity, its conversion into microwaves and its transmission by the antenna are all close together and no excessive power is accumulated on the circuit boards. Also, the units can operate stand-alone, which is increasing redundancy in case of micro-meteorites and/or electronic component failure.

9.2.6. Description of the GE⊕-LPS Power Levels and Delivery

For power transmission we have chosen to use the 5.8 GHz frequency as this is widely considered to be optimal for power beaming to Earth. An alternative for lunar operations, which would not be suitable for Earth, would be 24 GHz. The LPS rectenna will be 3D printed from lunar materials, primarily basalt and aluminium. The following tables illustrate the relations between the size and output of a LPS in four different configurations. Transmitting power from the GE⊕-LPS in EM-L1 to a rectenna on the lunar surface has a DC-DC efficiency of approximately of 57%. *(DoE, 1978 58%, Frazer-Nash, 2022 56%)*

Solar Collector Diameter: 300 m
Radius a: 150 m, Radius b: 176 m
Optimized PV Surface Area: 29,339 m^2
MGL = 50W/m^2 = ca. 2.0 MW at SPS and 1.1 MW at the rectenna
MGL = 91W/m^2 = ca. 3.6 MW at SPS and 2.0 MW at the rectenna
MGL = 180W/m^2 = ca. 7.1 MW at SPS and 4.0 MW at the rectenna
MGL = 286W/m^2 = ca. 11.4 MW at SPS and 6.5 MW at the rectenna

Solar Collector Diameter: 1000 m (Reference Design)
Radius a: 500 m, Radius b: 587 m
Optimized PV Surface Area: 325,992 m^2
50W/m^2 = ca. 22 MW at SPS and 12.5 MW at the rectenna
91W/m^2 = ca. 40 MW at SPS and 23 MW at the rectenna
180W/m^2 = ca. 80 MW at SPS and 45 MW at the rectenna
286W/m^2 = ca. 127 MW at SPS and 72 MW at the rectenna

Solar Collector Diameter: 1200 m
Radius a: 600 m, , Radius b: 704 m
Optimized PV Surface Area: 469,429 m^2
50W/m^2 = ca. 32 MW at SPS and 18 MW at the rectenna
91W/m^2 = ca. 58 MW at SPS and 33 MW at the rectenna
180W/m^2 = ca. 115MW at SPS and 65 MW at the rectenna
286W/m^2 = ca. 182 MW at SPS and 104 MW at the rectenna

9.3. Power Transmission

Power transmission via radio waves can be made more directional, allowing longer-distance power beaming, with shorter wavelengths of electromagnetic radiation, typically in the microwave range. A rectenna may be used to convert the microwave energy back into electricity. Rectenna conversion efficiencies exceeding 95% have been realized.

Power beaming using microwaves has also been considered for the transmission of energy from orbiting solar power satellites to Earth and the beaming of power to spacecraft leaving orbit has been considered. Power beaming by microwaves has the difficulty that, for most space applications, the required aperture sizes are very large due to diffraction limiting antenna directionality. For example, the 1978 NASA study of solar power satellites required a 1-kilometre-diameter transmitting antenna and a 10-kilometre-diameter receiving rectenna for a microwave beam at 2.45 GHz.

These sizes can be somewhat decreased by using higher frequencies, although frequencies beyond 10 GHz may have difficulties with atmospheric absorption and beam blockage by rain or water droplets. Because of the "thinned-array curse", it is not possible to make a narrower beam by combining the beams of several smaller satellites spaced further apart. For earthbound applications, a large-area 10 km diameter receiving array allows large total power levels to be used while operating at the low power density suggested for human electromagnetic exposure safety and reduced absorption by the ionosphere.

A power density of 230 W/m^2 at the center of the rectenna falling to 2 W/m^2 at the edge giving an average of 30 W/m^2 is considered optimal for power transmission with a frequency of 2.45 GHz to Earth from a SPS, while being safe for humans. An incoming power density of 30 W/m^2 distributed across an elliptical rectenna with 12 x 6.3 km diameter area (59,376,101 m^2) corresponds to a total power level of almost 1.78 GW. Such a rectenna size would make sense considering a location in the center of Germany as an example. Power from space can be delivered continuously as baseload power 24/7, independently from the weather. After conversion, this would deliver 12,614,400 MWh to the power grid per year.

For comparison, as of 2022, the largest solar farm in the world is the Bhadla Solar Park in India with a total capacity of 2.25 GW across an area of 56,655,990 m^2 *(YSG Solar, 2021).* Using an online calculator like the PVWatts Calculator *(NREL, PVWatts, 2023)*, its output is about 3,785,663 MWh per year. However, its location in the Indian desert is very fortunate for a solar farm (latitude 27° 32′ 22.81″ N). Locating the same size of solar farm to the center of Germany (latitude of Frankfurt 50° 6′ 38″ N), would deliver only 2,122,222 MWh per year. This is less than 17% of the rectenna output in the example above.

Following World War II, which saw the development of high-power microwave emitters known as cavity magnetrons, the idea of using microwaves to transfer power was researched. By 1964, a miniature helicopter propelled by microwave power had been demonstrated.

Wireless high power transmission using microwaves is well proven. Experiments in the tens of kilowatts have been performed at the Goldstone Deep Space Communications Complex in

California in 1975 and more recently in 2022 by the US Naval Research Laboratory at the U.S. Army Research Field in Blossom Point, Md. which transmitted 1.6 kilowatts of power over a distance of 1 km *(NRL, 2022).*

Generally, based on the 40 year-old assessment of the SPS efficiency chain *(DoE, 1978)*, a DC-DC transmission efficiency of about 57% can be assumed. Higher efficiencies are dependent on power semiconductors like GaN, which is a growing market in the terrestrial electricity industry.

A change to 24 GHz has been suggested as microwave emitters similar to LEDs have been made with very high quantum efficiencies using negative resistance, i.e., Gunn or IMPATT diodes, and this would be viable for short range links.

9.4. Rectenna

Once lunar regolith mining and processing commence, there appears to be no outstanding technical obstacles to producing the necessary components for constructing the rectenna from lunar materials - primarily basalt and aluminium - via robotic 3D printing manufacturing processes.

We have determined that 300 kW is needed for running a single processing and manufacturing operation. Multiplied by 4, such facilities and operations will require ca.1,200 kW. 100 kW is necessary for Closed Loop Life Support System (CLLSS) for the habitat and 40 kW is estimated for surface transportation. This is a total of 1,350 kWe and with some margin the target is to provide a minimum of 1.5 MW of electrical power continuously. Accounting for the lunar night, the need for power to charge a storage system will likely increase this requirement.

The transmitted power required at the ground is generated from the conversion of solar radiation into electrical energy by the satellite's solar arrays. Thus, the beaming distance, the magnitude of power required and efficiency of the WPT system have great influence over the sizing of the SPS solar arrays, the WPT antennae, and the corresponding rectenna on the lunar surface. An important aspect in the effectiveness of solar powered satellites is their distance from the ground receiver, determined directly by their orbit. Basically, once the beaming distance and the transmission frequency have been determined, the larger the aperture of the transmitting antenna the smaller the size of the rectenna and vice versa.

A GE⨁-LPS placed in a halo orbit at the Earth-Moon Lagrange point 1 (EM-L1) situated ~61,350 km from the Moon's centre on a line connecting to Earth could achieve line-of-sight power delivery to 76.4 ± 6.7° latitudes with zero interruption except for lunar eclipse. As this is also the assembly location, it is the preferred location for power transmission to the Moon. The rectenna can be located near the lunar equator if this is where the main mining and manufacturing operations are taking place.

GE⊕-LPS Rectenna Calculations 5.8 GHz from EML-1 (~61,350 km)
(AM0 3.7, 6.7%, AM0 13% and 21% at 50W/m2, 91W/m2, 180W/m2, and 286W/m2)

GE⊕-LPS	**Rectenna MWe**	**Rectenna Size**		
Dia. Ø m	3.7%, 6.7%, 13%, 21%	m	m2	Dia. Ø km
1,200	18-33-65-104	3,403 * 3,403	11,579,055	3.84
1,000	**13-23-45-72**	**4,083 * 4,083**	**16,673,840**	**4.60**
900	10-19-37-58	4,537 * 4,537	20,584,987	5.12
600	5-8-16-26	6,806 * 6,806	46,316,222	7.68
300	1-2-4-7	13,612 * 13,612	185,284,886	15.36

Figure 25: Rectenna Size Calculations

Initial calculations show that by transmitting microwave power with a frequency of 5.8 GHz from EM-L1 (~61,350 km from the lunar surface) to the rectenna, the above sizing trade-offs are available with each delivering different levels of power using MGL solar cells.

Using a MGL photovoltaic with an AM0 21%, a 1,000-meter diameter and transmitting at a frequency of 5.8 GHz, a GE⊕-LPS would generate 127 MW and deliver ca. 72 MWe and require a rectenna with the size 4.6 km^2. The trade-off is between the desired power output versus the rectenna size.

As a comparison, Ian Cash's proposed lunar CASSIOPeiA SPS located in an EM-L1 halo orbit, would have a 724 m diameter generating 182 MW and delivering 91 MWe at a circular rectenna with 2,437 m diameter (4.66 km^2) using a frequency of 24 GHz. This SPS would be launched from Earth and have a mass of 660 tonnes *(Cash, 2019).*

10. The GE⊕-LPS Production System Architecture

This section gives an overview of the GE⊕-LPS Production System Architecture and how it fits into the need and development of Space-Based Solar Power (SBSP) to address the impending climate and energy crises on Earth. The factors and technologies needed to implement the GE⊕-LPS are scalable into a larger system concept which leads to a business case or, better said, a 'rationale' for implementing the GE⊕-LPS concept on the Moon.

10.1. Mission Objectives

Primary Objectives

- Establish a scalable lunar manufacturing and logistics infrastructure to build Solar Power Satellites to be transferred to Earth orbit to deliver clean energy to Earth.

Secondary Objectives

- Produce SPS without severe impact on Earth's atmosphere by thousands of rocket launches.
- Establish a cislunar economy based on a realistic business case.
- Demonstrate to the public that positive action is underway to solve the climate crisis.
- Enable humanity's sustainable expansion into space following the Greater Earth idea.

10.2. Methodology

The current study considered the production of SPS with a high proportion of lunar resources to minimize launches through the Earth atmosphere and maximize the production of SBSP. To achieve this, the following process steps were undertaken at systems level:

- Study and evaluation of past and current concepts for Lunar exploration and economy.
- Identification of developing technologies and concepts, which could cause an accelerating effect.
- Study of robotic mining, beneficiation, and production possibilities on the Moon.
- Study of production of basalt fibre and MGL solar cells in particular.
- Baseline design for LPS and assessment.
- Identification and discussion of technological challenges.
- Initial market assessment.

10.3. Assumptions

ASSUMPTIONS

Logistics
1. A reusable heavy lift launcher with the economic launch capabilities of the type of SpaceX Starship will be available
2. Minimum soft-landing payload capability more than 10 tons on the lunar surface will be available
3. Propellant production on the Moon has been verified and can be scaled up
4. Research on a Lunar Space Elevator is well advanced
Communication & Navigation
5. A lunar communication network has been built up in previous missions and is in operation
6. A lunar and EM-L1 navigation system has been set up by previous missions and is in operation
7. Navigation and communication is covering the far side
ISRU
8. Through missions like Artemis, lunar automatic mining, beneficiation and production concepts have been verified and are developed well beyond TRL 3-4
9. Space Robotics and tele-robotic control techniques are well advanced and proven
Technology Development
10. An orbital SPS demonstrator has been successfully deployed
11. Current technology development (robotics, automation, electronics, material science etc) will continue to grow as fast as they have in the last decades and be backed up by large, growing terrestrial markets
Habitation
12. A crew size of 3 at EM-L1 and 3 on the lunar surface is sufficient for maintenance and control of the robotic fleet and automated production
13. Habitations from previous missions can serve as an emergency back-up
14. Biogenerative Life Support Systems are well proven
15. Shielding concepts in EM-L1 are well proven through previous missions
Legal
16. The use of lunar resources and territory for governmental and private developmental purposes has regulatory clarity and stays attractive for private investors
17. Ownership rights and priority rights for lunar mining claims are cleared

18.	Access of EM-L1, lunar orbits and especially the area of Sinus Medii and vicinity (for LSE base) is globally regulated and secured
19.	The Outer Space Treaty has been updated to encompass the realities of lunar development for terrestrial purpose
20.	An independent regulatory and developmental organization that is internationally implemented and recognized

Table 2: Assumptions

10.4. System Requirements

System Requirements	
FUNCTIONAL REQUIREMENTS	
Performance	
1.	The programme shall install a highly automated mining, beneficiation and fabrication infrastructure on the Moon.
2.	The system shall provide energy for automatic production during lunar day and storage energy for the Habitat during Lunar night.
3.	The system shall support a crew of 3 at EM-L1 and a crew of 3 at Lunar surface
4.	The system shall be capable to output one LPS per year.
Scalability	
5.	The system shall be scalable to increase and accelerate production
6.	The system shall be modular in design
Logistics	
7.	The system shall establish flexible and economic means of transportation between Sinus Medii (lunar crater Alpetragius) and EM-L1 *(A Space Elevator on the Moon, 2020).*
8.	The system shall be based on the availability of a reusable heavy-lift launcher with economic launch capabilities of the type of SpaceX Starship
OPERATIONAL REQUIREMENTS	
Duration	
9.	The system shall establish a long-term, sustainable production and logistics infrastructure on the Moon
10.	The habitats shall operate on maximum 180 days of resupply missions
Availability	
11.	The system shall be fully available during Lunar days

12. The system shall be expandable to operate during the full diurnal cycle
Survivability
13. The system shall not be disrupted by environmental impacts like micrometeorites, lunar quakes, dust etc, nor by technical failure
Communication
14. Data flow between machines on the Lunar surface and between machines and systems at EM-L1 shall be real-time
CONSTRAINTS
Cost
15. The programme shall cost considerably less than the Artemis programme
16. The programme shall produce additional revenues by offering services like transportation, propellant, tourism etc.
Schedule
17. The programme shall start at the beginning of next decade
18. The programme shall be prepared to be accelerated, depending on the climate and energy crisis on Earth
Environment
19. The programme shall be robust in vacuum, extreme temperature and radiation
20. The programme shall be robust against lunar dust
Regulations
21. The programme shall lobby for international laws and space policy decisions
Political
22. The programme shall cultivate and maintain public support
23. The programme shall communicate positivism and hope in a time of perpetual crises on Earth
Interfaces
24. Earth-Moon telerobotic capabilities have been demonstrated
25. LEO-to-LSE transfer operations have been established
Development Constraints
26. International competition instead of cooperation
27. Public sector – Private sector conflicts
28. Lack of awareness of the benefits and the feasibility of SBSP

Table 3: System Requirements

10.5. Design Drivers

System Drivers
Size
1. Reusable heavy lift launch vehicle Payload Size: ø8m x 8m/16m
2. LSE Climber payload size: ø1.5m x 8m (assumption)
Weight
3. Heavy Launch vehicle EM-L1 50 t, lunar surface: 12 t
4. LSE Climber: 100 kg per climber, scalable through counterweight and multiple climbers
Power
5. 12 kW inflatable mobile solar panels. Scalable.
6. 35 MWh energy storage for habitat during lunar night. Scalable
Level of Autonomy
7. Minimum LoA 4 (scale 0-5)
8. Maintenance and repair done by humans
Number of Launches
9. Target is a minimum piercing of the Earth's atmosphere
10. < 100 heavy lift launches from Earth (TBC)
Production Throughput
11. Target: 0.5 - 1 LPS per year
12. Propellant (TBD)
Lunar Surface - EM-L1 Transportation Throughput
13. < 600 tons per year by LSE, scalable
14. Lunar Landing Gantry (LLG) with rocket engines for heavy loads

Table 4: System Design Drivers

10.6. System Specifications

EM-L1 System Specifications
EM-L1
GEO-LPS
1. Size: GE⊕-LPS: Diameter 1000x1174 meters (See TN WP-2 2.2 Section 2)
2. Mass: GE⊕-LPS ~1,342 MT (See TN WP-2 2.2 Section 7.4)
3. Power: GE⊕-LPS > 91W/m^2 = ca. 40 MW at SPS and 23 MW at the lunar rectenna
4. Structure: Basalt fibre tubes, basalt cast connections
5. Antenna: Hybrid PV antenna with solid state DC-RF conversion, beam steering
6. Habitat: crew of 3-6 for 180 days, inflatable, shielding sintered regolith, Life Support: Biogenerative
7. Docking: 2 docks at habitat. Expandable at the outer nodes of the axes
GE⊕-LSE
8. Size: tether length > 300,000 km
9. Weight: 48 tons, scalable through counterweight and parallel climbers
10. Power: Climbers powered by solar panels, partially by laser beams during Lunar night
11. Habitat: crew of 3 for surveillance and maintenance/emergency
12. Docking: multiple docks as needed, scalable
13. Climber Payload: 100 kg both directions
14. Climber Dimensions, ø1.5m x 8m

Table 5: System Specifications

Lunar Surface System Specifications
Lunar Surface
Mining
1. Robots: 20 RASSOR type robots, scalable as needed
2. Weight: 100 kg
3. Dimensions: 1.5 x1.5 x 1.5 m
4. Power: 1 kW
5. Throughput: 200 kg per hour

Beneficiation
6. Main Processes: Roasting, condensation, cryo-liquification, reduction and electrolysis
7. Weight: (TBC)
8. Dimensions: 60m x 4m x 28 m, industrial building rack system
9. Throughput: 4000 kg per hour
10. Power: 300 kW initially scalable to 300 kW (including direct heat energy)
Fabrication
11. Factory Modules: 7 modules for PV/antenna, electric wires, cast basalt, basalt fibre pultrusion, sintered regolith, insulation/textile, AM spare parts
12. Weight: 10 tons per module (TBC)
13. Dimensions: 4.5 x 4.5 x 15 m per unit
14. Power: Electric: 300 kW, Heat 600 kW (TBC)
15. Throughput: 46 kg per day (TBC), scalable
Habitation
16. GE⊕-LPS habitat modules: one
17. Weight: 7 tons
18. Dimensions : ø 8m x 8m TBC
19. Power: 100kW plus storage
20. Supply cycle: 180 days
21. Life Support: Biogenerative
Surface Transportation Infrastructure
22. Transportation robots: 10, weight 100 kg each
23. Roads: 10 km (TBC)
24. Throughput: 400 kg / hour
Rocket Transportation Infrastructure
25. 4 Launch/landing pads
26. Propellant production
27. Blast wall
LSE Transportation Infrastructure
28. Base Station with cargo handling robots

29. Protected access area
30. Climber: Payload Weight and dimensions see above
31. Throughput: 600 tons per year, scalable

Table 6: Lunar Surface System Specifications

11. The GE⊕-LPS System Infrastructure

The GE⊕-LPS concept as presented in this study has been relying on rather conservative technical assumptions with a near-future realisation in mind. However, neither for the proposed Lunar Space Elevator (LSE) nor for in-situ space utilization ISRU on the Moon, are there any precedents. This is also the case for the mass-driver, which has been the proposed solution for any serious use of lunar resources during the last decades. The GE⊕-LPS concept is dependent on a robust cargo transportation system from the lunar surface to Earth-Moon Lagrange point (EM-L1) as well as on an industrial scale production of photovoltaics, semiconductors, and structural elements on the lunar surface.

The trade-off in favour of the LSE was chosen as the more efficient technology than a "mass-driver". Most mass-driver studies do not sufficiently consider the "mass-catcher" and delta-V necessary at the target point. Furthermore, a major problem is the near complete inflexibility in size and weight of the cargo capsule of a mass-driver. The LSE offers much more flexibility in this aspect and is likely to be a key economic driver for a long-term, future industrialized cislunar economy. Although both systems would rely on a rocket-based system in their initial and later phases, only an LSE has the potential to eventually replace most of the rocket flights necessary.

Another paradigm to question is if an A-to-B rocket-based transportation system makes sense for lunar production scenarios, or rather a modular transportation system, where each element is optimized to its task. The most demanding task in cislunar space transportation is launching a rocket from the gravity well of Earth and then through its atmosphere. The design of the shape and volume of most rockets produced today are determined by this task. With the GE⊕-CTS we propose a modular cislunar transportation System (CTS), which allows each vehicle to be optimally utilized. This necessitates the need for cargo relay stations and the exchange of payloads. However, this is a logistical process which has been in use for centuries on Earth and, with the possibility of robotic handling, should become a long-term advantage in a growing cislunar economy.

However, such an economy will only evolve when meaningful resources can be produced on the Moon. Each of these will mitigate the exploitation of our home planet Earth, where society still relies on carbon fossil fuels for more than 80% of its energy use and on limited resources of materials like lithium, cobalt etc. Every product produced with solar energy and local resources on the Moon will help human societies on Earth in their energy transition to a "net-zero future". The energy solution which may offer the most potential in the context of Europe's energy crisis and the global carbon dioxide crisis is the production of Solar Power Satellites (SPS) from lunar resources as proposed in this study. Once initial production capabilities are in operation on the Moon, many additional products may be developed as a result which will serve humankind on Earth and in space. One such product could be data centers which could even be integrated into future SPSs to serve the ever-growing energy intensive Artificial Intelligence industry.

Whereas in the field of in situ resource utilisation (ISRU) many laboratory studies and even prototypes already exist, still no testing and laboratory facility on the Moon exists yet. A remote-controlled, automated lunar material processing laboratory would be an essential early-phase facility for universities and industries to test and develop industrial uses of lunar resources.

Access to the Moon will rely heavily on a sufficient supply of rocket propellant, and the production of propellant using lunar resources will be perhaps the earliest and most immediate business case. At the present time there is a strong focus on producing propellant using water ice from the lunar poles *(Kornuta et al, 2019).* However, up to 80% of the mass of rocket fuel is oxygen, which is relatively easily recovered from regolith all over the Moon. Therefore, propellant could also be produced at the lunar equator using the available lunar-sourced oxygen and metals for solid fuels, obtaining hydrogen from regolith, or importing hydrogen from the lunar poles or from Earth.

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. 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.

Being able to produce the structural elements of a SPS on the Moon, and then assemble them at EM-L1, is already a great benefit. However, the supporting structure of a SPS only accounts for 10%–30% of its mass, depending on the size and technology chosen. Approximately 70% of its mass are the solar arrays with integrated solid-state DC-RF conversion and antenna. Electricity produced from photovoltaics (PV) is also needed for many production processes on the Moon. Thus, the industrial production of PV on the Moon will be a key enabling technology for lunar industrialization. The rapidly growing market for photovoltaics on Earth has been pushing the improvement of efficiencies and production technologies. Gallium arsenide (GaAs) solar cells have obtained the highest efficiencies, whereas silicon solar cells feed the mass market, but these rely on very elaborate and complex, energy intensive production processes. This is why a standard silicon solar panel only becomes carbon-neutral after around 3 years of operation. Thin-film solar-cell technology is also developing rapidly and offers many new alternatives in production. Blue Origin *(Blue Origin, 2023)* recently announced the development of 'Blue Alchemist' lunar solar cell technology which produces iron, silicon, and aluminium through molten regolith and purifies silicon to more than 99.999% to make solar cells.

Despite the abundance of silicon on the Moon, manufacturing silicon wafer based solar cells will require a very complex industrial process. Thus, the use of lunar derived pyrite to produce Monograin Layer (MGL) photovoltaics seems to be a more promising lunar-sourced alternative. This technology already exists in Europe for terrestrial PV production, and the crystalline material which it currently uses could even be sent to the Moon during the initial phase until pyrite harvesting and MGL production commences. As potential materials to produce semi-conductors on the Moon, silicon, ilmenite and recently pyrite are also under investigation. Aluminium for electrical conductors can also be produced on the Moon.

An important element for PV production is the substrate. Especially for MGL PV technology a transparent substrate would be beneficial since such cells could absorb solar energy from both sides. Kapton is a polyimide film used in flexible printed circuits (flexible electronics) and space blankets, which are used on spacecraft, satellites, and various space instruments. It is one of the few space-proven substrate materials so far. Whether a similar substrate can be produced on the Moon is at the moment an open question. For sure the richness of chemical compounds possible with polymers and hydrocarbons indicates that for a future lunar industry such production would be valuable. Another interesting research project, in which Europe already has relevant expertise, would be the production of polymers using lunar greenhouses to produce organic materials. This would also have major synergies with the development of food production, if a larger human presence on the Moon is desirable.

The current development in power semiconductors, driven by strong terrestrial markets like electric vehicles, is currently shifting SPS concepts from using magnetrons to using semiconductors for DC-RF conversion. The most promising advances have been achieved with Gallium Nitride (GaN). Efficiencies of 70% have already been reached for terrestrial use and progress up to 85% is expected to be seen in the future. Similar values may be expected to be achieved with semiconductors produced from lunar materials in the future. Using semiconductors for the generation of microwaves also allows to employ solid-state digital beam steering technologies, avoiding complex mechanical joints as in previous SPS concepts.

11.1. Limiting and Target Parameters

The first iteration of the GE⊕-LPS concept has been approached with the assumption that manufacturing SPSs on the Moon, may not require reducing the system mass to save a lot of weight as it is the case when SPSs are produced and launched from Earth. However, during the study it became apparent that the transportation capacity from the lunar surface to the assembly location at EM-L1 becomes the limiting factor, when scalability and production through-put are considered. This limitation is defined either by the propellant use of a rocket system and/or the limits of the Lunar Space Elevator (LSE). The mass budget of the preliminary design is shown in Table 7.

GE⊕-LPS Mass Budget	Mass in Metric Tons
Axes (without cladding)	157
Rim Beam	156
Solar-Antenna Elements	692
TOTAL mass without Habitat	**1.005**
Habitat	95
Habitat Shielding	242
TOTAL mass with Habitat	**1.342**

Table 7: Mass budget for a 1000 m diameter LPS with an output of 40 MW at SPS and 23 MW at the rectenna.

This estimation was based on a conservative mechanical joint node construction system, an area weight of the PV-Antenna elements of 0.75 kg/m^2 and a PV efficiency of 6.7%, resulting in a specific power of 23 W/kg. This is not high compared with other systems as shown in Figure 26. Researchers at CalTech have been pushing the desirable target up to 1800 W/kg of specific power for GaAs PV technology and solid-state RF technology *(Madonna, 2018)*.

Looking at the developments in these technologies in the last decade, this is not too unrealistic. However, the already quite advanced test tile of Caltech achieved only 9.2 W/kg of actual transmission *(Gdoutos et al., 2018)*, so there is still a long way to go.

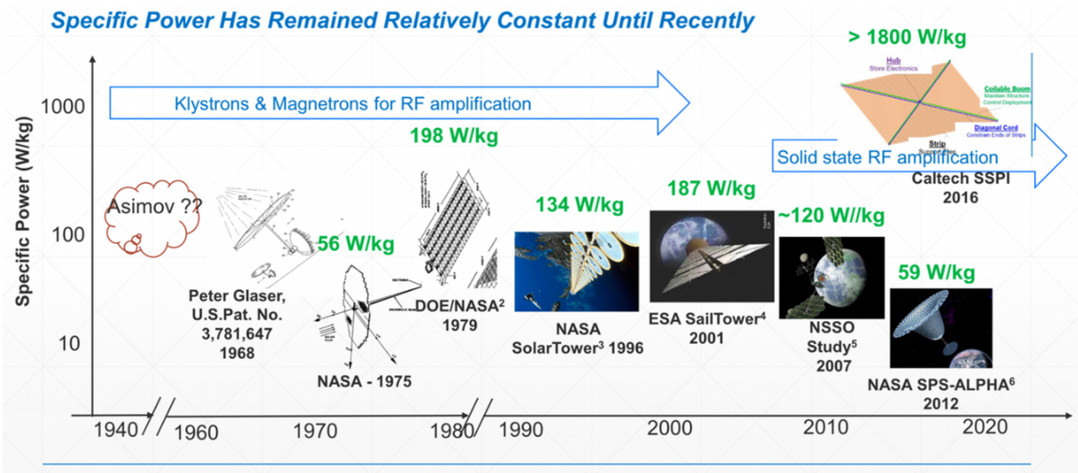


Figure 26: Specific Power of historic SPS concepts. (Madonna, 2018)

GE⊕-LPS Test Specifications	Mass in Metric Tons
DIMENSIONS	ø1000 x 1174 m
WEIGHT Axes (without cladding) 30 MT Rim Beam 30 MT Solar-Antenna Elements 350 MT	410 MT
WEIGHT incl. Habitat	747 MT
Target thin-film PV efficiency	21%
POWER at LPS	160 MW
POWER at Rectenna	91 MW
Specific Power (Without Habitat)	222 W/kg

Table 8: Test specification for a future GEO-LPS.

We believe that, making more ambitious assumptions, with more intensive research and development in this decade, the weight of the SPS structure made with basalt fibre composite elements can be reduced by a factor of 5, the weight of the PV arrays reduced by half, and the efficiency of the pyrite-based MGL PV increased by up to 21%. We will use these assumptions to estimate the needed capacities for mining, beneficiation, and transportation.

As a comparison, the Frazer-Nash cost-benefit study for Space Solar Power, based on Ian Cash's CASSIOPeiA design count with 698 W/kg *(Frazer-Nash Consultancy, 2022a)*. It can be rightly assumed, that each technological progress done to increase the efficiency of Earth produced SPS will also benefit a lunar production and values close to Earth-produced systems can be achieved.

11.2. Greater Earth Cislunar Transportation System - GE⊕-CTS

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).

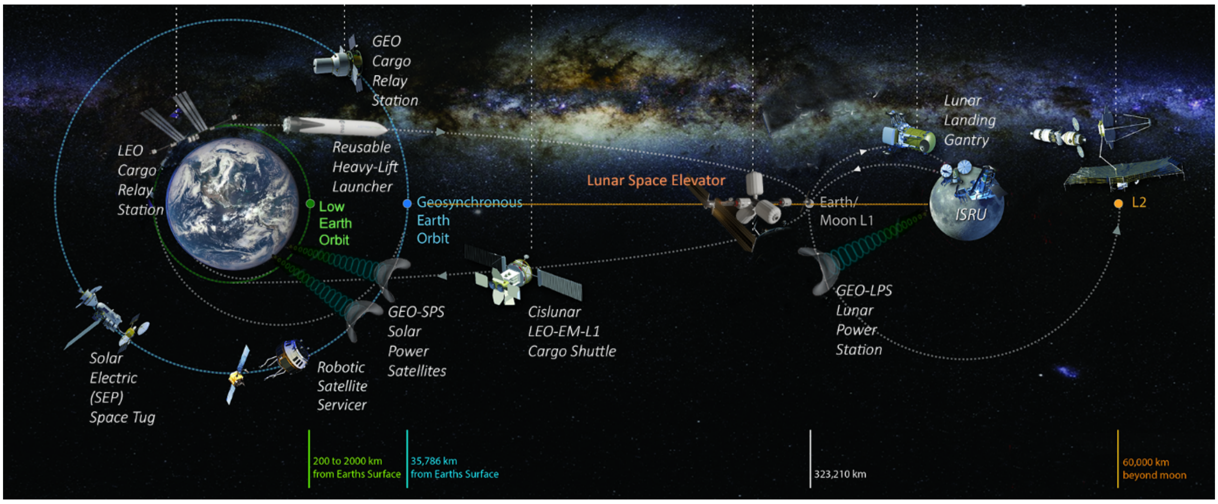


Figure 27: Greater Earth Cislunar Transportation System (Credit: P. Spudis modified by Astrostrom)

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 as seen in Figure 27.

Once the major spaceports are set up, the logistics chain can become an independent business or even a competitive business between different players. The segmentation of the transportation chain means that each vehicle can be optimised for the segment it is flying.

11.2.1. Earth-to-Low Earth Orbit

The first segment of the GE⊕-CTS will be deployed in LEO and, in the initial phases, will rely on existing launch technology. As this is a predominantly European system, in the earliest phases GE⊕-CTS will utilize the Ariane 6 launch system, which has been under development since 2014, as much as possible. Encouraging news from ArianeGroup indicates that the Ariane 6 could be upgraded with reusable boosters based on the Themis reusable launcher concept *(ArianeGroup, September 2022).*

Additionally, ArianeGroup is proposing the fully reusable SUSIE (Smart Upper Stage for Innovative Exploration) upper stage for crew and cargo that can return payloads or crew to

Earth *(ArianeGroup, July 2022).* ArianeGroup also states that SUSIE is designed with future rockets in mind. Thus, when fully reusable launcher designs are introduced, the spacecraft should be able to utilize these as well.

Figure 28: Ariane 6 and SUSIE (Credit: ArianeGroup)

However, it may also be practical and economically advantageous to utilize other launch systems such as SpaceX or those from other launch providers in this phase.

Ariane 6 comes in two configurations with the following characteristics:

- A62: up to 10.3 t into LEO, 1.7 t into MEO, 4.5-5 t into GEO, 2.8–3 t into LTO
  A62 cost per launch: €75 million.
- A64: up to 20 t into LEO, up to 12 t into GEO, 8.2–8.5 t into LTO
  A64 cost per launch: €115 million.

In comparison with SpaceX Falcon 9:

- Reusable Falcon 9: 16.7 t in LEO, 5.5 t into GTO
  Cost per launch: $50 million
- Expendable Falcon 9: 22.8 t in LEO, 8.3 t into GTO
  Cost per launch: $67 million

The modular approach of the GE⊕-CTS concept may mitigate the need for a heavy lift launch system as launching 10 tonnes to the Moon would entail launching 10 tonnes to LEO and then transferring it to the cislunar transport system. This would also stimulate the competition in the launch market and further ease space access.

11.2.2. European Reusable Medium-Size Launcher (ERML)

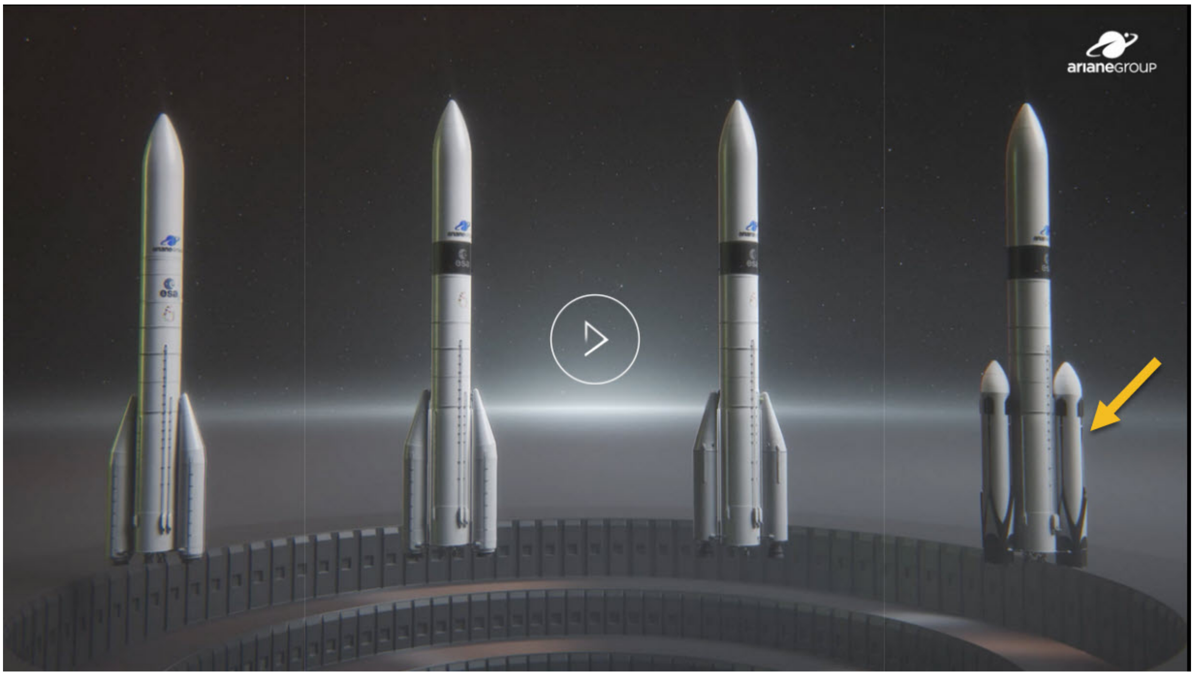


Figure 29: Ariane 6 with Reusable Boosters (Credit: ArianeGroup)

Once the core infrastructure of the Greater Earth Cislunar Transportation System (GE⊕-CTS) is established, crew and cargo flow can be handled with economical small reusable rockets. As mentioned above ArianeGroup has plans to upgrade the Ariane 6 with reusable boosters.

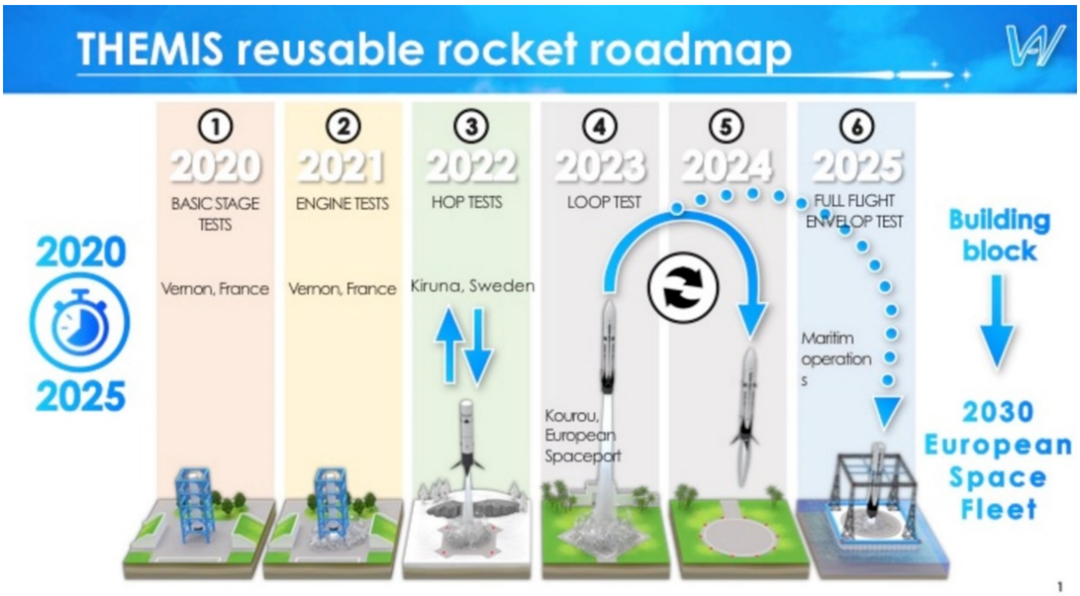


Figure 30: ESA Themis Reusable launcher roadmap. (Credit: ESA)

Also, a fully reusable medium lift launcher called Themis is under development (Figure 30). These launchers would have the capacity to deliver 15-20 metric tonnes (MT) payloads to LEO and have short turn-around times. As seen with SpaceX's Falcon 9 launch system, launch costs can be reduced significantly in this way.

Figure 31: European Reusable Medium-Lift Launcher (ERML) (Credit: Astrostrom)

11.2.3. European Reusable Heavy Lift System (ERHLS)

The need for a European reusable heavy-lift launcher 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⊕-LPS System. Unfortunately, it is not foreseen that European launch vehicles currently under development will be able to transport large payloads with the necessary cadence to implement an effective SBSP program.

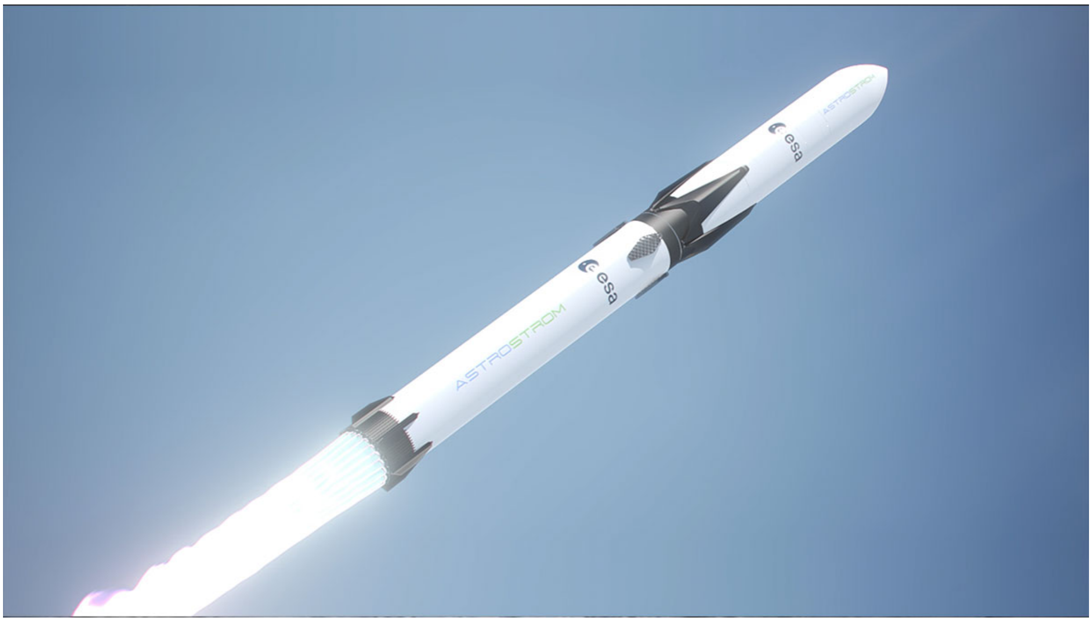


Figure 32: European Reusable Heavy Lift Launcher (Credit: Astrostrom)

To address this issue, in July 2022, the European Space Agency released an Invitation to Tender (ITT) for studies of low-cost, European heavy lift launcher (PROTEIN) that could put more than 10,000 tons of space hardware into LEO per year *(ESA ITT 1-11440).* Such a new capability would be transformational for the European launch industry and would surely open important new applications in space and on Earth. At 100 tons to orbit per launch, this cadence would be 100 launches per year. This is significant but insufficient for deploying the numerous GW-scale SPS systems - if they are built on Earth and not the Moon - necessary to achieve the desired contribution of SPS to helping meet the European climate and energy goals.

After losing access to Russian launch systems due to the sanctions imposed by European states in the context of the 2022 Russian/Ukraine military operations, the need for independent launch capability in Europe has substantially increased.

11.2.4. European Human Lunar Launch System

The GE⨁-CTS modular system is mainly focussing on transporting cargo. In the beginning phases, human transportation will rely on a direct rocket approach to minimize the crew's exposure to the radiation hazards of space flight.

Figure 33: Crewed Version of the European Reusable Heavy Lift System (Credit: Astrostrom)

In April 2021, NASA awarded a contract worth $2.89 billion to SpaceX which includes both an uncrewed and a crewed lunar landing demonstration that is part of the Artemis III mission *(NASA, Artemis, 2021)*. The agency plans to exercise an option under this contract, known as Option B, asking the company to evolve its current Artemis III Starship Human Landing System design to meet an extended set of requirements for sustaining missions at the Moon, and conduct another crewed demonstration landing.

The SpaceX HLS could also become an option for GE⨁-CTS to establish its initial lunar operations base. However, it would be prudent for Europe to develop its own human rated lunar system by simultaneously developing such crew capabilities in the context of developing a European Reusable Heavy Lift System (ERHLS).

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. The first such facility would most likely be for the in-situ production of propellants from lunar resources.

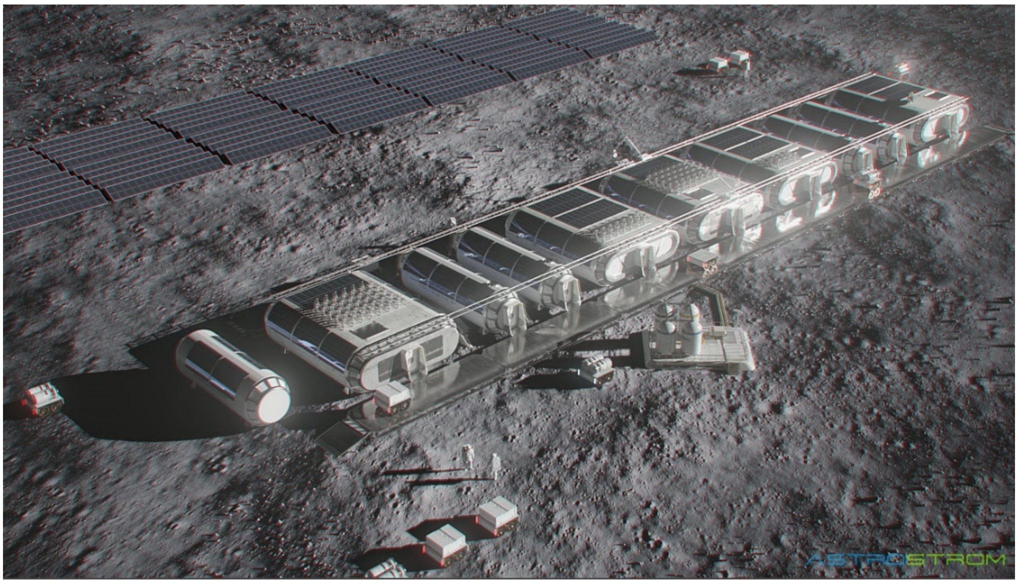


Figure 34: Lunar Materials Processing Operations (Credit: Astrostrom)

11.2.5. LEO Cargo Relay Station (LEO-CRS)

Figure 35: LEO Cargo Relay Station (LEO-CRS) (Credit: Astrostrom)

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. Once the structure reaches a sufficient dimension, solar arrays based on the proposed Monograin Layer (MGL) photovoltaics technology can be deployed, tested and optimized. If successful, these can be used to perform a space-to-Earth WPT demonstration to various locations on the equatorial path of the platform. Tether materials that may utilized in the development and deployment of the Lunar Space Elevator (LSE) may be tested and optimized. These could be deployed to create a centrifuge device that would simulate 1/6 gravity. As an easily accessible platform for European space activities, it could provide low-cost orbital exposure for university departments and businesses to develop a range of technologies and products.

Once the LEO-CRS has expanded into a multi-use platform and testbed for the above activities, Ariane 6 and eventually newer fully reusable launchers can deliver cargo, supplies and eventually people to the platform. Cargo deposited at the LEO-CRS can be picked up by chemical and/or ionic drive shuttles which will transport them directly to a storage hub located at the Earth-Moon Lagrange point 1 (EM-L1). From EM-L1 the cargo is picked up by Lunar Landing Gantries, which allow soft-landing on the lunar surface and lowering the cargo/habitat on transportation robots for final positioning. This cargo relay station will also become a depot and trading station for Moon-generated supplies like (oxygen, propellants etc) for other space missions. As such, the LEO-CRS becomes an essential element of the GE⊕-CTS.

11.2.6. GEO Cargo Relay Station (GEO-CRS)

As the GE⊕-LPS system evolves and the first SPS is being prepared to be delivered to an Earth orbit, a GEO Cargo Relay Station (GEO-CRS) becomes necessary. It will have similar functions as the LEO-CRS. Initially it is planned to assemble lunar-produced SPS components at EM-L1. However, as transportation and production capacity will increase over time, SPSs could be assembled in parallel near the GEO-CRS. Thus, the individual components can be transported by the Cislunar Cargo Shuttle (CCS) and/or the Lunar Space Elevator (LSE). The LSE would have an end station similar to the EM-L1 Hub in the vicinity of GEO and with enough distance, so that the cargo can “fall” into a GEO slot. The GEO-CRS can also be important once an accelerated GE⊕-LPS programme is considered. In this case, the structural basalt fibre parts would be delivered from the Moon and hi-efficiency PV and antenna elements delivered from Earth. Such a programme could start as 80 to 20 ratio of resources from Earth and the Moon and develop into a 20 to 80 ratio of resource origin.

11.2.7. LEO-to-EM-L1 Transportation

Chemical and/or ionic drive shuttles using solar electric propulsion (SEP) will provide the back-and-forth transportation of large and fast cargo/crew transports between the LEO Cargo Relay Station and the hub at the Earth-Moon Lagrange point. These have a standard interface to the cargo containers and allow automated pick-up and delivery to-and-from these platforms.

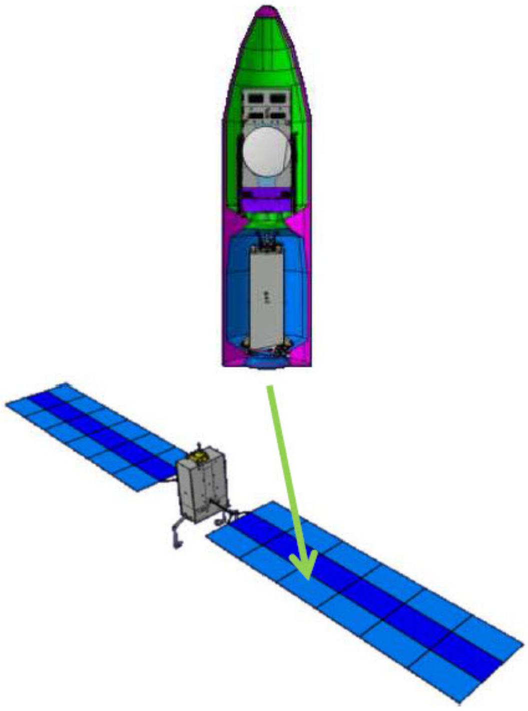


Figure 36: A proposed Solar-Electric Space Tug under Ariane 6 fairing and fully deployed (Masson et al., 2017)

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. The Cislunar Cargo Shuttle is foreseen to be powered with an ionic drive utilizing solar electric propulsion (SEP). However, depending on technological development and the cargo protection requirements when traversing the dense radiation environment of the Van Allen belts, this vehicle could also be a hybrid drive - a liquid propellant stage which could achieve high speed when navigating the Van Allen belts to reduce the exposure time to particle events, and a ionic drive which would be used for the remainder of the flight. Figure 36 shows an Ariane 6 space tug as an enabler for European exploration missions which was proposed in 2017 *(Masson et al, 2017).* Figure 37 shows a concept design for the GE⊕-CTS Cislunar Cargo Shuttle (CCS).

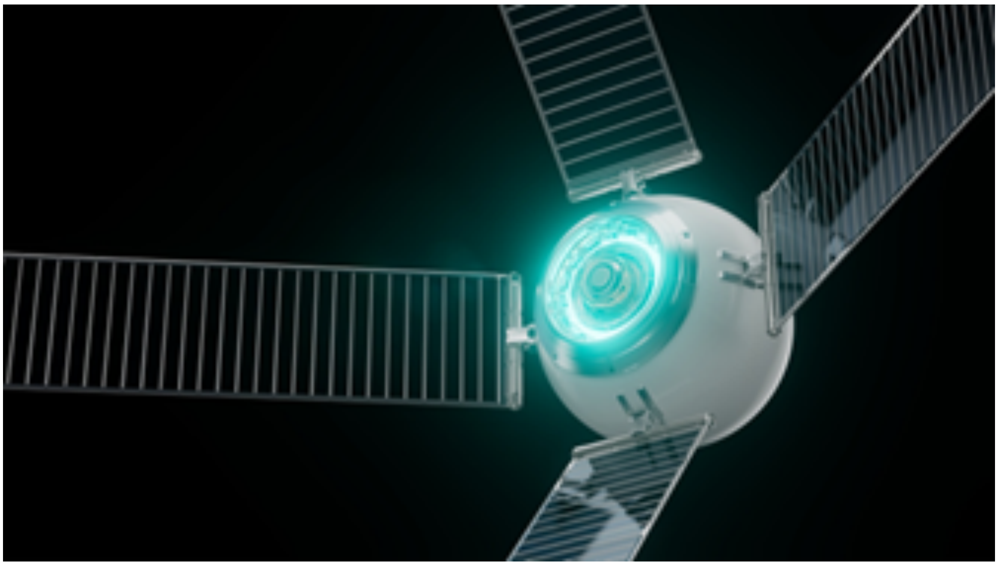


Figure 37: Cargo pickup and delivery robot with ion drive (Credit: Astrostrom)

11.2.8. Standardized Cargo Containers

The introduction of the standard ISO container and the ISO pallets on Earth for intermodal freight transport has made transportation much easier and more efficient, and this has accelerated the global economy. A similar system as shown in Figure 38 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.

Some preliminary requirements of these containers would be:

- Operable under microgravity ("0-g"), reduced gravity (1/6-g) and possibly 1g
- Able to hold different cargo from bulk goods to delicate piece goods
- Controlled loading/unloading in different gravity conditions
- Transportation interfaces in different gravity conditions
- Fits into reusable launcher, in LSE and on surface cargo robots
- Collapsible when empty
- Robust and dust-repellent
- Equipped with a tracking system
- Resistant to space-weathering
- Compatible with temperature-range experienced in space

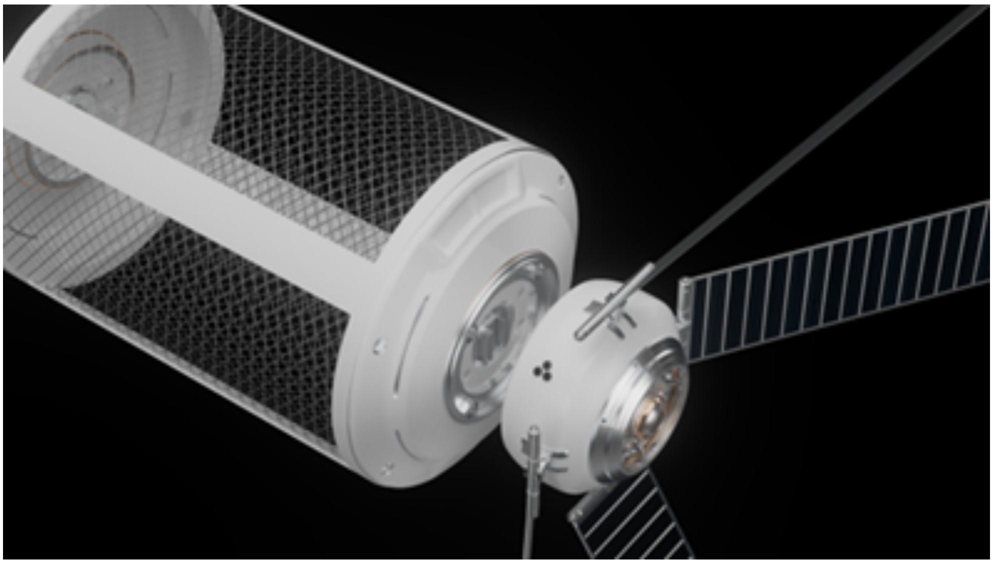


Figure 38: Collapsible Cargo Container (Credit: Astrostrom)

11.2.9. The Cislunar EM-L1 Hub

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. There will be cargo and supplies to be delivered to and from the Moon and the Earth. In addition to the construction site(s) around EM-L1, robotic shuttles will go back and forth to LEO and Lunar Landing Gantries (LLG) will go up and down to the lunar surface. At EM-L1 will also be the construction site for Solar Power Satellites. A habitat will be at the GE⊕-LSE on the lunar equator.

As the time lag from EM-L1 to the Moon and back is much less than that for Earth-Moon, it is a better location for safe teleoperation of robots on the lunar surface. As lunar activities increase, there will be an increasing need for freight handling of goods destined for the Moon, as well as those from the Moon. Early lunar exports are likely to be low-value-added goods such as oxygen, water, raw regolith, and some metals, but as more capabilities are established the exports will increase in value: rocket propellants, foodstuffs from lunar greenhouses, increasingly sophisticated entertainment like dance and other performances, and so forth.

A facility at EM-L1 can serve as a communications node for lunar operations. In terms of propellant, it is cheaper to go from EM-L1 to GEO and back to EM-L1 than it is merely to go from LEO to GEO. Over the long term, it makes sense to stage GEO operations from EM-L1 such as salvage of the hundreds of tonnes of scrap circulating in GEO. Crews could fall down to GEO, retrieve a defunct satellite or other space debris and return to EM-L1 to process it. These materials would be very valuable for a recycling operation in a lunar economy.

Eventually, EM-L1 could become the optimal location to aggregate mission components for a trip to the asteroid belt or to Mars. Propellants would come from the Moon, while spacecraft come from Earth. The acceleration of growth of such a spaceport during the next centuries can be imagined by analogy to the growth of sea harbours and airports in past centuries. Such growth will be facilitated by there being nearly unlimited energy available.

11.2.10. Lunar Landing Gantry (LLG)

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. The LLG picks-up the containers from above and has a lowering mechanism to either finally place the cargo by landing at the destination site or lower it onto surface transportation robots which pick the cargo up at the landing pad. The LLG consists of a platform with an attachment and lowering system for the payload. Solar panels on the top of the LLG deliver electrical power for the mechanical operations. Rocket engines are located at each corner which are directed at an angle away from the LLG. A reaction control system is also located at the corners. The propellant tanks are attached on the longitudinal side as seen in Figure 39 and Figure 40.

The LLG will be refuelled with propellant produced on the Moon.

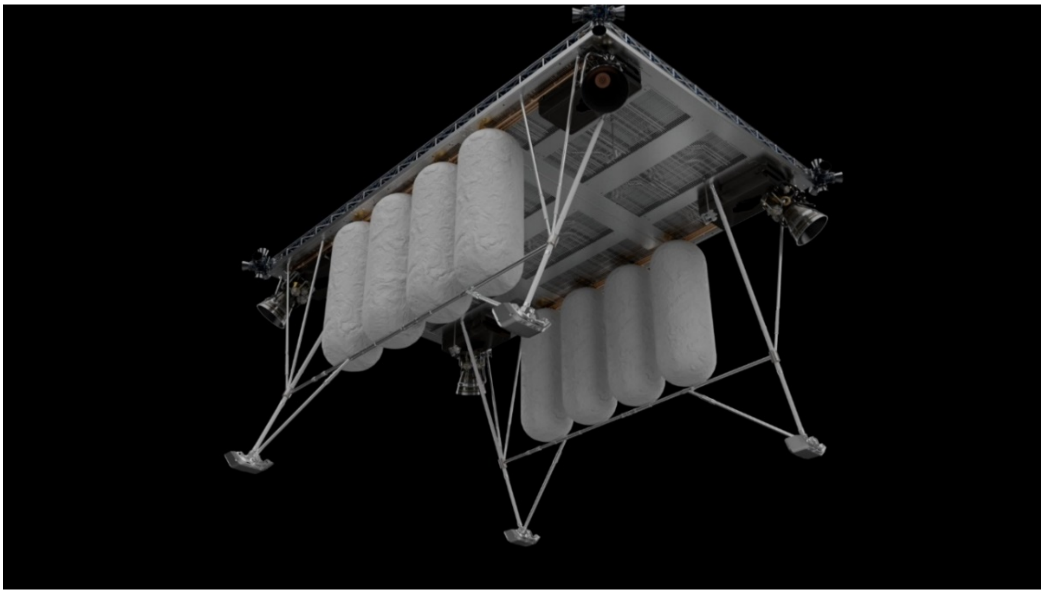


Figure 39: Astrostrom's concept of a future European Lunar Landing Gantry (Credit: Astrostrom)

Figure 40: Astrostrom's concept of Lunar Landing Gantry with a factory module attached underneath.

11.2.11. Greater Earth Lunar Space Elevator (GE⊕-LSE)

An efficient, reliable, and flexible transportation system from the lunar surface to EM-L1 and back is a key element for building SPSs with lunar resources and for any future lunar economy. As such, the most significant part of the Greater Earth Cislunar Transportation System (GE⊕-CTS) is 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 the Earth-Moon Lagrange points, EM-L1 or EM-L2. The means of transportation will consist of vehicles that will climb between these two locations powered by electrical energy using wheeled "crawlers".

The 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. For the GE⊕-LPS system, the GE⊕-LSE potentially offers an economical and reliable means to deliver lunar manufactured elements to a relatively stable orbital assembly point.

The Earth-Moon Lagrange points 1 & 2 are two points in space where the GE⊕-LSE docking port could maintain a stable, lunar synchronous position. The 0.055 eccentricity of the lunar stationary orbit means that these points are not fixed relative to the lunar surface: the EM-L1 is 56,315 km +/- 3,183 km away from the Earth-facing side of the Moon (at the lunar equator) and EM-L2 is 62,851 km +/- 3,539 km from the center of the Moon's far side, in the opposite direction. At these points, the effect of the Moon's gravity and the effect of the centrifugal force resulting from the elevator system's synchronous, rigid body rotation cancel each other out. The Earth-Moon Lagrangian points L1 and L2 are points of unstable gravitational equilibrium, meaning that small inertial adjustments will be needed to ensure any object positioned there can remain effectively stationary relative to the lunar surface. The cost advantage of launching from the Moon using a lunar elevator instead of chemical rockets will surely be even greater, due to the far lower construction cost - perhaps as little as 1% of a terrestrial elevator - as estimated by Pearson et al *(Pearson, J. et al., 2005).*

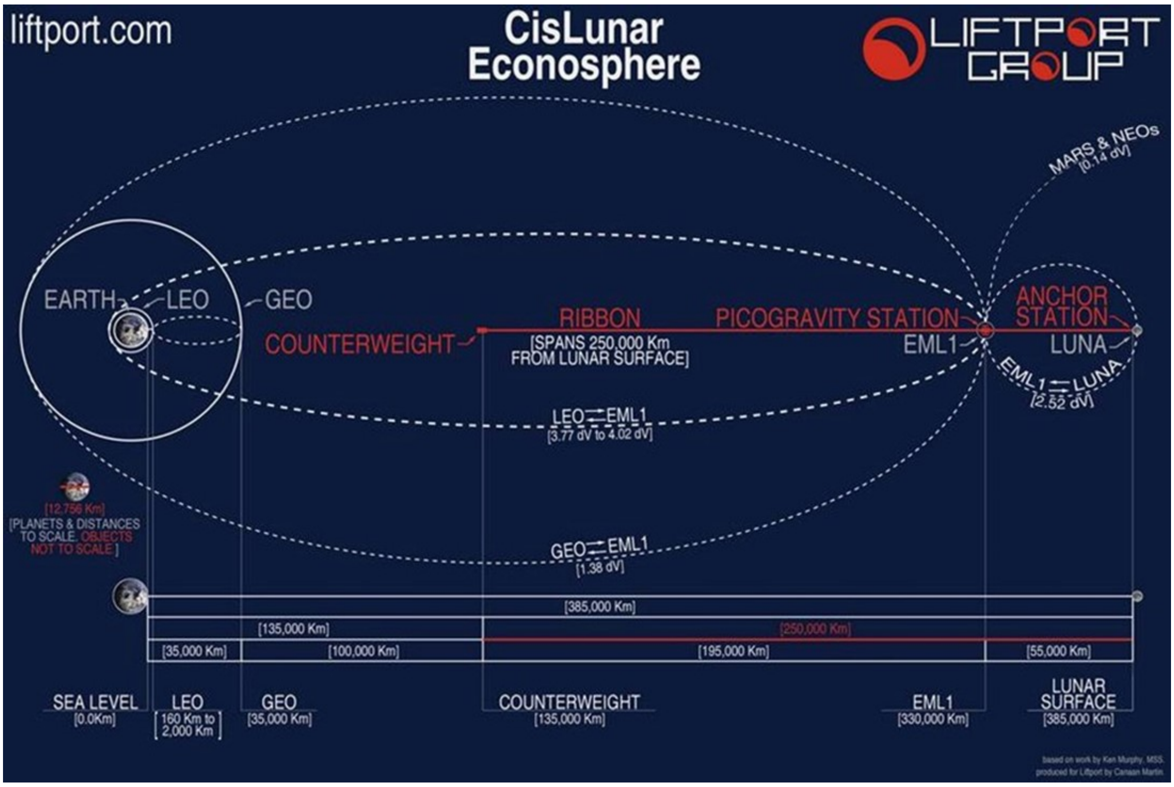


Figure 41: Lunar Space Elevator (Credit: Liftport.com)

In order for a lunar space elevator to remain static (i.e. stationary with respect to the surface of the body it is attached to) its centre of mass must be in a stationary orbit, with the force of gravity on the tether below the centre of mass being balanced by a counterweight above the center of mass, thereby keeping the tether in tension. *(Eubanks, Radley, 2016).* Thus, the weight of the limb of the cable system extending down to the Moon would have to be balanced by the cable extending further up or be topped by a more massive counterweight.

For EM-L1, it has been calculated that, to suspend 1 kilogram of cable or payload just above the surface of the Moon would require 1,000 kg of counterweight, 26,000 km beyond EM-L1. A smaller counterweight on a longer cable, e.g., 100 kg at a distance of 230,000 km - more than halfway to Earth - would have the same balancing effect. A longer tether in the direction of Earth could be sufficient as a counterweight, with the additional advantage that it could be extended almost to Earth GEO. The average Earth-Moon distance is 384,400 km. The potential advantages of such a direct Earth-Moon transportation system, by enabling cargo transportation using electricity alone, are obvious. *(Penoyre and Sandford, 2020).* Without the attraction of Earth's gravity, a LSE passing through EM-L2 would require 1,000 kg of counterweight at a distance of 120,000 km from the Moon for the cable's lowest kilogram. EM-L2 may be a desirable location when using a mass driver, but for a LSE the best location is EM-L1.

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

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. Tether materials such as Dyneema and Zylon are already commercially available in large quantities, *(Eubanks, Laine, 2011) (Radley, 2017)* and are currently the best candidates for GE⊕-LSE construction. Lunar sourced basalt fibre may be sufficient for reinforcing and extending the elevator once it has become operational *(Pearson, J. et al., 2005)*.

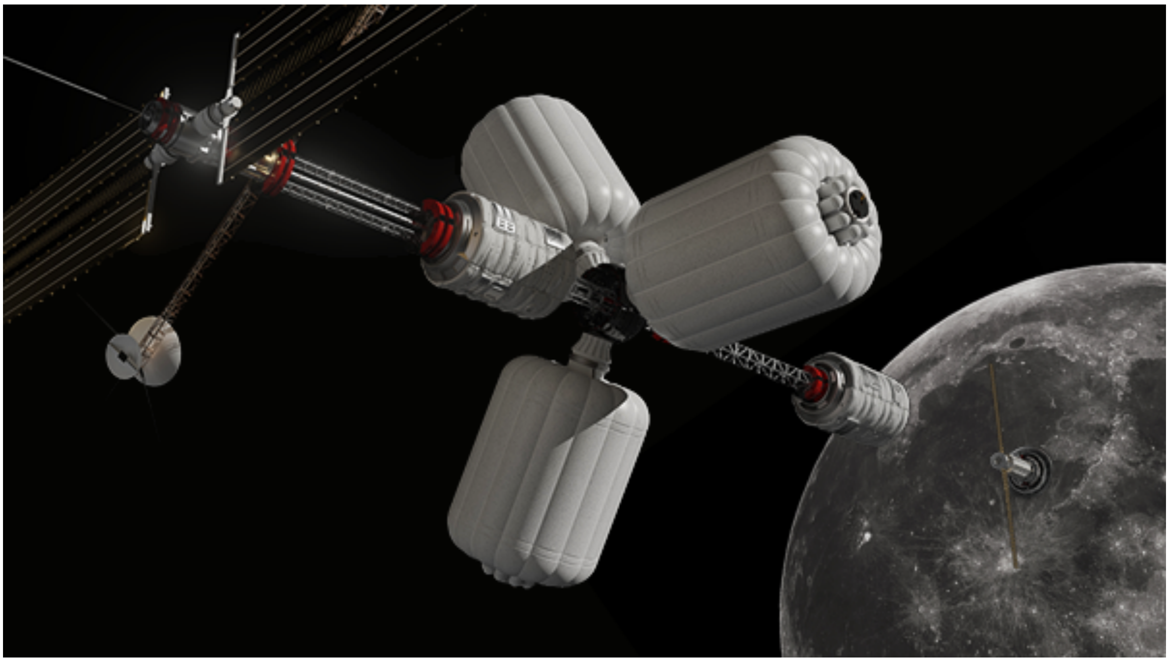


Figure 42: Lunar Space Elevator and EM-L1 Hub (Credit: Astrostrom)

It has been proposed that a 48-ton lunar space elevator could be built and packaged on to a single heavy-lift launcher. The cost of LSE development would be affordable by comparison to other launch systems and could repay its launch cost within a single month by delivering a cargo of He-3 if climber speeds of 0.7 km/sec could be sustained, which would equal about 24 hours of travel from the Lunar surface to EM-L1 or vice versa. If six evenly spaced climbers can travel on the tether simultaneously, achieving 80 ascents and descents per month in total, this would result in payload throughput of 8 tons per month in each direction *(Radley, 2017).*

Once a GE⊕-LSE is deployed, its transport capacity could be expanded by adding more cables including those built out of basalt fibres produced on the Moon. Thus, lane by lane, the redundancy and capacity of the GE⊕-LSE can be increased. The GE⊕-LSE will not only enable mass transportation of lunar products to EM-L1 but will also ease the transportation of humans and fragile goods to the lunar surface for as long as rocket-powered lunar landings still bear a high-risk factor.

The scalability of the GE⊕-LSE must be researched more intensely and is dependent on many factors. Basically, the higher the mass of the payload lifted from the Moon, the more massive the counterweight towards the Earth side must be. The payload per climber is relatively small, since the most critical factor is to bring it out of the gravity well of the Moon. Multiple tethers with multiple climbers running in sequence could distribute the weight. Each climber has 100 kg payload. At a height of 5,000 km the payload could be transferred. Thus, each climber could make two trips from the lunar surface during a 24-hour period. Hypothetically, 27 tethers from the lunar surface connected to a cargo relay station located at 5,000 km, then 9 tethers from there to EM-L1 could deliver 11.2 tonnes to EM-L1 per 24-hour cycle, totalling 4,088 MT per year. This corresponds to about two SPSs with matured technology (700 W/kg), each providing 1.44 GW per year. With a higher counterweight, the payload of the climbers could be doubled or quadrupled, and this would result in the capacity to produce 4-8 SPSs per year with a nominal capacity of 1.44 GW each. However, for the moment this is speculation without further research. For increasing the counterweight sintered regolith can be transported to near GEO, while on the return trip, collected space debris could be brought to the lunar surface and serve as a valuable recycling material and component source.An additional approach to increase throughput could be to establish an interchange station at around 5,000 km from the lunar surface, where the gravitational influence of the Moon is already considerably less as shown in Figure 43.

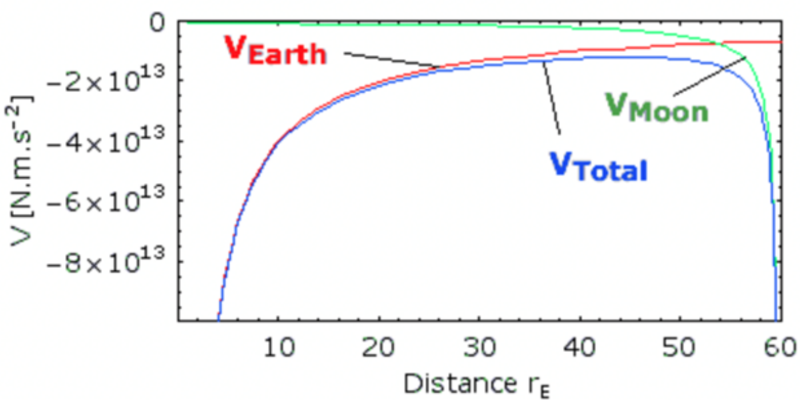


Figure 43: The influence of Moon's gravity exponentially drops towards EM-L1.

Also, at around 5,000 km the Moon shadow would hit a station only for a very short period. Thus, if energy is beamed by laser onto the solar panels of the climbers, the GE⊕-LSE could operate nearly continuously. Such a relay station would be built with a basalt trusswork and have robot arms interchanging the payload as shown in Figure 44. Eight cables would service the lunar surface and three cables EM-L1. Due to the lower gravitational influence of the Moon, the climbers moving towards EM-L1 could be accelerated considerably faster and carry more payload.

This will result in an Earth-Moon transportation system with an economic hub located at or adjacent to the EM-L1 hub of the elevator. Due to its uniqueness, EM-L1 will eventually become an important cislunar space infrastructure location, used by many countries, similar to the Suez and Panama canals on Earth.

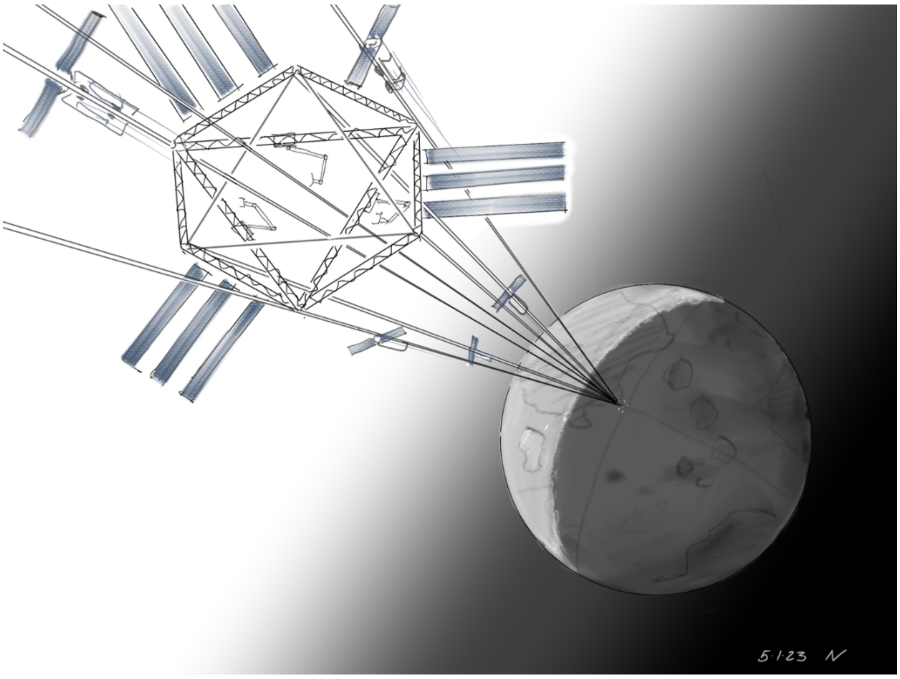


Figure 44: A cargo relay station at 5,000 km above the lunar surface could possibly increase the throughput of a GE⊕-LSE. (Credit: Astrostrom)

11.3. Lunar Surface Facilities

The GE⊕-LPS concept proposes to establish a highly automatized lunar facility to mine and process lunar material for the manufacture of the SPS components which would then be sent into a robotic assembly point at the Earth-Moon Lagrange point EM-L1.

Having identified the transportation capacity as the limiting factor for the production output, the surface facilities can be scaled up. Thus, the approach of this study is to start with relatively small units, which can be multiplied and thereby scale up the output.

11.3.1. Site Planning 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. 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 45 and in Figure 46.

Preliminary site planning suggests locating the major elements to the north of the GE⊕-LSE surface base station. Very close in the north will be the fabrication site, where the final cargo from EM-L1 arrives. The surface habitat is located above this location. The habitat is the closest element to the launch and landing pads located eastwards. Rockets will land from northwest and launch towards the east to avoid coming close to the GE⊕-LSE tether. There will be a separate propellant factory east of the launch pads which may require the importation of hydrogen from the pole regions and/or methane from Earth to be combined with the plentiful oxygen found in the lunar regolith which could be transported from the pole to the equator using the Lunar Landing Gantry that also delivers cargo from EM-L1 to the lunar surface. Northwest of the factories will be the beneficiation site, which is located close to the mining site, which will expand towards the northwest. The rectenna will be located to the southwest. This preliminary site planning also leaves a lot of room for further site development towards the southeast.

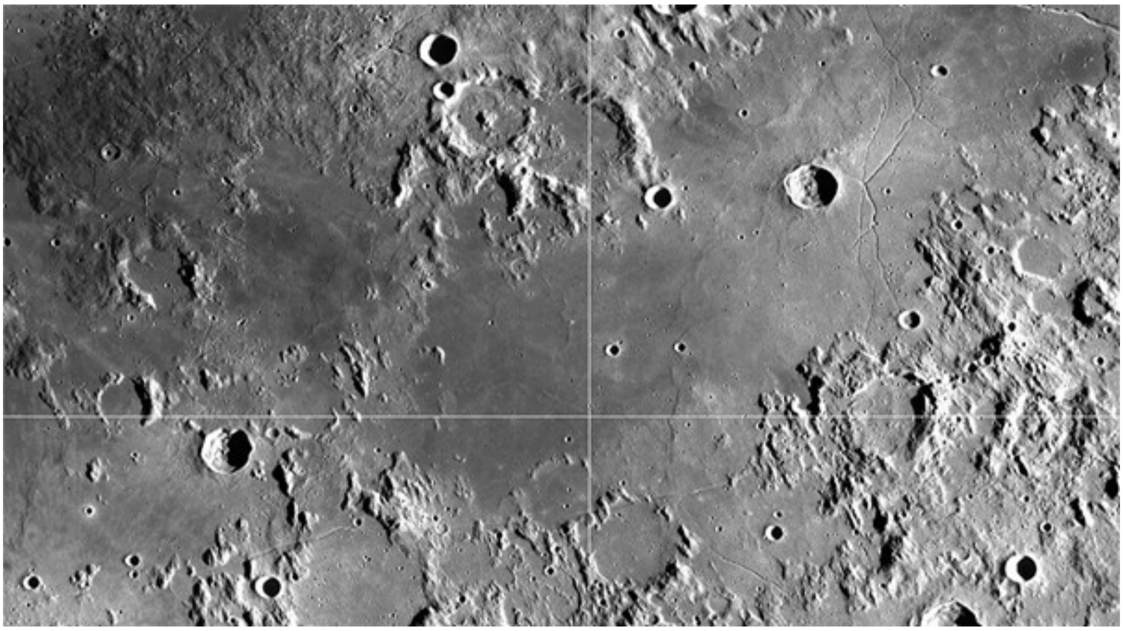


Figure 45: Sinus Medii. The crosshairs are showing the prime meridian and the equator, where the ground station of the GE⊕-LPS will be located.(Source: Wikipedia)

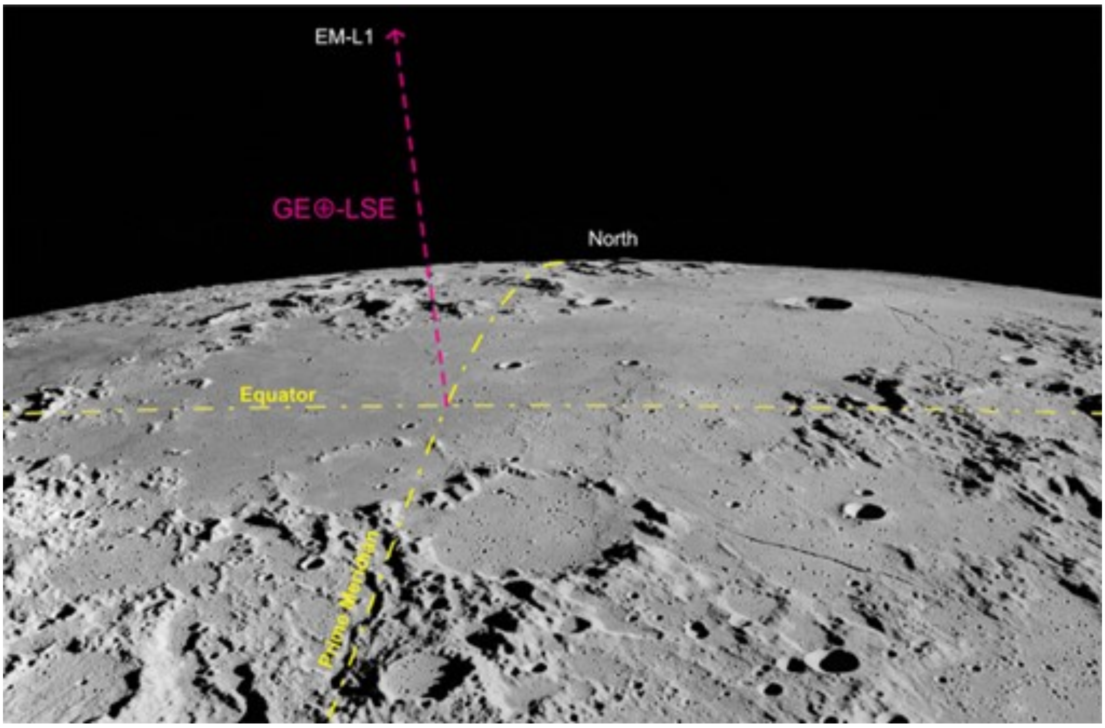


Figure 46: View of Sinus Medii with equator and prime meridian. Also shown is the ribbon of the GE⊕-LSE. (Background image Source: Wikipedia)

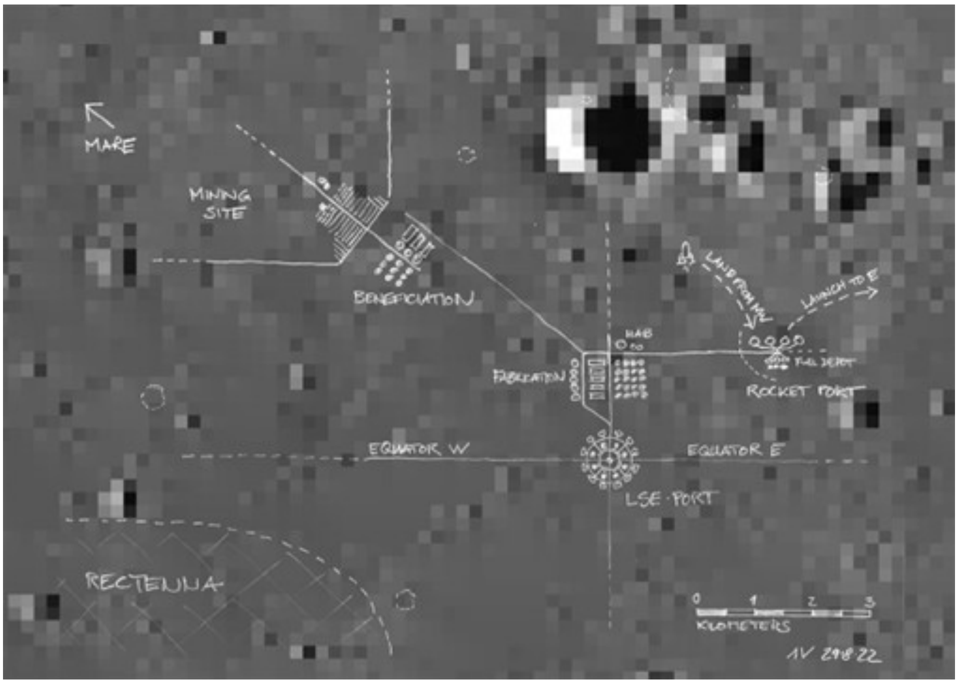


Figure 47: Overlay of preliminary site planning with picture.

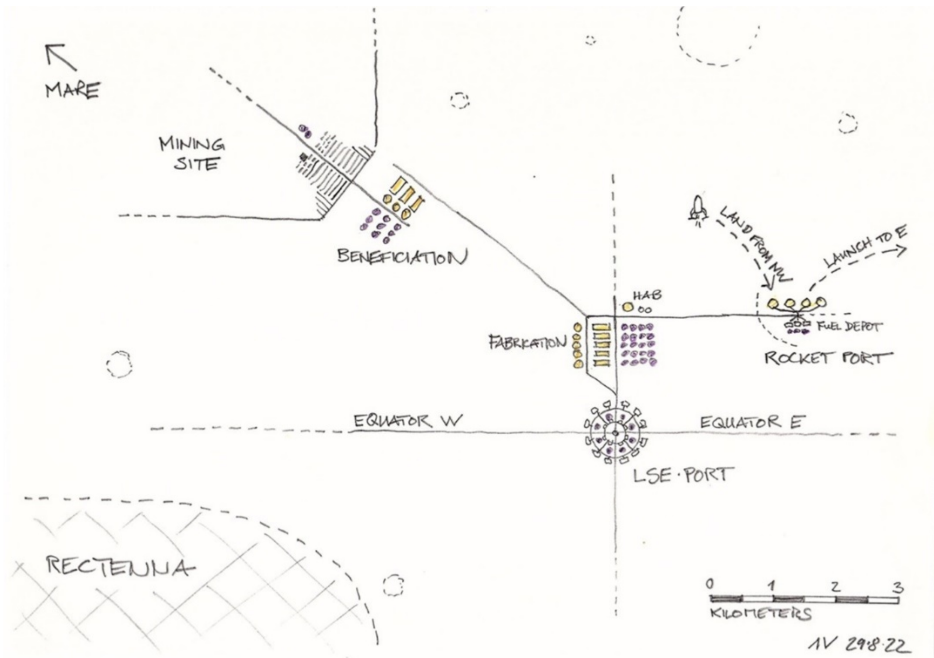


Figure 48: Sketch with scale of the preliminary site planning, showing LSE port, rocket port, the HAB, mining, beneficiation, and fabrication sites. (Credit: Astrostrom)

11.3.2. Civil Engineering Works

For the surface facilities to be sustainable and not only temporary, a series of civil engineering works will also be necessary. These will be mainly the construction of the launch facilities, power facilities, the connecting roads and foundations for the foreseen buildings.

11.3.3. Launch and Landing Pads

In the early phases of establishing the GE⊕-LPS system, there is a need for rocket-based transportation. However, for flexibility, redundancy and emergency use there will be the need for the rocket transportation infrastructure to be maintained even after the operation of the GE⊕-LSE has commenced.

For the transportation of cargo and humans there will likely be different classes of rockets. In the first phases – until a significant propellant production is put into operation - there will be a series of deployable cargo and crewed rockets landing, from which the fairings, propulsion systems and other equipment can be reused as valuable raw materials and volumes. For example, an initial habitat could be a repurposed crewed lander vehicle with its built-in and functioning life support system and covered with regolith for radiation protection.

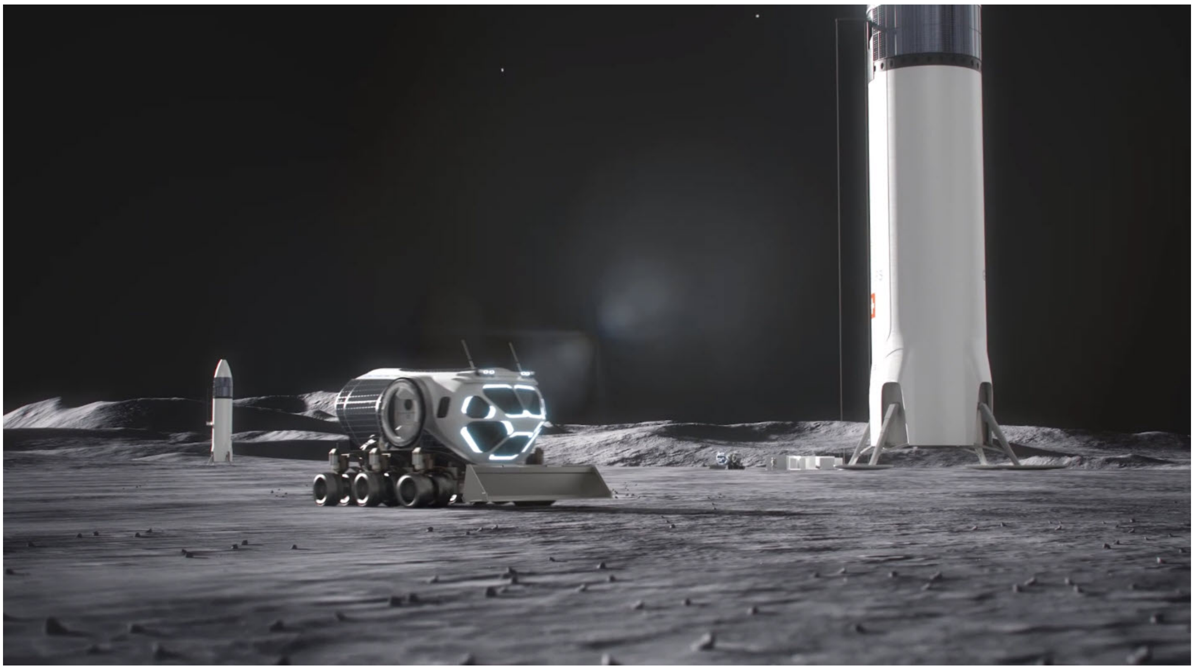


Figure 49: Two HLS vehicles unloading cargo and rovers. (Credit: Astrostrom)

Additionally, the rocket fuel tanks can be reused in the beneficiation plant to collect volatiles and liquid oxygen (LOX).

The landing and launch infrastructure will be far enough (2-3 km) from any critical infrastructure, so the impact of a failed landing is minimised. The most critical is the blast protection of the spaceship itself and surrounding infrastructure *(Mueller et al., 2012).* It is proposed to build up a land-and-launch system with refuelling after landing.

The landing infrastructure consists of the following elements:

- 3 landing pads for redundancy, accessible by roads
- Dust blast walls
- Electronic and visual guidance system
- Illumination and surveillance system

- Energy System
- Robotic propellant handling system to empty and fill tanks
- Cleaning robots to keep pads and roads dust free
- Mobile crane for handling non-standard cargo and lifting rockets onto transportation robots. (Note: The Lunar Landing Gantry has an integrated crane.)
- Emergency team with use of pressurised and unpressurised rovers
- Propellant storage and refuelling infrastructure
- Exhaust blast cavern
- Emergency escape infrastructure
- Permanently ready emergency rocket with possibly direct, gravity-based access from the habitats

Human-rated rockets may be separated from the busier cargo rocket infrastructure.

11.3.4. Power Facilities: Surface Mobile Solar Panels

To commence initial surface operations, 100 kW of power generation capacity could be delivered in the form of mobile photovoltaic arrays each capable of delivering 12 kW of power. These will be expandable circular arrays packaged and mounted on electric rovers with ion-lithium battery packs. This will enable optimal directional focusing of the PV arrays as well as precise locational capabilities and energy storage. The expandable array will have a diameter of 10 meters and 150/We per m^2 of output using CIGS or MGL PVs from Earth with an AM0 efficiency of 10-15%. Up to 100 of these devices could be delivered with the first Arrival mission of the HLS below or in late supply flights as seen in Figure 50. Figure 51 shows an individual Mobile PV Device and the power characteristics. Figure 52 shows the deployment of one of the devices.

Figure 50: Several Mobile PV devices deployed during the initial Arrival mission. (Credit: Astrostrom)

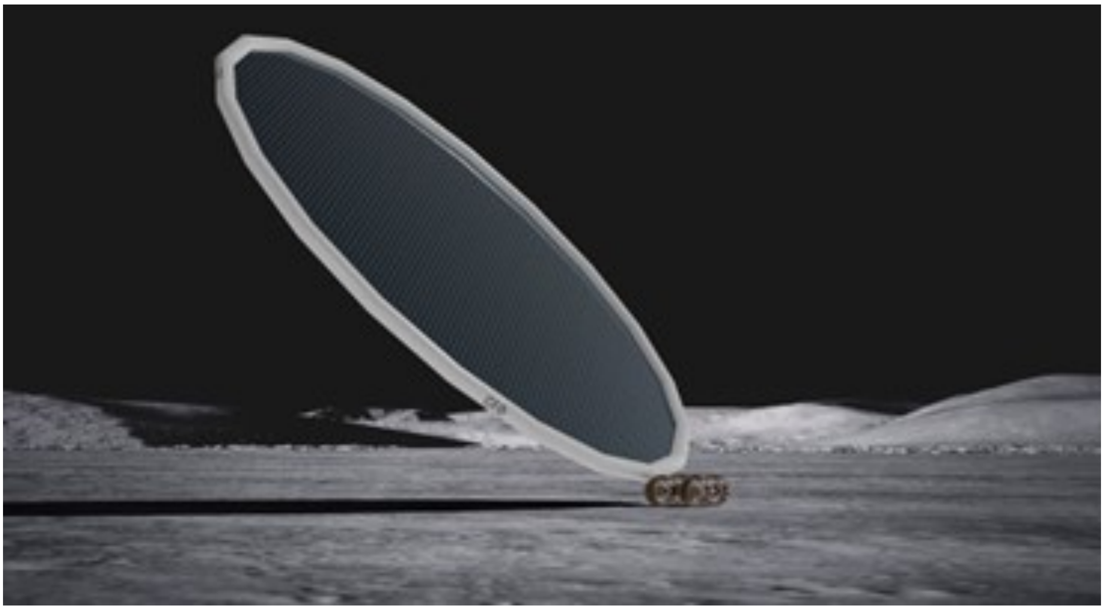


Figure 51: Mobile PV device (Credit: Astrostrom)

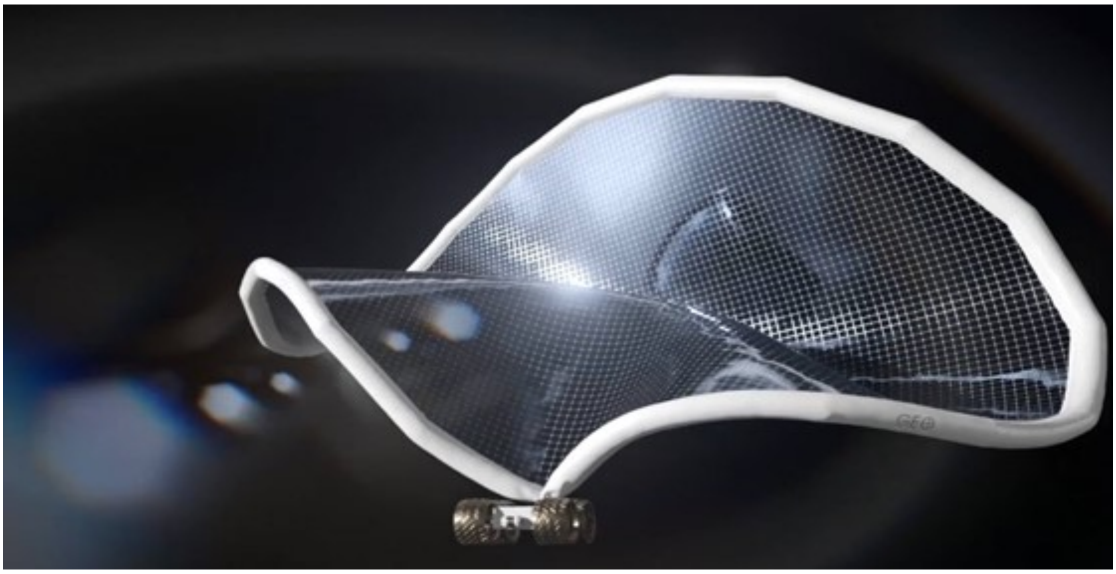


Figure 52: Deployment by Inflation of Mobile PV device (Credit: Astrostrom)

PV 10 m dia. = 78.54 m^2 surface area
CIGS PV: 150 W/ m^2 = 12 kW capacity
Mass of array including torus: = +/- 100 kg
Mass of rover: 40 kg
Mass of modular exchange battery rack including 4 batteries: 160 kg

To supply the whole 1.5 MW of power with the mobile PV device, 125 Mobile PV Devices would be needed.

11.3.5. Heat Energy

Heat energy will be mainly needed for the melting processed in beneficiation, extraction and production. Nakamura, Smith and Irvin did intensive research with terrestrial solar concentrators and glass fibre energy transmission. They estimate that a future space system could deliver as much as 870 W/m^2 at AM0 with a 10m glass fibre cable. The specific weight was calculated to be 5.78 kg=kW for an oxygen production plant *(Nakamura et al. 2015)*.

Figure 53: Ground test model of the Optical Waveguide (OW) solar energy system (Credit: Nakamura)

With the current assumption of heat needed for the GE⊕-LPS surface systems with 350 kW a payload of 2 tons of solar concentrators would be needed.

11.3.6. Energy Storage for the Habitat

In the initial phase of operations, the current setup of the GE⊕-LPS system is using the fact, that machines not working are not using energy (or only minimally, although humans will use some energy continuously). Which means that the entire production operations will be halted during lunar night and only the habitat must be supplied with energy. All heated elements like furnaces would have to be well insulated to avoid damage by excessive cooling. When later a SPS is active in lunar orbit, the rectenna can supply the necessary energy.

Palos et al., 2020 have evaluated various ISRU based electric energy storage systems. According to their scoring system, the following combination of technologies would be the most recommendable:

Linear Fresnel reflectors →Direct illumination →Sintered regolith with fins →Pumped fluid loops →Stirling engine →Pumped fluid loop →Radiator in eternal darkness.

Hu, Li and Li proposed an efficient linear Fresnel collector for solar concentration with thermal energy reservoir (TER) coupling with a Stirling power generator. Their concept uses the fuel tanks of descent modules and lunar regolith (see Figure 54). The average power output of their system is 6,8 kW during lunar night. The system specific power is 6.5 W/kg without accounting for the fuel tank and regolith. The total launch mass would be 1000 kg and 42 tons of regolith would have to be processed *(Hu, et at, 2021).*

The total mass of the 'Kilopower' nuclear power system designed and fabricated by NASA is about 1,246 kg with the output power 7 kW, and the system specific power is 5.6 W/kg.

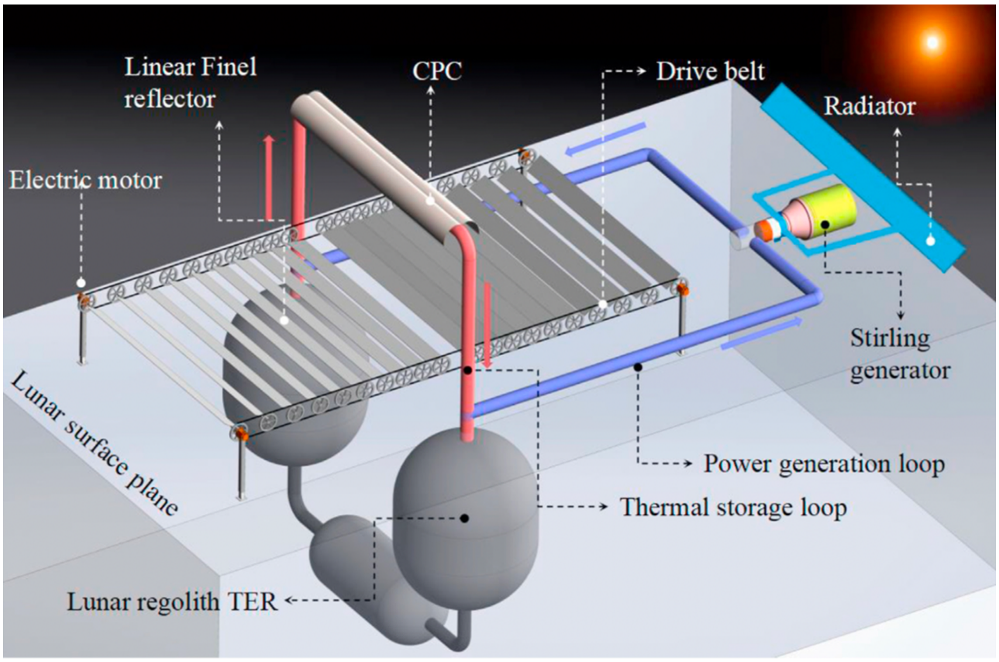


Figure 54: Schematic design of solar thermal storage power generation system based on lunar ISRU (Hu, Li and Li, 2021).

The photovoltaic battery power generation system mainly includes solar panels and batteries. The energy density of present commercial lithium-ion battery is about 200-300 Wh/kg, which is about two times larger than the batteries used in Mars Exploration Rover project, Mars Express Project and HAYABUSA Project. In order to provide 350 h x 6.5 kW power for energy supply of one lunar night, the weight of the batteries needs at least 7583.3 kg mass. For the continuous operation of the GE⊕-LPS surface habitat 35 MWh of storage capacity are needed. This results in 15 of the above-mentioned systems or approximately 15 tons of soft-landed payload.

11.3.7. Roadworks

Roads are very flexible and facilitate transportation once they are built. Therefore, a certain amount of surface work will be needed, although this could be the result of the initial mining operations. The surface of the roads can be produced by sintering. Important parameters are stable traction, the reduction of friction and energy needed for transportation, and to create a rolling environment with minimum dust to preserve the wheels, axles and gears.

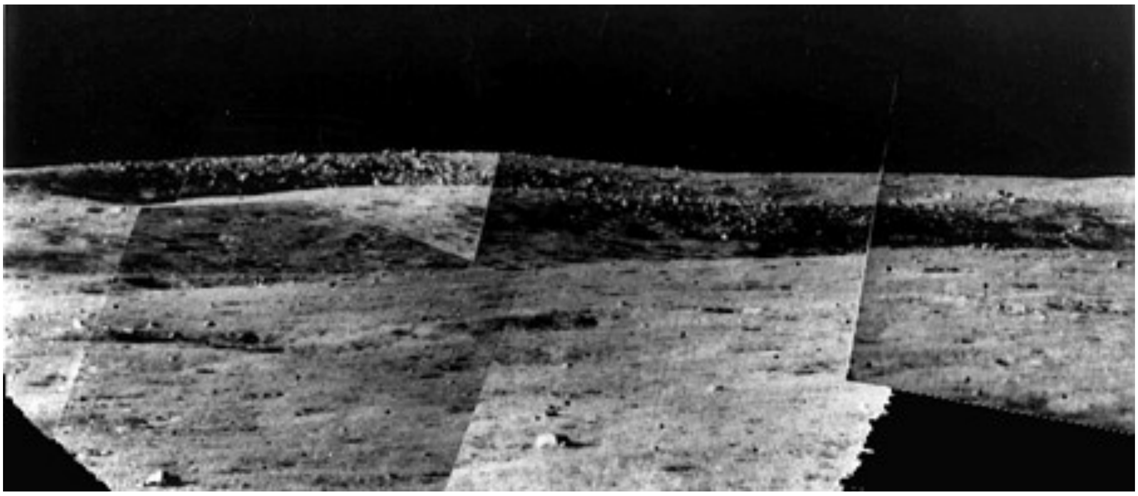


Figure 55: Surveyor 6 panoramic view looking across a nearby boulder strewn crater rim. Credit: NASA

The main challenges for road vehicles are airlessness, low gravity, and solar effects, especially temperature extremes. The GE⊕-LPS site at the prime meridian on the equator does not look topographically very challenging. The images from Surveyor 6 also give the impression that rocks may not be a major concern as in other lunar regions as seen in Figure 55. Thus, it is assumed that RASSOR robots used for mining can also be deployed for levelling the roads. Individual stones can be picked up by a robot with a robot arm and used for filling holes. Other robots can sinter the levelled surface to create a dust sealed surface with low friction and good traction as shown in Figure 56.

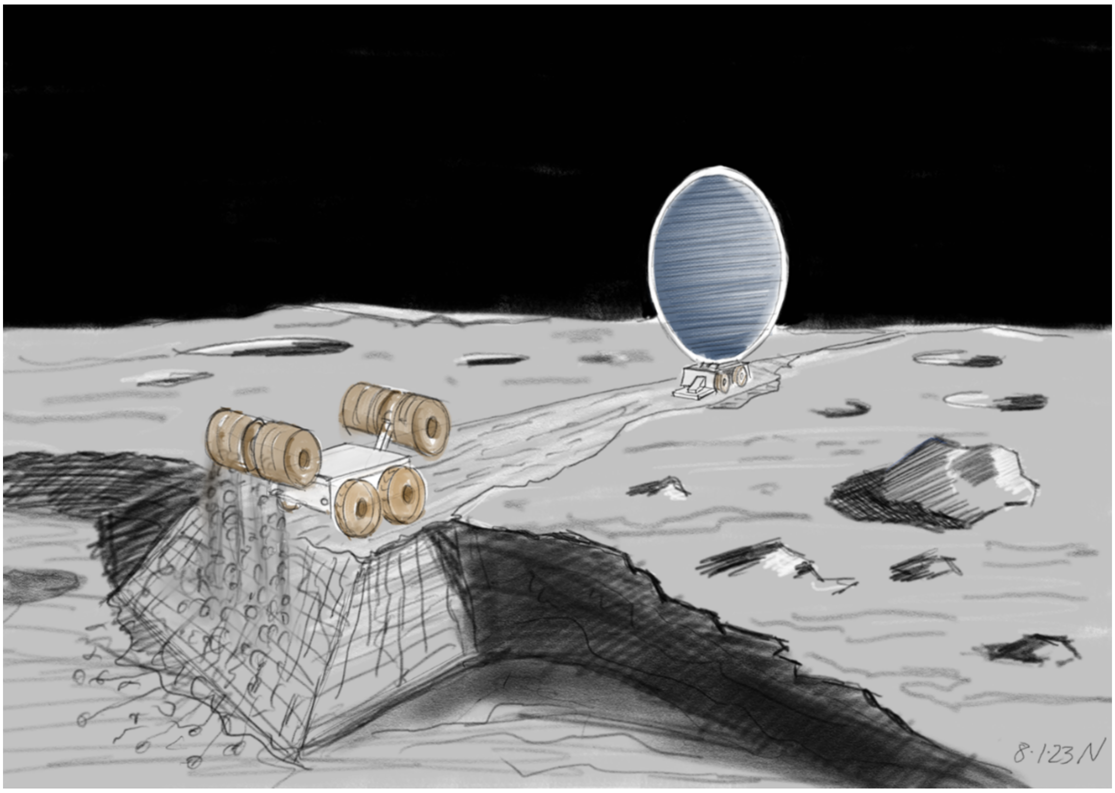


Figure 56: A RASSOR robot levelling a road with a sintering robot following. (Credit: Astrostrom)

However, lunar dust is likely to be one of the main design drivers for a lunar surface transportation system. The effects of dust on robotic road transportation are:

- (Sensor) Vision impairment
- Incorrect instrument readings
- Dust coating
- Loss of traction
- Clogging of mechanisms
- Abrasion
- Thermal control problems
- Seal failures
- etc

For these reasons dust cleaning robots may also be considered necessary. It should also be studied whether sintering of rail systems could significantly improve a long-term cargo mass transportation system on the Moon.

The Chinese Chang'E-3 mission measured dust deposits for the first time. The results showed that a total deposition mass at a height of 190 cm above the lunar surface during 12 lunar daytimes in the northern Mare Imbrium was about 0.0065 mg/cm2, corresponding to an annual deposition rate of ~21.4 µg/cm^2, which is comparable with that of Apollo's result to some extent *(Li et al, 2019)*. This is not very much compared to terrestrial cities or even mining environments, however, the dust movements and depositions on the Moon must be studied more.

11.3.8. Mining

Rassor Mass Flow	Kg Per hour	Kg Per day	T Per year*
1 RASSOR	200	4,800	864
4 RASSOR	800	19,200	3,456
16 RASSOR	3,200	76,800	13,824
20 RASSOR	4,000	80,600	17,280
32 RASSOR	6,400	153,600	27,648

Table 3: Table showing mining performance of RASSOR type robots.
Digging only during the lunar day, 1 year = 180

We identified the NASA KSC Swamp Work Regolith Advanced Surface Systems Operations Robot (RASSOR 2.0) *(NASA, KSC-Tops-7, 2013)* as an already quite far developed lightweight lunar soil collecting robot. Since the GE⊕-LPS production system is essentially based on the use of lunar soil and avoids rocks, RASSORs could 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 RASSOR prototype can carry 90 kg of regolith. For GE⊕-LPS we would use a slightly larger version, which could carry 150 kg. If mining only takes place during the lunar day, expected mining performance is shown in Table 3.

11.3.9. Beneficiation and Processing

Lunar soil, regolith, or Moon dust is mostly oxygen and silicon along with iron, calcium, aluminium, magnesium, titanium and traces of chromium, manganese, sodium, potassium, phosphorus, sulphur and miniscule amounts of many other elements. It also contains traces of hydrogen, helium, methane, CO, CO_2, and nitrogen implanted by the solar wind that can be extracted in limited quantities by mining tons of regolith and heating it to about 700^0 C.

Numerous processes for extracting oxygen and metals from lunar regolith have been proposed. Most of these use chemical reagents like HF, fluorine, chlorine and other substances not common on the Moon. Since the GE⊕-LPS mining is on the equator, polar water must be imported. A process that does not require water and/or large quantities of corrosive and imported chemicals is desired. Solar wind implanted volatiles like hydrogen, helium, carbon, and nitrogen can be extracted by roasting huge quantities of regolith at 700 degrees C. 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.

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. The economics of all processes must be determined by doing research on the ground in vacuum chambers that simulate the lunar environment, at lunar analog research bases and eventually, at a "Lunar Industrial Research Park" on the Moon where hard facts can be determined. This Lunar Industrial Research Park should be highly autonomous and be remotely controllable from Earth and be set up as soon as possible. Mining the Moon for these materials does not require water, acids, halogens or other substances which are rare or practically non-existent on the Moon *(MoonMiner.info, 2013)*.

Estimated material output of regolith mined per Ton	In kg
Iron Fe	130 kg
Aluminium Al	65 kg
Titanium Ti	40 kg
Magnesium Mg	55 kg
Silicon Si	200 kg
Oxygen O2	400 kg
Sodium Na	3 kg
Potassium K	1.2 kg
Sulfur (best case from 1% Troilite)	1 - 3.5 kg
Calcium Ca	8 kg
Chromium Cr	2.5 kg

Manganese Mn	1.8 kg
Phosphorus P	0.6 kg
VOLATILES	
Water H_2O	0.023 kg
Nitrogen N_2	0.004 kg
CO2	0.012 kg
Hydrogen H_2	0.043 kg
Helium 4	0.022 kg
Methane (CH_4)	0.011 kg
CO	0.0135 kg
Helium 3	0.000007 kg

Table 4: Estimated average of resources in MARE Basalt, Source: Stoeser, D.B., Rickman, D.L. and Wilson, S. (2010) 'Design and Specifications for the Highland Regolith Prototype Simulants NU-LHT-1M and -2M', p. 24.

Table 4 shows, that for pyrite-based PV production the necessary amount of sulphur will be the driver for the mining. Iron monosulfide or troilite FeS is the most common sulfide mineral on the lunar surface. It forms about one percent of the lunar crust and is present in any rock or meteorite originating from the Moon. In particular, all basalts brought by the Apollo 11, 12, 15 and 16 missions contain about 1% of troilite. Best practice at the moment to produce pyrite crystals is to use FeS and S. Troilite may also be separable from the lunar regolith by a combination of mechanical sifting and electrostatic beneficiation. Sulphur can be extracted from troilite itself.

Assuming that from one ton of mined regolith one can gain 9 kg of troilite and generate 6 kg of pyrite crystals in the best case. Current MGL PV technology needs about 200g per m^2 of crystal coating. This probably could be reduced slightly (10% – 20%) in future.

For a PV surface area of nearly 500,000 m^2, about 100 tons of MGL pyrite crystals would be needed. This would result in mining and processing a minimum of 16,667 tons of regolith. This could be achieved with 20 Rassors within one year.

Material separated per unit of regolith	Percentage	
Volatiles	0,01 %	
Troilite FeS	1%	
Ilmenite $FeTiO_3$ for TiO_2 and Iron	9%	
Regolith for Basalt production	20%	
Regolith for Metal production	49,99%	
Regolith for Further Roasting and processing	20%	

Table 5: Estimate of pre-processed regolith.

Assuming that all mined regolith is roasted to extract the volatiles first, after the material is sifted and electrostatically and magnetically separated, 1% of troilite and about 9% of ilmenite can be extracted. The ilmenite is further processed to gain oxygen, titanium dioxide and iron. From the remaining 90%, one part goes into basalt production and the rest will be processed for metals as shown in Table 5.

From this the amount of raw materials which can be extracted per ton of mined regolith may be estimated, as shown in Table 6.

Estimated material output of regolith mined	Per Ton In kg	Per year* with 20 Rassor (17,280 tons) in tons
Basalt	200 kg	3456
Pyrite (Synthesized from Troilite)	6 kg	104
Ilmenite (for semiconductor use)	10 kg	173
Titanium dioxide, TiO_2 (processed from Ilmenite)	40 kg	691
Iron Fe (processed from Ilmenite and regolith)	100 kg	1728
Aluminium Al	30 kg	518
Titanium Ti	20 kg	346
Silicon Si	100 kg	1728
Oxygen O2	200 kg	3456
Magnesium oxide	100 kg	1728
Ferrous oxide	50 kg	864
Sodium Na	0.5 kg	9
Potassium K	0.24 kg	4
Others	44 kg	760
Slag	100 kg	1728
VOLATILES		**In kg**
Water H_2O	0.023 kg	397
Nitrogen N_2	0.004 kg	69
CO2	0.012 kg	207
Hydrogen H_2	0.043 kg	743
Helium 4	0.022 kg	380
Methane (CH_4)	0.011 kg	190
CO	0.0135 kg	233
Helium 3	0.000007 kg	0.1

Table 6: Estimated material output after beneficiation of regolith mined.

Please note, that the quantities of the volatiles are in kilograms and not in tons. However, over time there is quite a large amount of material being processed, which can be traded with other actors in cislunar space. If pyrite can be successfully used for PV production on the Moon, sulphur becomes a relatively precious element on the Moon. Thus, its use as a cement binder, which has been proposed by many researchers, may not be economically ideal, leaving aside its other critical physical properties of such a binder.

11.3.10. Propellants

The most immediately needed lunar resource will be rocket propellant to build up the GE⊕-LPS system. However, the need will decrease once the GE⊕-LSE is in operation. The amount of volatiles is too small to produce serious quantities of propellant near the equator. These valuable substances are better used for life support, production gases and polymer production.

However, oxygen production is plentiful and can contribute a good part to propellant. This leaves the following option for propellant manufacturing at the Moon's equator:

1. A valid solid rocket propellant can be developed and managed,
2. water ice and/or hydrogen is imported from the poles,
3. water and/or hydrogen is imported from Earth or from asteroids.

Since the proportion of oxygen in rocket propellant can be up to 80%, the option to import hydrogen et al. can make sense.

With the beneficiation of lunar-soil a considerable amount of oxygen will be produced, which can already reduce propellant shipments from Earth. On the equator the production of solid rocket fuel would be possible. However, for reusable and often flying shuttles like the Lunar Landing Gantry LLG liquid propellant is required. Thus, there would be the need for importing either water or better LOH from the lunar poles. Before there are roads or railroads established between the lunar poles and 0/0 at the equator the LLG can easily transport LOH from the poles to GE⊕-LPS production site. While descending from EM-L1 the LLG can deliver supplies to the station at the poles and pick up LOH and deliver it in a ballistic flight to Sinus Medii. This would be the most immediate and practical approach.

Propellant storage would be located close to the launch and landing site at Sinus Medii. LOX would be transported by transportation robots from the beneficiation plant to the propellant storage.

11.3.11. Water and Carbon Production

Water and carbon production derived from volatiles can be used to build up the CELSS. Eventually, since the life support system will be closed loop, higher stock of volatiles will build up. A large bioreactor could be built-up with algae to recycle oxygen and produce food. About 30 percent of astronauts' food could be replaced by algae biomass, due to its high protein content. The scarcity of carbon and water will encourage future Moon miners to build up a carbon economy at an early stage. Recycling and growing food will be important even in a highly automated production environment.

However, future lunar exploration missions may reveal more resources. Already the presence of considerable amounts of water ice in the polar regions has been suggested. It is also speculated, that in the polar cold traps, there may be frozen carbon dioxide. Other data from the Japanese Kayuga mission suggest, that there may be considerable amounts of carbon beneath the lunar surface, especially in the mare regions *(Yokota et al., 2020).*

The Lunar Crater Observation and Sensing Satellite (LCROSS) mission by NASA further spurted more promising hope for the future moon miner: *"LCROSS is fascinating not just due to water on the Moon, less controversial by 2009, but other substances: 5.7% carbon monoxide, 1.4% molecular hydrogen, 1.6% calcium, 1.2% mercury, 0.4% magnesium. Sulfur is detected as hydrogen sulfide (H2S) and SO2, at levels 1/6th and 1/30th of water, respectively. Nitrogen is seen within ammonia (NH3), at 1/16th water's abundance. Trace amounts (less than 1/30th of water) are detected for ethane (C2H4), CO2, methanol (CH3OH), methane (CH4) and OH. [62] Volatiles compose at least one-tenth of the soil mass. The poles differ radically from any part of the Moon we have visited or sampled." (Crotts, 2011).*

11.3.12. Polymers

Algae-Based bioreactors can also be used to produce biopolymers. As Kapton polyimide film is the most durable film for space applications its production on the Moon from synthesized volatiles needs more investigation.

Clearly, more intense research must be carried out to comprehensively understand the value of lunar resources on the Moon for industrial production. Synthetic materials have contributed significantly to modern technology, so that their production on the Moon will be serious boost for a lunar industrialisation.

11.3.13. Materials Processing Facility

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.

A flow chart for the material flow in the GE⊕-LPS production system is shown in Figure 57. 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. For the main production of the metals, iron, aluminium, titanium and silicon, fluorine imported from Earth would be needed. This can be imported as potassium fluorine in solid form and can be recovered during the reduction processes.

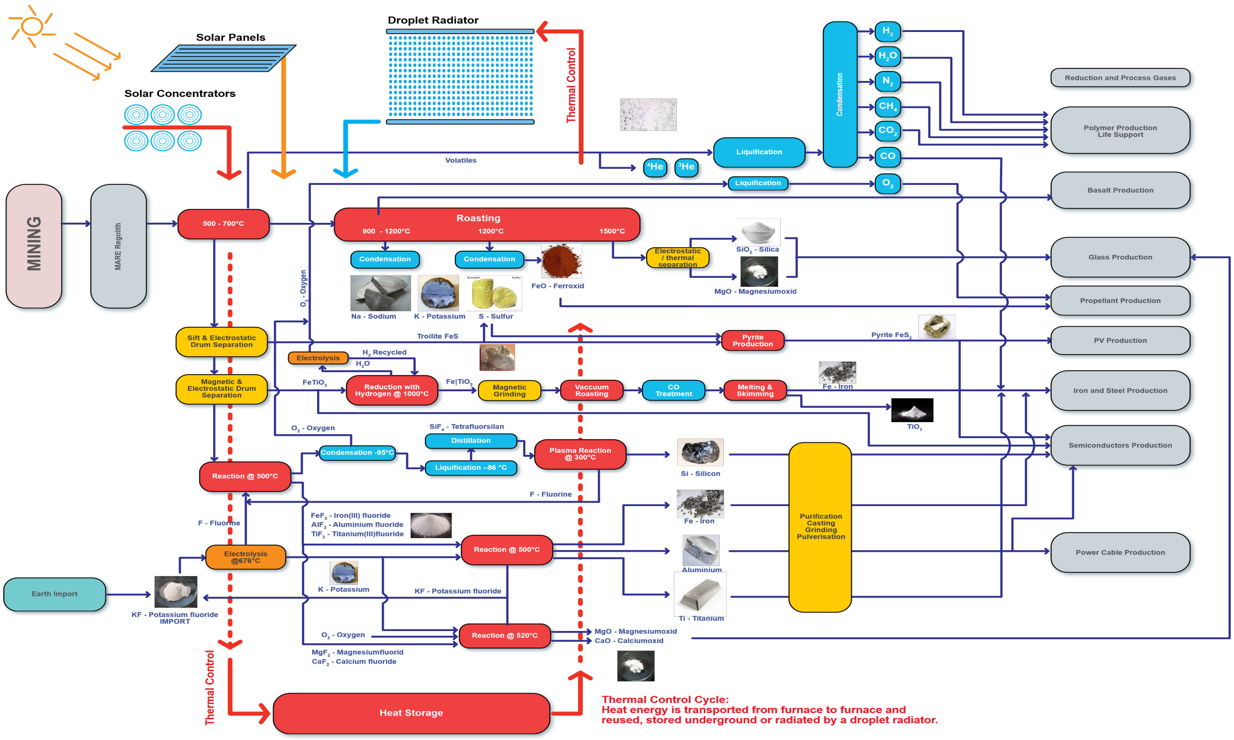


Figure 57: Flow chart of the material flows in the GE⊕-LPS beneficiation plant. Most processes are only heat based to avoid terrestrial imports. Also shown is a heat management system with heat storage.
(Credit: Astrostrom)

Most solids would be purified and processed as powders, which allows effective transport in containers and readiness for additive manufacturing. Metals can also be prepared as bars for further melting, casting, rolling and extrusion processes. Since many of the heating and condensation processes are vertically organized a rack building system as shown in Figure 58 which can be accessed on different levels both by astronauts as well as by robots, seems likely to be optimal. Similar chemical plants on Earth are built in a similar manner. The rack structure can be realized with elements made out of 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 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.

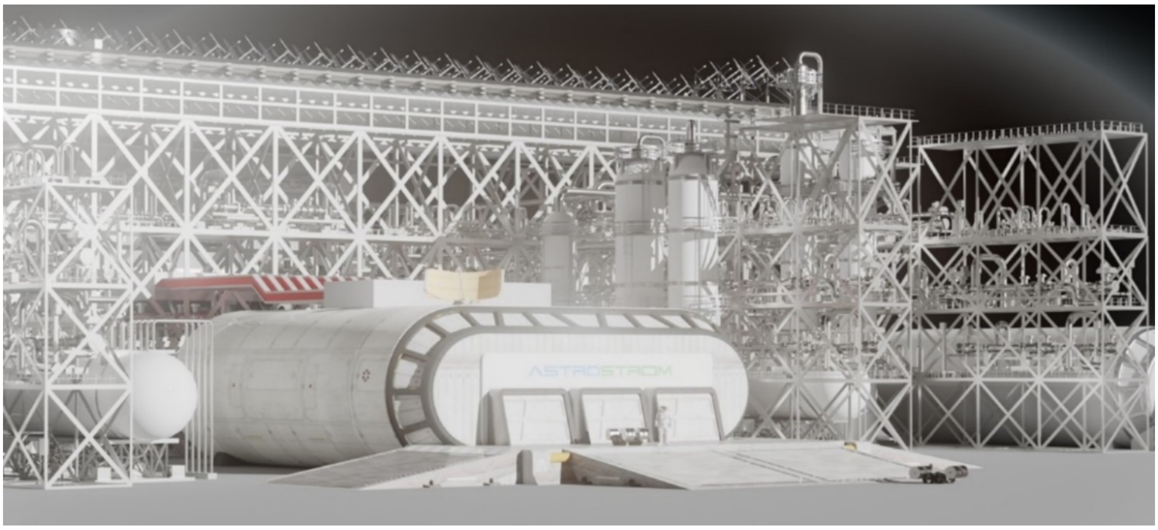


Figure 58: Artist's impression of GE⊕-LPS beneficiation plant. The basalt racks system allows modular scalability of all the processes. (Credit: Astrostrom)

Excess process heat which cannot be stored can be radiated by a droplet radiator on the North side of the facility. At its final state such a facility could look like what is shown in Figure 59. The material flow would be from west-to-east and from top-to-bottom. A conveyor belt transports the lunar soil on top, from where it is distributed to the furnaces located on the north side. Volatiles and other gases are separated in vertical condensers and stored in vertical tanks. A process control centre and material research lab are located in the centre. The end products are stored in a storage building on the east of the facilities, from where transportation robots pick up the containers and deliver them to the manufacturing facilities.

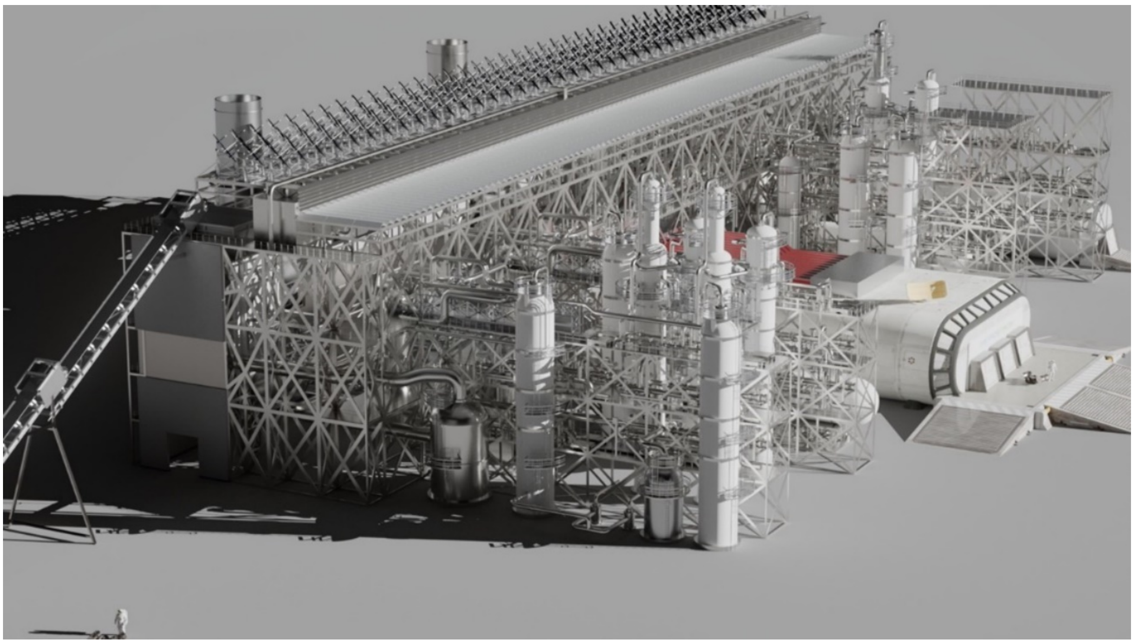


Figure 59: Artist's impression of GE⊕-LPS beneficiation plant. On the roof solar concentrators and solar panels collect the energy needed to heat the furnaces for their various processes. (Credit: Astrostrom)

11.3.14. Parts and Component Fabrication

Raw materials on the Moon are inherently valuable. However, their real economic value is achieved by creating added value to these materials by converting them into useful products. In the case of GE⊕-LPS, the main goal is to deliver energy the lunar surface and eventually to deliver green baseload energy to the Earth by producing SPSs from lunar materials. However, once production capacity is established on the Moon, it can also serve other markets. This will lower the market entry threshold for other stakeholders and generate a self-acceleration flywheel effect as described in section 14.5.

This will further allow the reduction of terrestrial imports, but also for the generation of a growing cislunar economy. The key to getting the lunar production started is energy. Thus, the early production of solar panels, propellant and basalt for structural purposes will be key drivers of the GE⊕-LPS production and for a further growth of a lunar economy.

11.3.15. Factories

For the construction of the GE⊕-LPS system two main areas of fabrication have been identified and specifically, the individual factories mentioned below:

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

<u>Basalt Casting Factory</u>

Structural joints as well as a variety of mechanical and utility product can be cast out of basalt. The casting moulds can be 3D printed out of iron.

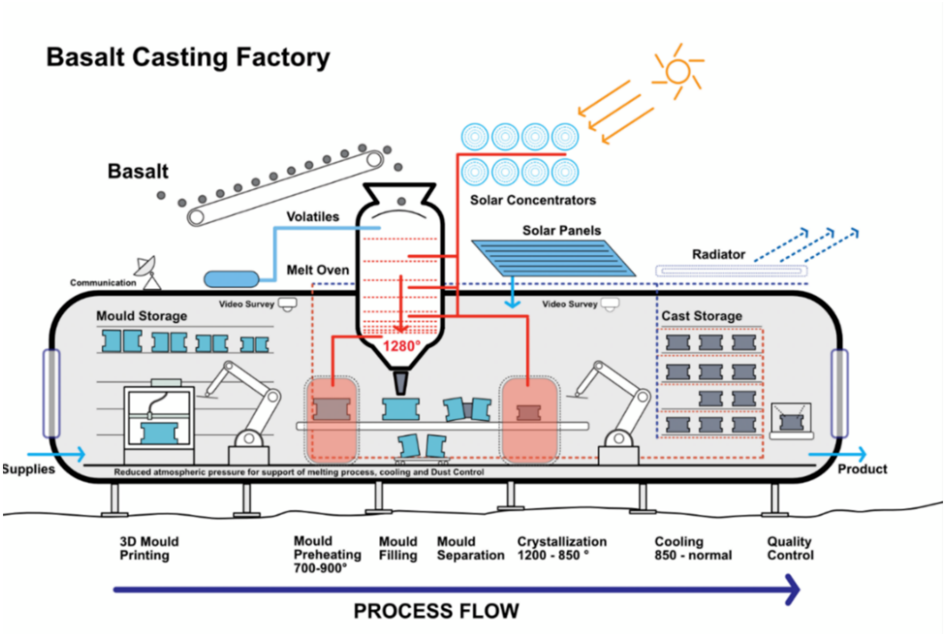


Figure 60: Basalt Casting Factory Diagram. (Credit: Astrostrom)

Basalt fibre and Pultrusion Factory

Structural elements for LPS can be produced out of basalt fibres formed into tubes by a pultrusion process. Fibres can also be used to reinforce other materials and for production of insulation mats in the insulation factory.

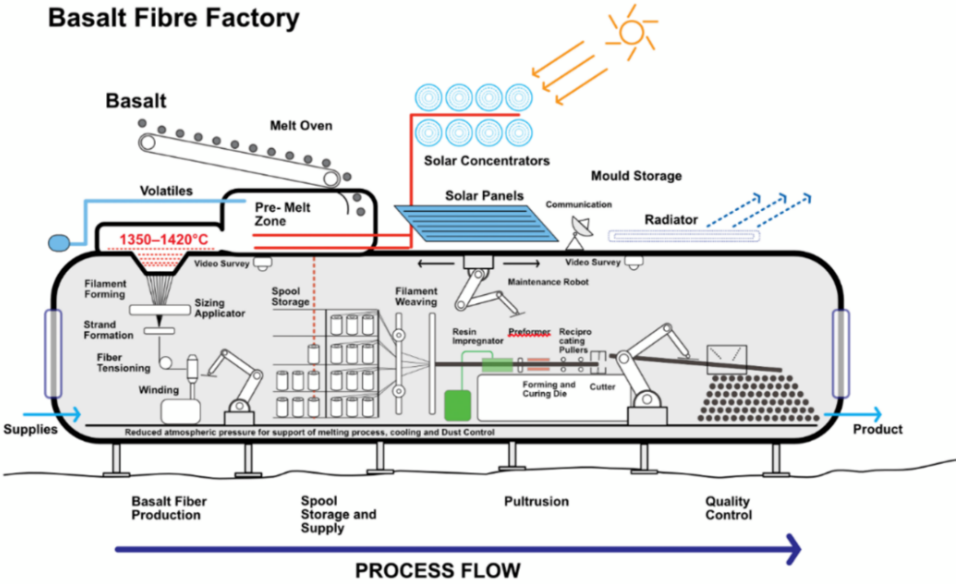


Figure 61: Basalt Fibre Factory. (Credit: Astrostrom)

Regolith Sintering Factory

Regolith can be sintered to tiles to be used for road and launch pad construction. Also, for the construction of furnaces.

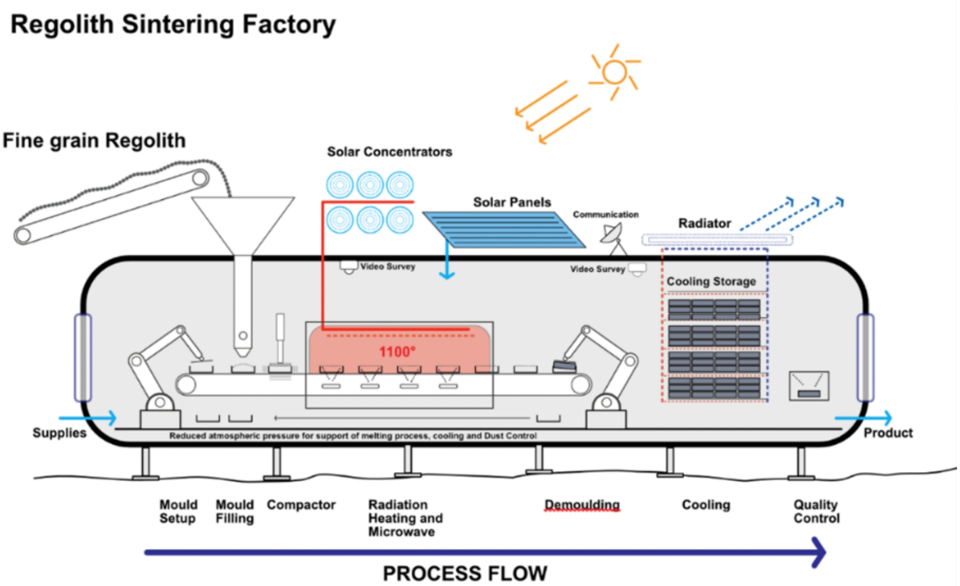


Figure 62: Regolith Sintering Factory (Credit: Astrostrom)

Electric Wiring Factory

Electric wires in different dimensions will be needed to build up the lunar grid and to construct the rectenna. Insulation of the wires can be made of basalt fibres.

Polymer factory

The possibility for the production of synthetic materials on the Moon needs to be further studied. The use in the construction of LPS would be in the following areas:

1. Transparent substrate for the hybrid PV-antenna production
2. Matrix for the pultrusion process of basalt fibres
3. Chemical bonding of structural tubes in space.

Hybrid PV-Antenna Factory

This factory will use modern fully automated thin-film electronics production technologies to produce the hybrid PV antenna elements with integrated solid-state DC-RF converters.

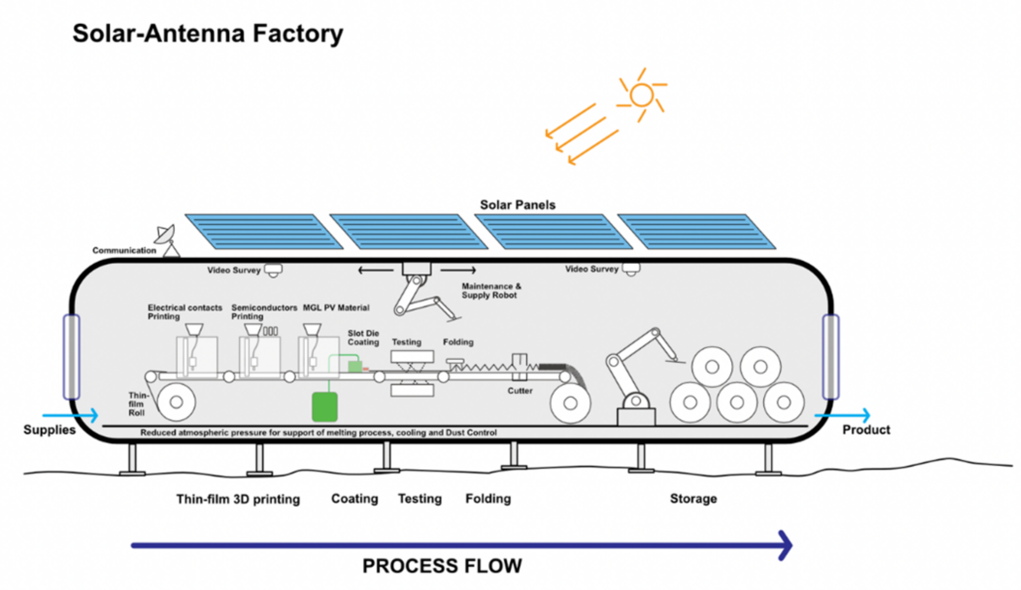


Figure 63: Concept design for a lunar solar-antenna element factory. (Credit: Astrostrom)

Additive Manufacturing Spare Parts Factory

This factory will be equipped with robotically serviced additive manufacturing machine, which will work with metal powders as well as with basalt compounds.

Additional supporting factories will be:

- Glass Factory
- Insulation material factory
- Paint factory

The output of the beneficiation plant allows for more useful products to be manufactured, which will further allow the reduction of terrestrial imports, but also for the generation of a growing cislunar economy. The key to getting lunar production started is energy. Thus, the early production of solar panels, propellant and basalt for structural purposes will be key drivers of the GE⊕-LPS production and for further growth of a lunar economy.

11.3.16. Fabrication Zone

All non-propellant production will be located at a linearly organized fabrication zone to create synergies for material logistics, energy and heat management as shown in Figure 64. 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 factory to another as in Figure 65. 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.

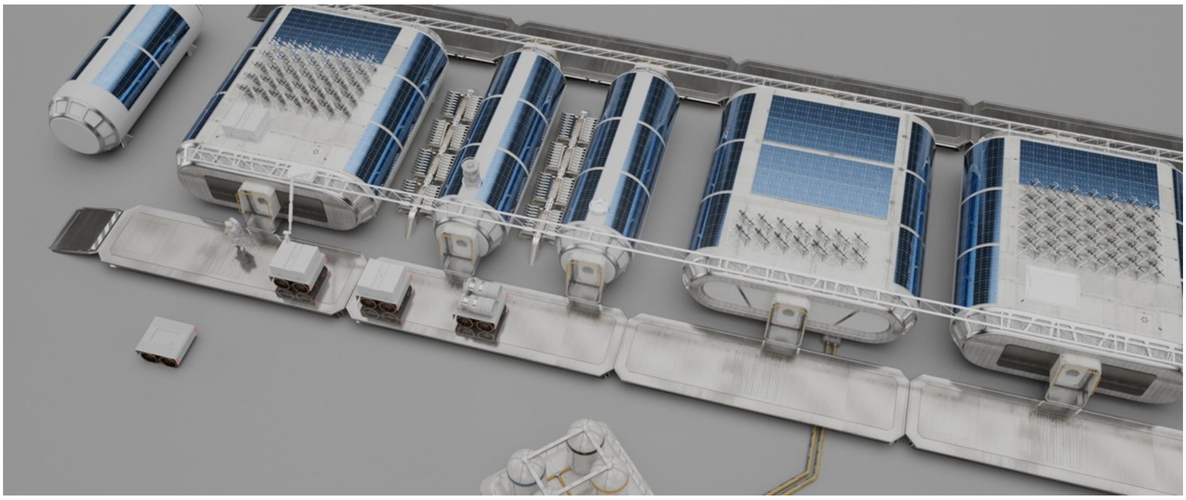


Figure 64: Linear organisation of factory modules. (Credit: Astrostrom)

The linear arrangement can be expanded to both sides as needed. It can also be mirrored sideways for further growth. The principal production within the factories was described in work package 2.

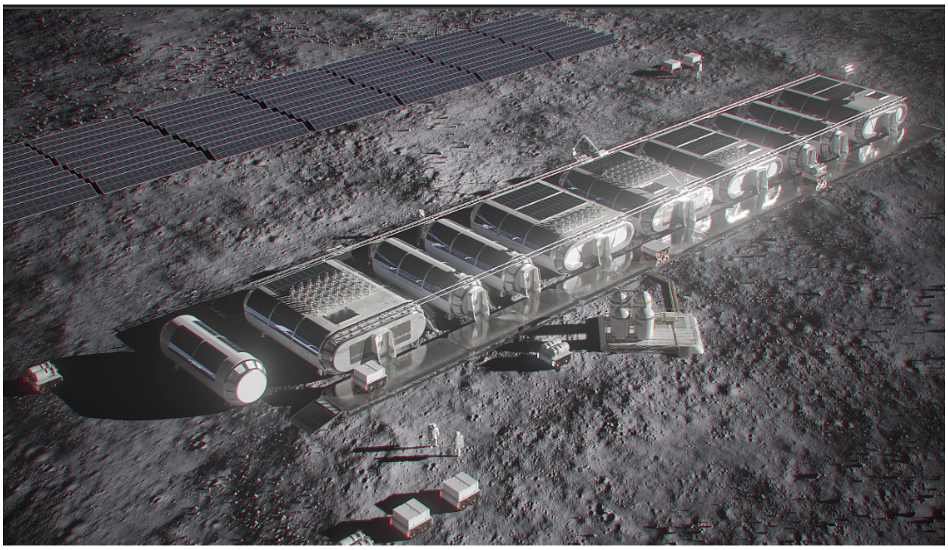


Figure 65: Fabrication zone with delivery and unloading robots. (Credit: Astrostrom)

11.3.17. Lunar Surface Habitat

The surface habitat for the GE⊕-LPS programme will come highly preconfigured in the payload bay of a heavy-lift rocket such as the SpaceX HLS or similar. After landing, the rocket will be lowered and positioned horizontally with the aid of inflatable cushions as shown in Figure 66.

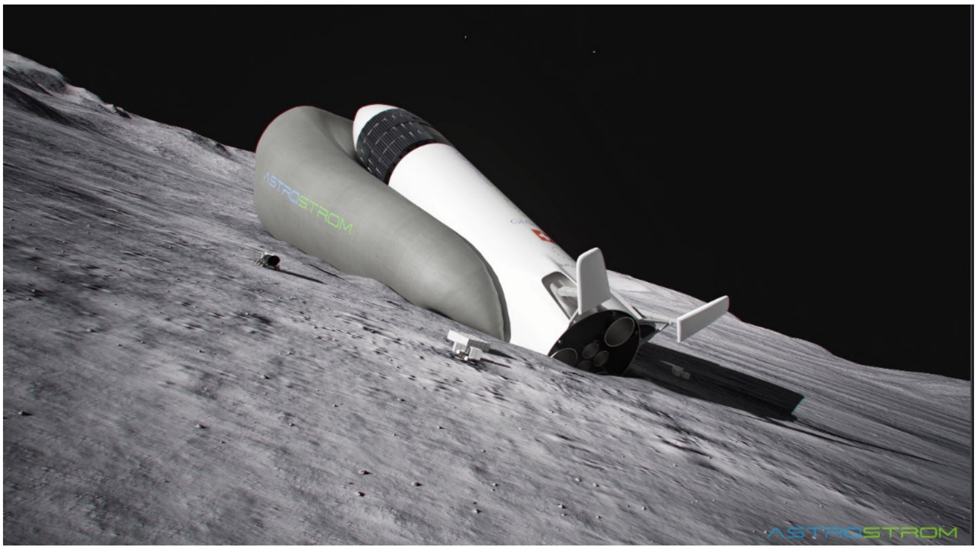


Figure 66: Lowering the rocket vehicle via an inflatable cushion. (Credit: Astrostrom)

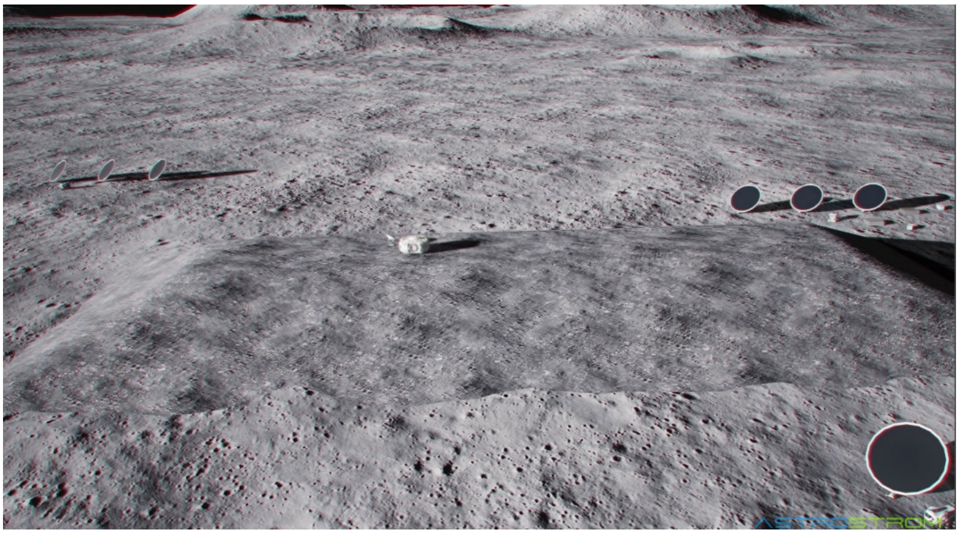


Figure 67: Habitat with regolith radiation protection. (Credit: Astrostrom)

The habitat will be protected with a layer of regolith as shown in Figure 67. The three astronauts, who are the maintenance engineers for the robot fleet and later the automated fabrication, will start work by arranging the habitat outfitting. Meanwhile the construction robots and mining robots start covering the rocket fairing with regolith for radiation protection. The empty fuel tanks of the rocket will be later converted to greenhouses and expand the existing small ECLSS System. This will allow the habitat to host more people over time. A similar concept to convert the Starship into a habitat was published in April 2023 by a group of researchers *(Monat, S., et all, 2023).*

The GE⨁-LPS Lunar Surface Habitat operates under 1/6 g conditions. The crew will be mainly occupied with keeping the mining robots, the processing and the fabrications systems running. Thus, it can be assumed that extravehicular activities will be on a daily basis. For the lunar dust contamination, suitports as well as a dock to a pressurized rover will be provided. This habitat could be built, using a redundant rocket fairing, which is covered by regolith for radiation protection. It is assumed, that it will be in cylindrical shape.

A functional diagram is shown in Figure 68. Currently a modularity for growth is not foreseen. However, when the GE⨁-LPS project may progress, there may already be several preceding lunar missions with a possible habitat evolution and standard docks, which may lead to a meaningful combination and create lunar village.

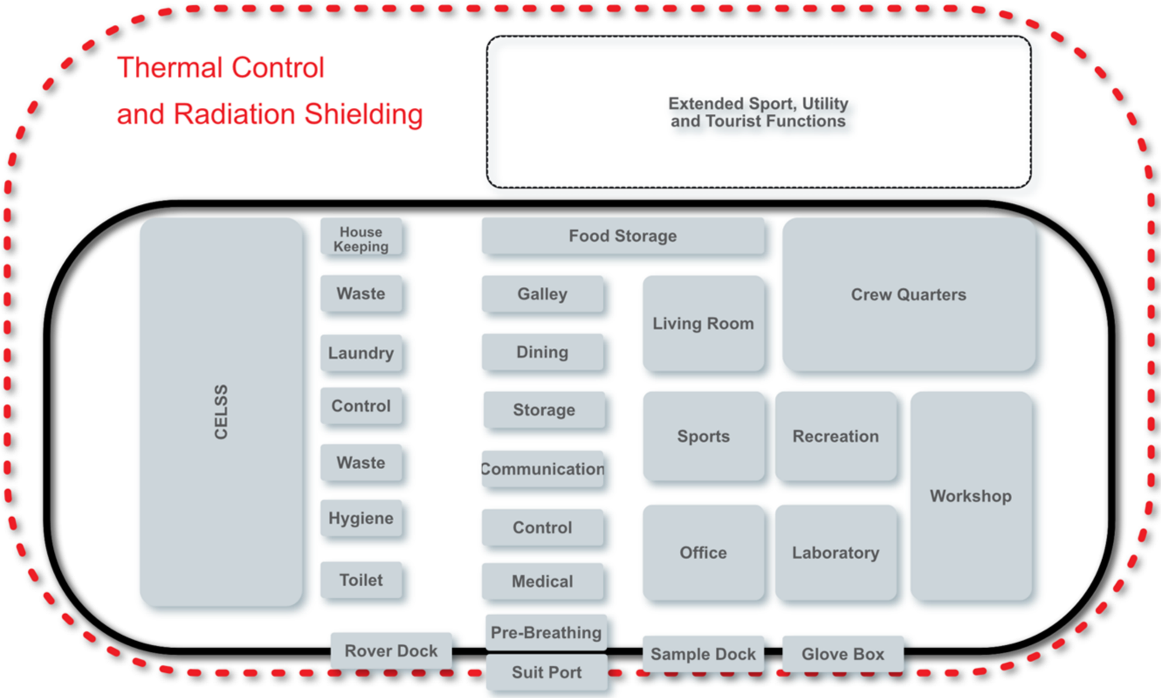


Figure 68: GE⊕-LPS Lunar Surface Habitat, functional diagram. (Credit: Astrostrom)

11.3.18. Surface Mobility

The GE⊕-LPS surface mobility will be built up on wheeled robots with the same chassis. This will allow economies of scale and also interoperability of the robots. Thus, according to need mining robots can become transportation or armed robots and vice versa. The robots are powered by exchangeable batteries, which they receive from a mobile battery charging station.

11.3.19. Mining Robots

During the study large-scale surface miners have been examined. However, light weight and small-scale robotic soil collection system appeared be more favourable. The NASA RASSOR robot is already quite developed. The system is capable of standing up in a vertical position to dump its contents into a receiving hopper without using a ramp. This eliminates the need for an onboard dumping bin, thus reducing complexity and weight. During loading, the bucket drums excavate soil/regolith by scoops mounted on the drums exteriors that sequentially take multiple cuts of soil/regolith while rotating at approximately 20 revolutions per minute. During hauling, the bucket drums are raised by rotating the arms to provide clearance above the surface being excavated. The mobility platform can then travel while the soil/regolith remains in the raised bucket drums. When the excavator reaches the dump location, the bucket drums are commanded to reverse their direction of rotation, which causes soil/regolith to be expelled out of each successive scoop. RASSOR has wireless control, telemetry, and onboard transmitting cameras, allowing for teleoperation with situational awareness. The unit can be programmed to operate autonomously for selected tasks (NASA, RASSOR 2013).

For the GE⊕-LPS mining a larger, slightly more powerful version of the RASSOR as shown in Figure 69 would be employed. The robot is a combined mining robot and transportation robot.

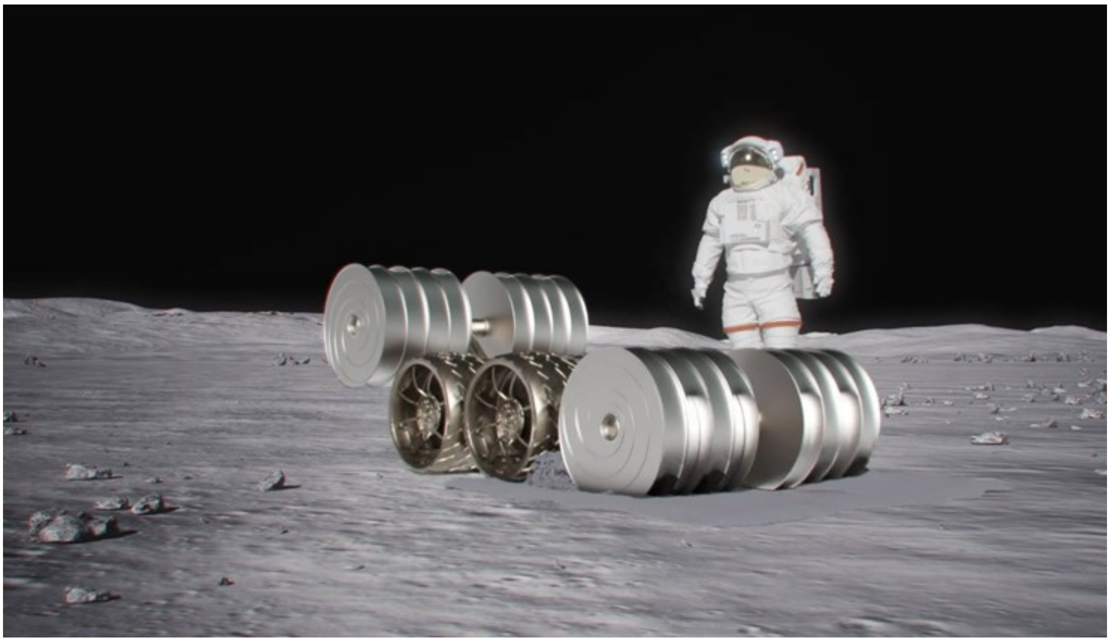


Figure 69: Astrostrom's Mining Robot as seen in the First Steps Video. (Credit: Astrostrom)

11.3.20. Logistics Robots

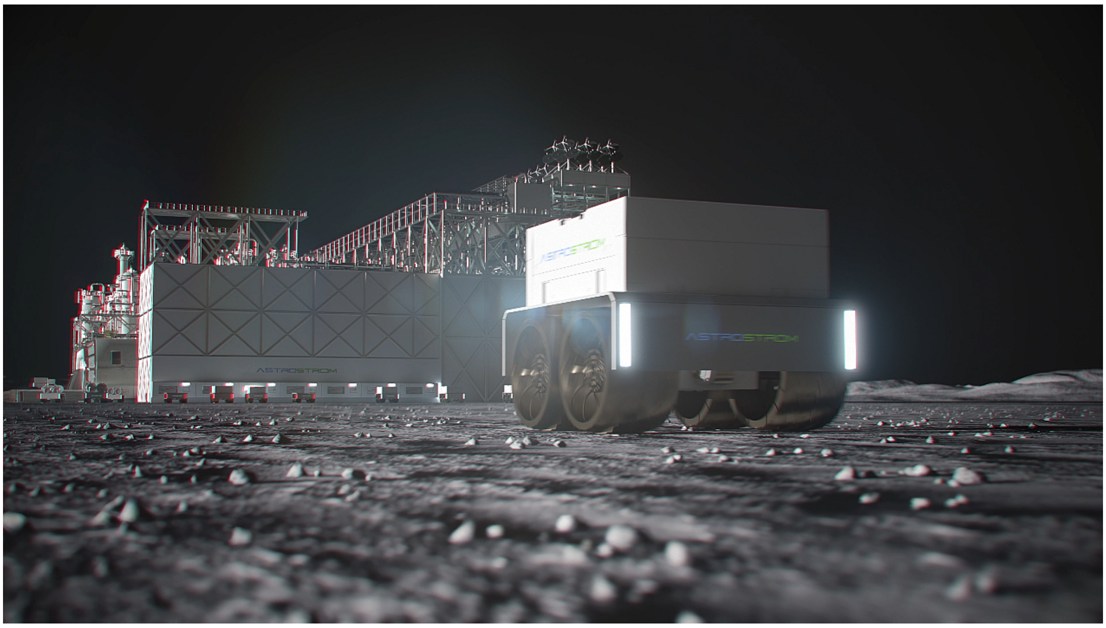


Figure 70: Logistic Robot transporting material from processing plant to fabrication facility. (Credit: Astrostrom)

The logistics surface robots are used for all cargo mobility task on the site. They collect the refined materials from the beneficiation plant and transport them to the factories. They also pick up the finished components and transport them to the LSE surface station. Further they can pick up larger modules landed by the Lunar Landing Gantry and transport them to their destination. They share the same chassis as the RASSOR robots; however they have dust protectors. Some of them will be equipped with one or two robot arms to pick up stones or handle other situations like stuck robots etc.

11.3.21. Road Work Robots

For the roadworks, a RASSOR type robot can be used to level the road. A transportation robot equipped with a robot arm located at the front would pick up loose stones and fill holes with it. After the levelling work is done a sintering robot follows and sinters the road with microwaves. The inflatable mobile PV devices largely deliver the necessary power.

11.3.22. Unpressurized Rover

For the human crew a unpressurized rover will be necessary, which allows fast movement on the surface in space suits. It would mainly be used for maintenance and surveillance tasks.

11.3.23. Pressurized Rover

For longer tasks, a pressurized rover for the crew will be needed. It will be equipped with two suitports and will be able to support up to three astronauts for up to 10 days. This allows longer excursions as well as a backup location for any emergencies in the habitat.

11.3.24. LSE Surface Station

The LSE Surface Station is located next to the landing zone of the main departure and arrival point for the cargo. Here the lunar side of the LSE tether is anchored to the Moon. The transportation robots bring the components the LSE surface station, where it will be transferred by a robot arm. As soon as a climber arrives, the arriving cargo (if any) will be unloaded by this robot arm and the climber reloaded with new cargo. With an intermediate station situated at 5,000 km distance, this process could happen about 4 times per sol. When the LSE is expanded there could eventually be 8 or 16 additional tethers arranged in parallel in a circular formation around the original tether.

11.4. Cislunar Space Facilities

The GE⨁-LPS cislunar space facilities described here are the ones at EM-L1. (For the LEO Cargo Relay Station refer to the GE⨁-Cislunar Transportation System.)

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 shot from the Moon shouldn't 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.

However, there are numerous additional reasons why EM-L1 is an important part of a cislunar economy, as mentioned in the Space Review article by Ken Murphy, 2011:

1) In terms of propellant, it is cheaper to go from EM-L1 to GEO and back to EM-L1 than it is merely to go from LEO to GEO. Over the long term, it makes sense to stage GEO operations from EM-L1. It makes especially sense for SPS, which will be most likely located in GEO.
2) The time lag from EM-L1 to the Moon and back is much less than that for Earth-Moon. As a result, it is a better location for safe teleoperation of robots on the lunar surface.
3) EM-L1 is an on-ramp to what are known as the Interplanetary Superhighways (IPS). These are a network of ridges and ripples in space created by the gravitational effects of the planets and Sun. A satellite pushed onto the IPS will travel very, very slowly along this network to its destination, where it can kick itself into a halo orbit around a Lagrange point and collect data. Locations of interest would include the Sun-Mars L-2 and Sun-Jupiter L-1, to observe the Asteroid Belt; the Sun-Venus equilaterals at L-4 and L-5 to provide communications relay when Mars is on the other side of the Sun from Earth; Sun-Saturn L-2 to look at the Kuiper Belt; Sun-Neptune L-2 to look at the Oort Cloud; Sun-Mars L-1 as a waypoint on the way to Mars and the Asteroid Belt; Sun-Earth L-1 to watch the Sun; Sun-Earth L-2 to watch the stars. The key is that all these instruments would also be able to return via the IPS to EM-L1 for regular maintenance and servicing. As more probes are added to the network, instead of being discarded into the void, there will be an increasing stream of probes in need of work.
4) As lunar activities ramp up, there will be an increasing need for freight handling of goods destined for the Moon, as well as those from the Moon. Early lunar exports are likely to be low-value-added goods such as oxygen, water, raw regolith, and some metals, but as more capabilities are established the exports will start creeping up the value-added chain: foodstuffs from lunar greenhouses, unique crafts created locally from local materials, increasingly sophisticated entertainment like dance and other low-gravity performances, and so forth.
5) EM-L1 is an ideal location to aggregate mission components for a trip to an asteroid. Propellants can come from the Moon, while spacecraft come from Earth.
6) A facility at EM-L1 can serve as a communications node for lunar operations to overcome the line-of-sight issue. Additionally, with solar sails "pole-sitting" above the north and south lunar poles, communications with the far side can be established.
7) Port services. While probes returning on the IPS will end up in the neighbourhood of EM-L1, they will need to be picked up. The same applies to free-flyer platforms sent on low-energy trajectories around the Moon for production runs. A space tug would be a good tool to have, and pilots will be needed to fly it.

GE⊕-LPS Cislunar Space Facilities include:

- EM-L1 Hub Station
- The GE⊕-LSE
- LPS Construction Site
- Construction Robots
- LPS

11.4.1. The EM-L1 Hub Station

The EM-L1 Hub Station serves as an intermediate relay station integrated into the elevator construction. The EM-L1 Hub Station will have storage facilities for supplies and propellants. It will have docking ports for the Lunar Landing Gantry and the Cislunar Cargo Shuttle. It will contain a habitat.

Construction can start with a triangular truss of identical dimensions to the rim truss of the GE⊕-LPS. A robot arm can travel on that beam and exchange cargo with the Lunar Landing Gantry. The cargo can be fixed on the truss for later use as shown in Figure 71. This singular truss can grow and form a triangle with the main tether of the GE⊕-LSE passing through its center. Thus, the robotic arms can also reach the elevator climbers. This system can continue to grow at its periphery, but also along the elevator axis. A standard payload interface would have to be developed to allow different cargo types to be attached to the truss. Additionally, a habitation module can be attached as well.

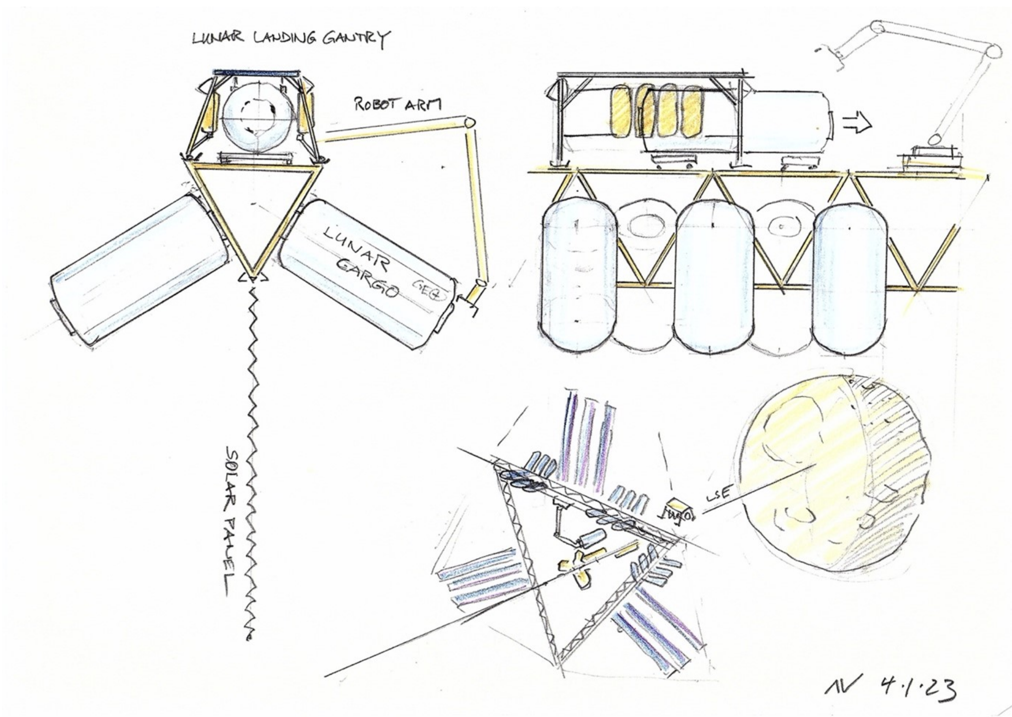


Figure 71: The EM-L1 gateway station can start with a simple truss and grow from that. (Credit: Astrostrom)

The GE⊕-LSE will be deployed from the EM-L1 Hub Station by extending the cables simultaneously Earthwards and Moonwards. The EM-L1 Hub Station surrounding the GE⊕-LSE will have storage racks and robotic arms loading and unloading the climbers.

11.4.2. The GE⊕-LPS Construction Site

The GE⊕-LPS construction site is a few 100 meters to the side of the GE⊕-LSE Central Station. Cargo transporter robots bring the elements manufactured on the Moon via the elevator to the construction robots which assemble the GE⊕-LPS supporting structure and deploy the hybrid PV-antenna elements as shown in Figure 72. The construction will start from the center with two main axes. Then from the ends of the axes a ring beam is started. Another scenario is also possible, whereby the hybrid PV-antenna elements are already deployed while the ring beam is being constructed. In this case, energy could be sent to the lunar surface already during the construction phase.

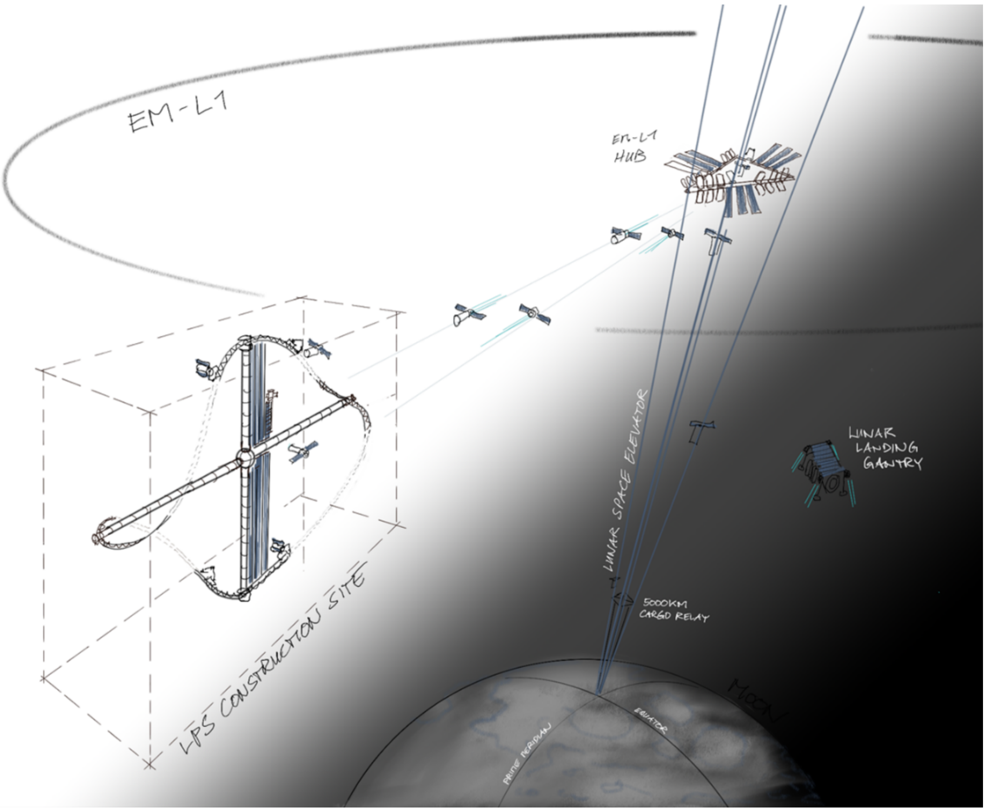


Figure 72: Sketch showing the LPS construction site at EM-L1 with the Lunar Space Elevator in the background. Cargo shuttles are bringing the elements from the EM-L1 hub to the construction robots, where they are assembled. (Credit: Astrostrom)

11.4.3. EM-L1 SPS Assembly Site

Over the near-term, the utility of EM-L1 is constrained by a lack of physical infrastructure. However, as the hub of the GE⊕-CTS and the arrival point of the of the Lunar Space Elevator this will change, as it becomes the ideal construction site for for Solar Power Satellites destined for Earth energy needs. Lunar sources and manufactured components for the solar power satellites will be transported via the GE⊕-LSE to its hub at EM-L1 and then dispatched to assembly locations connected to the GE⊕-LSE or placed in a halo or Lissajous orbit. Most of the orbital assembly work will be carried out by robots under the supervision of a small human crew that is there to ensure quality operations and to troubleshoot possible unforeseen technical challenges.

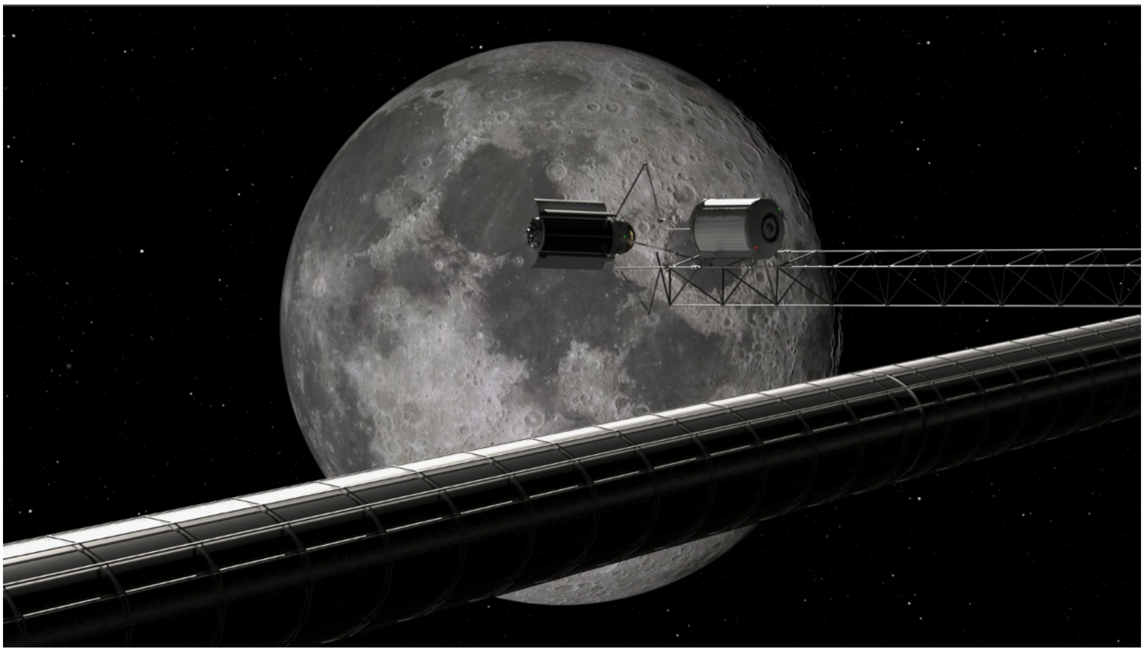


Figure 73: Construction of a Solar Power Satellites at EM-L1 (Credit: Astrostrom)

Once the construction of an SPS has been completed it can be gently transferred from EM-L1 to GEO using a rocket powered transfer vehicle or space tug and integrated ion drives powered by its own solar generation.

11.4.4. Construction Robots

One 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 74. 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 75.

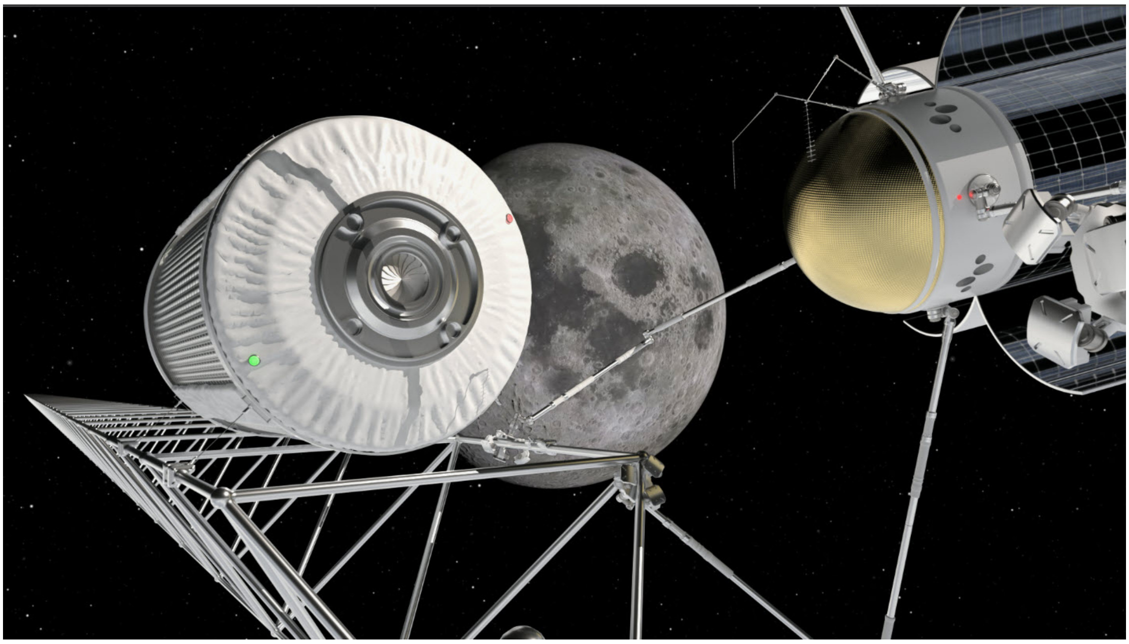


Figure 74: Construction robot assembling the ring truss of the GE⊕-LPS. (Credit: Astrostrom)

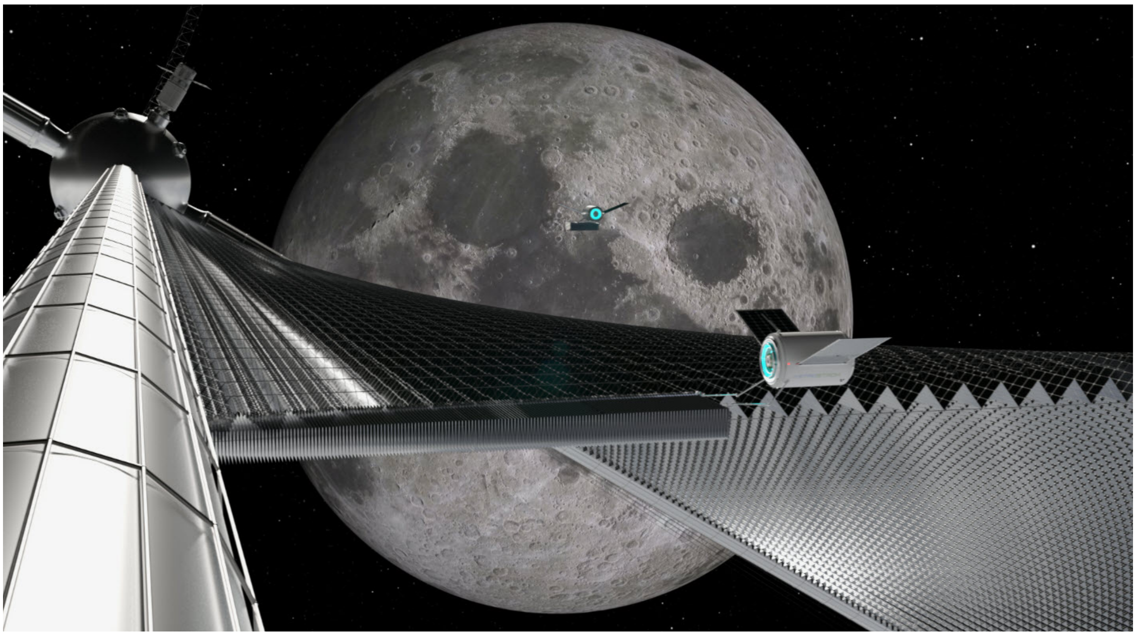


Figure 75: Small robot with ionic drive deploying the hybrid PV-antenna modules. (Credit: Astrostrom)

11.4.5. The GE⊕-LPS

Once the GE⊕-LPS is constructed it will be repositioned to a longer distance from the GE⊕-LSE, but still within the influence of the Lagrange point. As shown in Figure 76, it will beam power down to the rectenna located near the prime meridian at the equator to deliver baseload energy to the lunar grid.

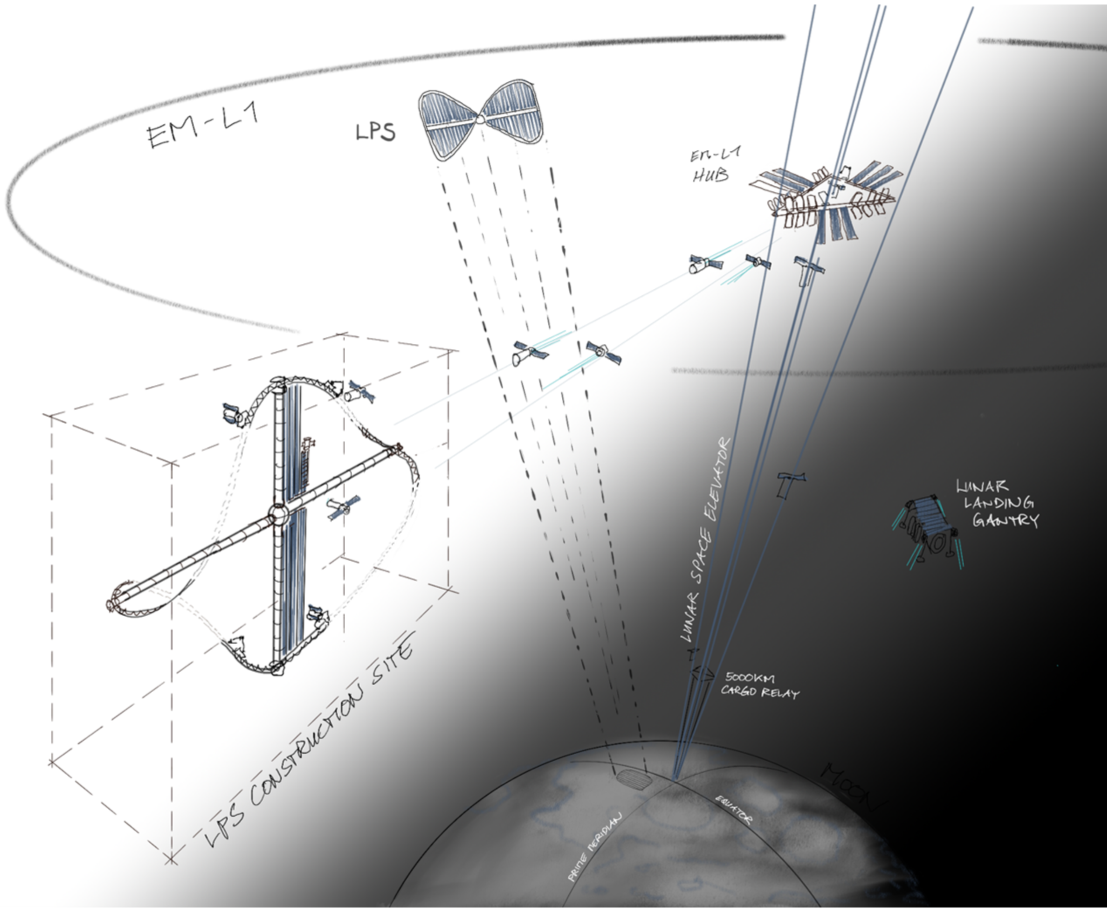


Figure 76: Sketch of finished GE⊕-LPS. In the background, beaming energy down to the rectenna on the Moon. (Credit: Astrostrom)

11.5. The GE⊕-LPS Construction System

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.

The GE⊕-LPS Construction System will allow the construction of similar masts for illumination and survey as well as for tramways, towers, bridges, cargo and maintenance hangars, cranes, supporting structures for machinery in mining, beneficiation and manufacturing as well as the central and outer rims for the GE⊕-LPS as shown in Figure 77.

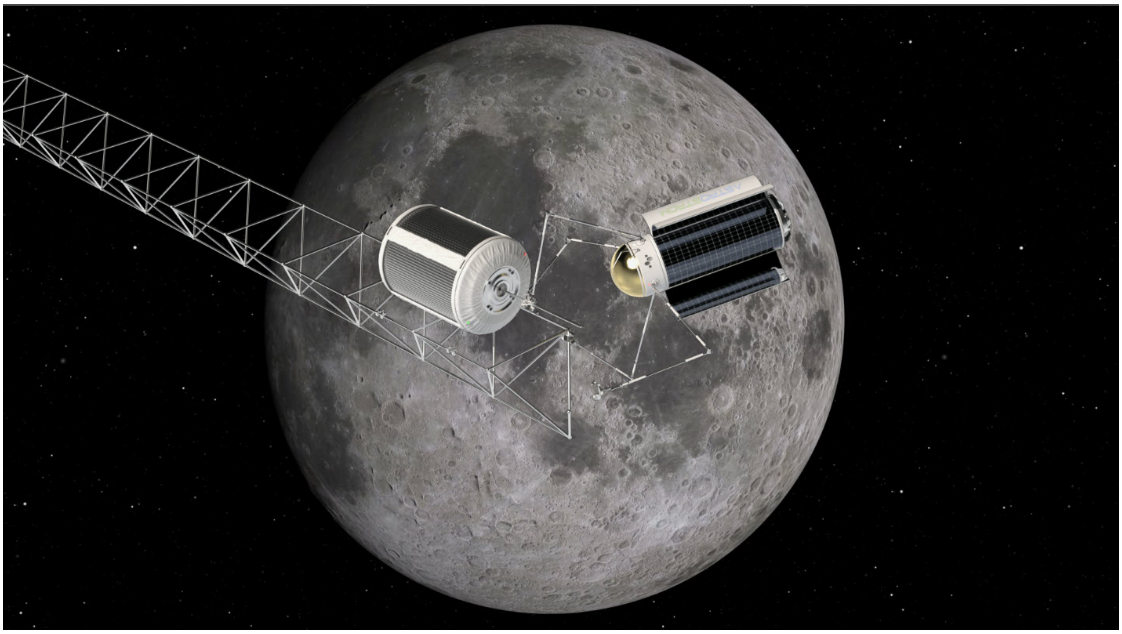


Figure 77: Robotic construction of the outer rim of LPS with the GE⊕-LPS Construction System.
(Credit: Astrostrom)

11.5.1. Initial Habitat Integration

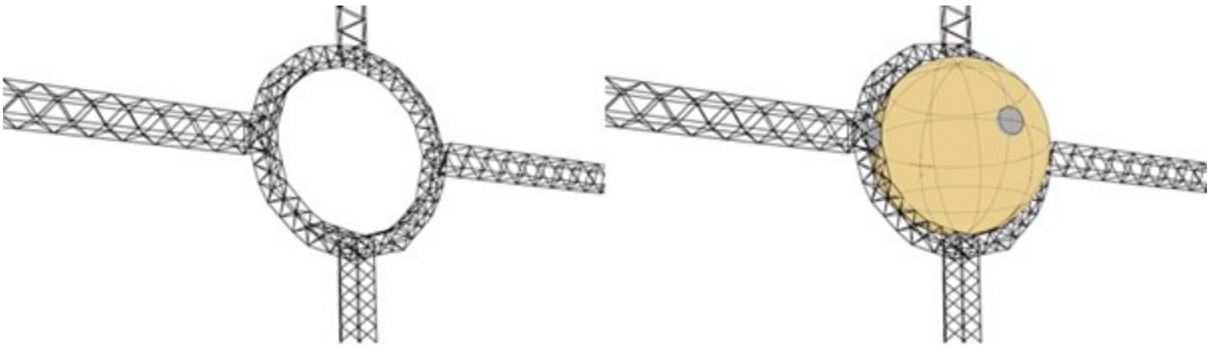


Figure 78: Framework at the center of GEO-LPS (left) and with deployed habitat bladder on the right.
(Credit: Astrostrom)

At the core of the GE⊕-LPS power satellite is the habitat. It is also where the construction process begins. Using the GE⊕-LPS Construction System, a dodecagonal ring truss of 18 m inner diameter will be built. From there the longitudinal and the cross axis will be constructed simultaneously in all directions. Within the ring truss the inflatable bladder of the habitat the habitat will be deployed. The habitat bladder will be delivered folded from Earth with less than 18m diameter, and with six ports in all directions. Once deployed and attached to the GE⊕-LPS space frame, installation of basalt fibre insulation plates and cladding with aluminium-based, sintered regolith tiles for radiation shielding can start. As a substructure for the cladding a geodesic framework can be built around the inflated bladder.

As the outside cladding is finished, the interior fitting-out starts. First the ECLSS system will be installed and brought into operation, so further EVA-suit-free fitting-out is possible. The interior structure will be built up with aluminium and cast basalt tiles produced on the Moon.

In the sphere with a diameter of approximately 18 meters, 5 floors will be deployed with varying ceiling heights.

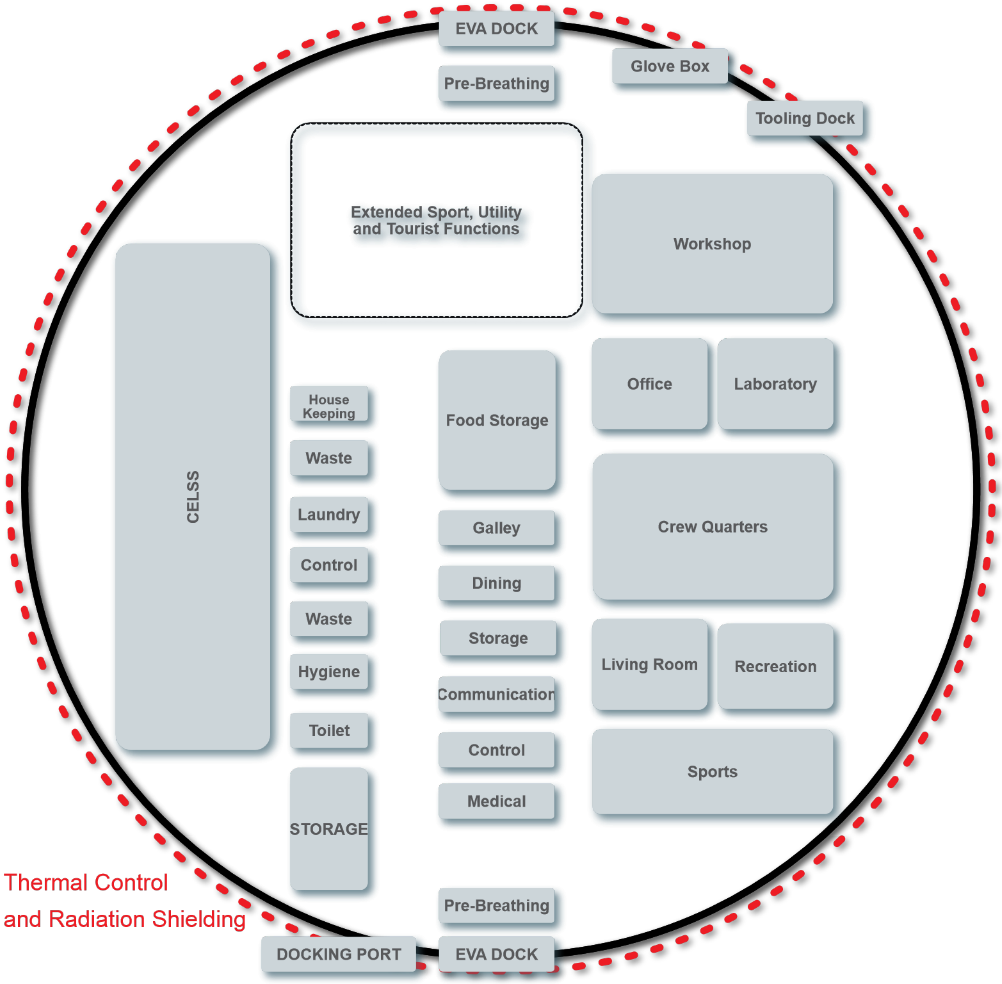


Figure 79: Diagram showing the basic initial habitat functions. (Credit: Astrostrom)

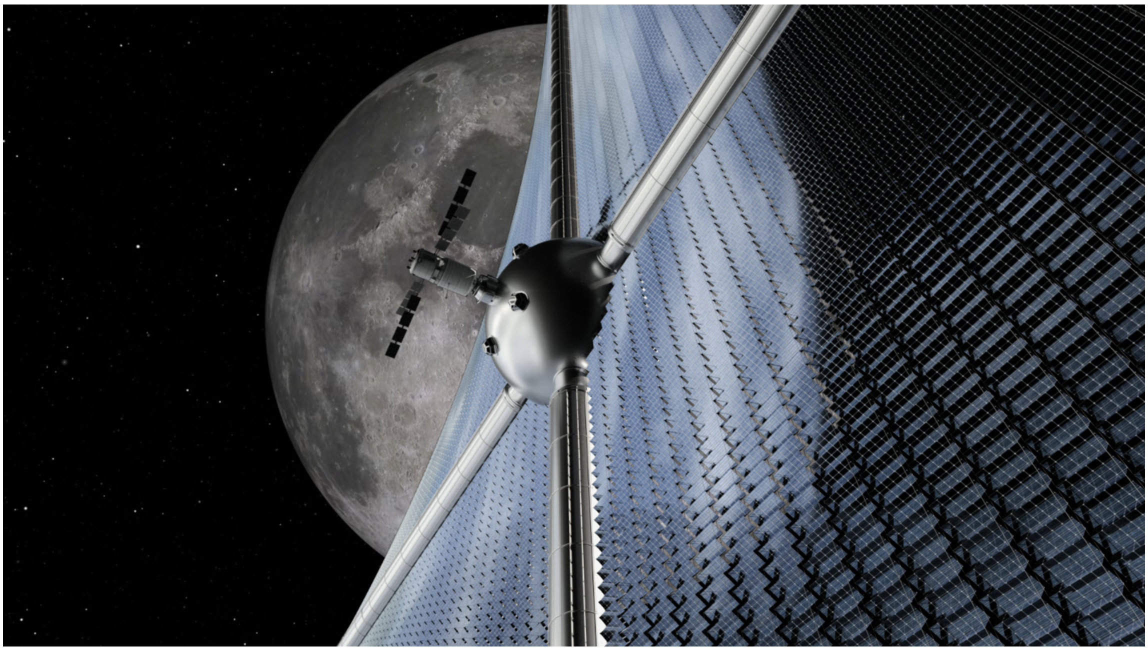


Figure 80: Artist's impression of the habitat at the centre of GE⊕-LPS with Crew Transfer Vehicle docked. Notice the viewing cupolas on the sphere. (Credit: Astrostrom)

11.5.2. The GE⊕-LPS Solar Energy Collector & Transmit Antenna

The idea of the V-shape solar-antenna elements has been outlined in the Section 9.2. Here we outline a concept panel – which still must be verified in engineering and production – to spark new thinking towards the development of SPS.

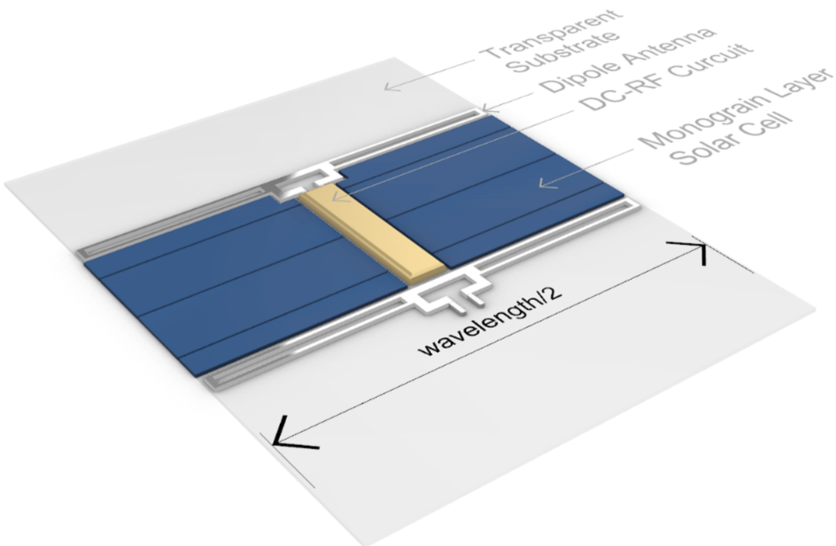


Figure 81: Baseline design of the solar-antenna element. (Credit: Astrostrom)

The pull-technology idea is to print the photovoltaics, the electronics and the antenna onto a transparent thin film substrate as shown in Figure 81. For these substrates polyimide is used on Earth. It needs to be investigated to what extent this or a similar carrier could be produced from lunar materials like chemically strengthened glass. The monograin layer 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.

This element can basically operate independently and can be mass-produced. However, each element will be interconnected with a bus system to optimize the beam generation and steering according to the retro-directive pilot beam received.

11.5.3. Outline of a Baseline Process for Continuous Production

The above element gets repeated, so it fits on a 26 cm wide film, which can be printed continuously as shown in Figure 82.

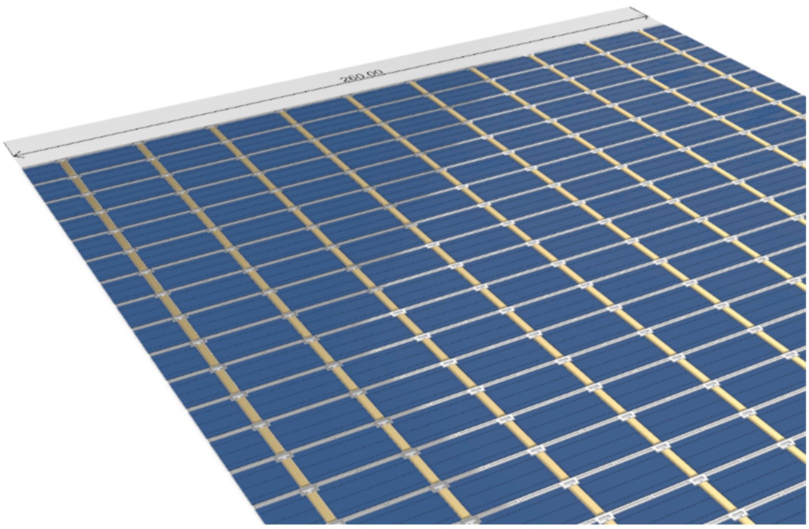


Figure 82: Continuously printed film with the solar-antenna element. (Credit: Astrostrom)

Inkjet-printing, which is well known from home and office applications, is one candidate for this production. During the recent decade, inkjet technology has made large inroads into the industrial domain. Several research studies at the laboratory or industrial scale demonstrate the strong advance of digital and specifically of industrial inkjet printing. In fact, inkjet has become a mature technology for graphical applications. Even in functional printing like printed electronics, 3D, and bio/pharma/medical applications, there have been successful implementations of inkjet technology.

It works by generating small droplets with high frequency to realize a pattern. The inkjet-printing heads are made of one or several nozzles generating droplets. In particular, there have been several successful publications using inkjet printing to manufacture PVs where the droplets are widely generated on demand (called drop-on-demand, DOD). The most recent ink-jet printing technology uses piezoelectric crystals to form the droplets. Under an electrical field, a piezoelectric material is mechanically deformed. First, applying a negative voltage on the piezoelectric crystal allows filling the nozzle by decreasing its pressure. Then, a positive voltage leads to the droplet expulsion by increasing the pressure inside the nozzle. Inkjet-printing is a fully digital printing technique. The desired pattern is obtained using software: no mask or cylinder is required. More importantly, several studies have proven the great advantage of inkjet printing as a digital technology allowing freedom of forms and designs: large area PVs with different artistic shapes were already demonstrated.

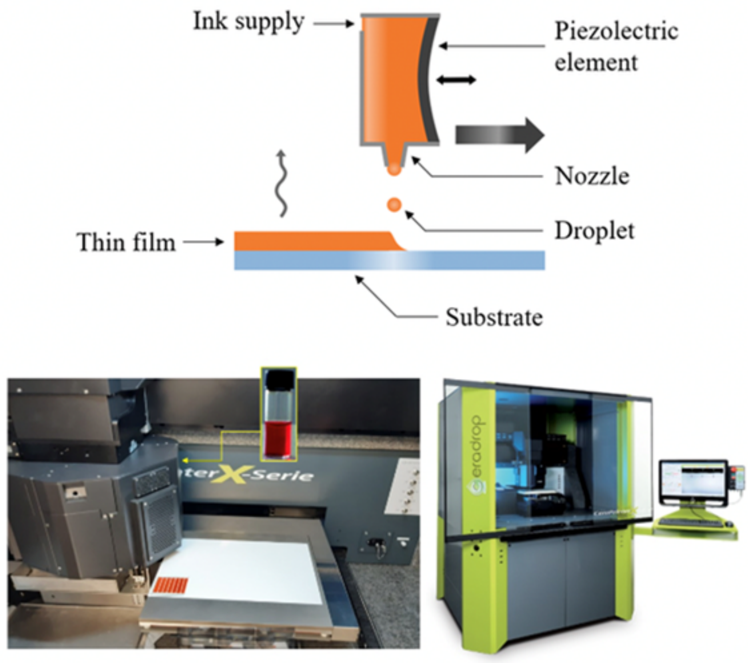


Figure 83: Roll-to-Roll Processing

Considering that large area formation and roll-to-roll (R2R) processing can be done by inkjet printing, it can be a good choice for preparing homogeneous and thin layers for constructing PV modules. R2R is a well-established process used for instance for the printing of newspapers. For this process, the flexible substrate is a continuous roll of material. It requires a high amount of material and allows the production of large-scale modules, as needed for GE⊕-LPS. As a failure during the run could impact the whole production, discrete R2R could be preferred. After this, testing of the panels will be performed with light and a rectenna. In case there is a failure detected, the process can stop immediately. The faulty strip would be cut, removed, and the remaining roll would be bonded together again.

After R2R printing the solar-antenna-element goes through a folding machine, where the material is pre-folded by 60-degree angles as shown in Figure 84.

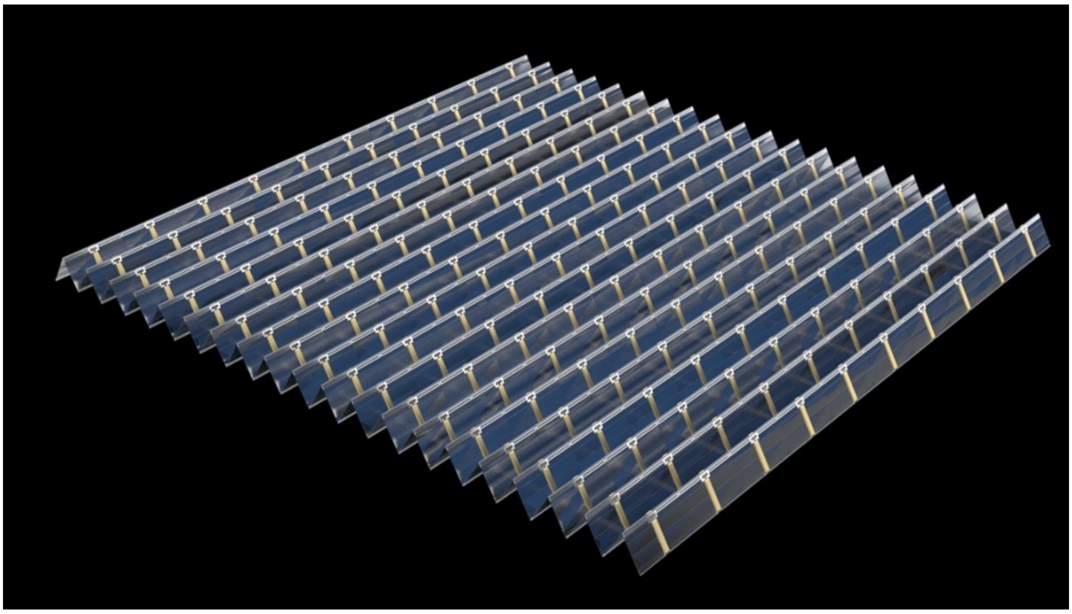


Figure 84: Section of a V-shaped solar-antenna element. (Credit: Astrostrom)

11.6. Scalability: From GE⨁-LPS to GE⨁-SPS

The main scalability options for producing a GE⨁-SPS (Greater Earth Solar Power Satellite) are the efficiency of the photovoltaics and the size of the power station. The efficiency of the photovoltaics has technological limits but are expected to improve over time and the size has limits posed by solar winds and maneuverability of a too large structure. The following shows the scaling of the basic "Butterfly" GE⨁-LPS concept extrapolated towards a GE⨁-SPS system supplying energy to Earth using MGL photovoltaics with AM0 3.7%, AM0 6.7%, AM0 13% and AM0 21%, and with diameters up to 5,000 meters. Transmitting power from the SPS in GEO to Earth has a DC-DC efficiency of approximately 57%. *(DoE, 1978 58%, Frazer-Nash, 2022 56%)*

By manufacturing the GE⨁-SPS from mostly lunar resources there would be more flexibility for deciding the size of the power satellite. In addition to scaling the size of the SPS to achieve higher power output for terrestrial energy production, the lunar fabrication facilities will need to be expanded accordingly.

Solar Collector Diameter: 1,000 m
Radius a: 500 m, Radius b: 587 m
Optimized PV Surface Area: 469,429 m^2
50W/m^2 = ca. 22.1 MW at SPS or 13 MW at the rectenna
91W/m^2 = ca. 40 MW at SPS or 23 MW at the rectenna
180W/m^2 = ca. 80 MW at SPS or 45 MW at the rectenna
286W/m^2 = ca. 127 MW at SPS or 72 MW at the rectenna

Solar Collector Diameter: 2,000 m
Radius a: 1,000 m, Radius b: 1174 m
Optimized PV Surface Area: 1,303.969 m^2

$50W/m^2$ = ca. 88.5 MW at SPS or 71 MW at the rectenna
$91W/m^2$ = ca. 161 MW at SPS or 92 MW at the rectenna
$180W/m^2$ = ca. 319 MW at SPS or 182 MW at the rectenna
$286W/m^2$ = ca. 506 MW at SPS or 289 MW at the rectenna

Solar Collector Diameter: 4,000 m
Radius a: 2,000 m, Radius b: 2,348 m
Optimized PV Surface Area: 7,902,844 m^2
$50W/m^2$ = ca. 354 MW at SPS or 202 MW at the rectenna
$91W/m^2$ = ca. 645 MW at SPS or 367 MW at the rectenna
$180W/m^2$ = ca. 1,275 MW at SPS or 723 MW at the rectenna
$286W/m^2$ = ca. 2,026 MW at SPS or 1,155 MW at the rectenna

Solar Collector Diameter: 5,000 m
Radius a: 2,500 m, Radius b: 2,935 m
Optimized PV Surface Area: 12,348,193 m^2
$50W/m^2$ = ca. 553 MW at SPS or 315 MW at the rectenna
$91W/m^2$ = ca. 1,007 MW at SPS or 574 MW at the rectenna
$180W/m^2$ = ca. 1,992 MW at SPS or 1,136 MW at the rectenna
$286W/m^2$ = ca. 3,165 MW at SPS or 1,804 MW at the rectenna

Using the 'GE⊕-LPS Test Specifications' from Section 11.1 which indicates a specific power output of 222 W/kg, a GE⊕-SPS providing 1.44 GW of power would have a mass of about 6,486 MT. With further development in lunar-sourced photovoltaics and technical enhancements to the helical SPS designs, the above power levels may be further enhanced by adding solar concentrators (mirrors) to the GE⊕-SPS system.

The initial design of the GE⊕-LPS transportation and production systems has been conceived with modular expandability in mind. For more intensive mining operations, more and/or larger mining robots can be employed. Beneficiation is conceived in a modular industrial plant with a structural rack system which can be easily expanded as required. Factories are modular units in a linear arrangement, so if the output needs to be increased more modules can be added.

The capacity of the transportation system can be expanded by using more rockets. The EM-L1 space facilities are conceived to grow from the arrival point of the Lunar Space Elevator in a radial manner. The expansion of the LSE will need to be studied in more detail, but this would seem possible once a base system is installed.

11.7. SPS Transfer to GEO

Once a GE⊕-SPS is finished it will need to be transferred to GEO to enter operation. The delta-v required from EM-L1 to GEO is 1,380 m/s with chemical propulsion using the Oberth effect. Current electric ion thrusters produce a very low thrust (milli-newtons, yielding a small fraction of a g), so the Oberth effect cannot normally be used. This results in the journey requiring a higher delta-v and frequently a large increase in time compared to a high thrust chemical rocket. Nonetheless, the high specific impulse of electrical thrusters may significantly reduce the cost of the flight. For missions in the Earth–Moon system, an increase in journey time from days to months could be unacceptable for human spaceflight but could be sufficient for cargo. The delta-v needed for ion thrusters from EM-L1 to GEO is in the region of 1,400 – 1,750 m/2 *(Delta-v budget, 2023).*

More detailed calculations have to be done, but it is assumed, that all available Cislunar Cargo Shuttles could be joined on their way back to LEO-CRS and could produce at least a part of the necessary delta-v for the given mass of the SPS. Additional chemical propulsion may be needed. Like this the SPS could go immediately into operation once arriving at GEO.

An alternative and plausible scenario would be to also assemble SPSs in GEO in parallel. This would allow a faster construction of the additional SPSs to meet Earth's energy goals. The Cislunar Cargo Shuttles would always be ensured to have cargo on their way back to LEO-CRS. Additionally, once the LSE is extended near to GEO, cargo shuttles can pick up the components there and bring these to GEO. Using one or both of the equilibrium points in GEO, the assembly conditions would be very similar to EM-L1. With this parallel assembly scenario and a increased transportation and production over time, the GE⊕-SLPS system would gradually increase capacity and production.

11.8. Technology Readiness Assessment of Relevant Technologies

11.8.1. Technology Readiness Level: Definitions and Explanations

TRL	ISO standard 16290:2013 Definition	Explanation
1	**Basic principles observed and reported**	Scientific research begins to be translated into research and development.
2	**Technology concept and/or application formulated**	Practical applications can be invented, and research and development started. Applications are speculative and may disproved.
3	**Analytical and experimental critical function and/or characteristic proof-of-concept**	Active research and development is initiated, including analytical / laboratory studies to validate predictions regarding the technology.
4	**Component and/or breadboard functional verification in laboratory environment**	Basic technological components are integrated to establish that they will work together in a laboratory environment, which is highly controlled. Bench scale.
5	**Component and/or breadboard critical function verification in relevant environment**	The basic technological components are integrated with reasonably realistic supporting elements so they can be tested in a simulated environment, more like the target environment. Pilot scale (power/dimension).
6	**Model (physical prototype) demonstrating the critical functions of the element in a relevant environment**	A representative model or prototype system is tested in a relevant environment. This is either exposed to the analogous environmental conditions on Earth for ground systems, or in space for satellite systems with conditions analogous to GEO. e.g. for satellite technologies, they have been operated in space, either in isolation or as part of another system. Pilot scale (power/dimension).
7	**Model (physical prototype) demonstrating the element performance for the operational environment**	System prototype demonstration in a space environment. A prototype system that is near, or at, the planned operational system. At or near full scale.
8	**Actual system completed and accepted for flight ("flight qualified")**	In an actual system, the technology has been proven to work in its final form and under expected conditions, through test and demonstration (ground or space). Full Scale.

9	**Actual system "flight proven" through successful mission operations**	The system incorporating the new technology in its final form has been used under actual mission conditions. Full scale.

Table 9: Technology Readiness Level: Definitions and Explanations

Development Degree of Difficulty	Definition
Very Low	There are no unknowns that require further work to allow this technology to be deployed. Increasing the scale of deployment is not considered a challenge.
Low	There are few unknowns that require further work to allow this technology to be deployed at scale, and there is a straightforward approach to addressing them. Increasing the scale of deployment is not considered significantly challenging.
Medium	Some further work is required to perfect this technology and, although the approach is not clearly defined, it appears to be similar to other technological developments. Increasing the scale of deployment is considered somewhat challenging but has been achieved for analogous technologies.
High	There are significant unknowns present. It will take some work and iteration in order to develop an approach to mature the technology. Increasing the scale of deployment is considered challenging and beyond what has been achieved for analogous technologies.
Very High	There are significant unknowns present and a high likelihood of unknown unknowns that are yet to emerge. It will take significant work and iteration in order to develop an approach to mature the technology. Increasing the scale of deployment is considered extremely challenging and well beyond what has been achieved to date.

Table 10: TRL Difficulty Level

11.8.2. GE⊕-LPS Transportation System

Subsystem element	Subsystem function	Critical technology	Development Challenges	GE⊕-LPS Implementation	TRL	Development Degree of Difficulty	Data Source
Reusable Launcher	Large volume payload launcher, which can fly from Earth to LEO, hand-over cargo and land, refuel and launch again within a short time frame.	Reusable rocket engines, aerobraking and precision landing	Optimizing the live time of the systems. Keep maintenance cycles low.	European access from Kourou. Main access to LEO-CRS	7	Medium	TBD (SpaceX Starship development)
LEO Cargo Relay Station	LEO Station with storage and cargo handling robots. Docking ports and propellant depots. Serves also as initial demonstrator for multiple new space technologies	Robotic cargo handling and standard docking ports.	Develop an open interface for cargo containers. Develop robotic construction.	Stepping stone to the Greater Earth System. Will enable flight to the Moon with ionic drive shuttle. Will become a fuel station with imported Lunar propellant,	7	Low	TBD (ISS and MIR experience)
Cislunar Cargo Shuttle	Transport cargo back and forth from LEO to EM-L1	Standard space containers and docking interfaces. Fully automated handling	Radiation protection passing the Van Allen Belt.	Before the LSE is implemented this will be the workhorse of the programme.	6	Medium	TBD (Deep Space One, Artemis Lunar Gateway at NRHO)

Subsystem element	Subsystem function	Critical technology	Development Challenges	GE⊕-LPS Implementation	TRL	Development Degree of Difficulty	Data Source
EM-L1 Hub Station	Construction site post as well as main access point to the lunar surface	Deep space station radiation protection and emergency scenarios. Standard space containers and docking interfaces. Fully automated handling	Radiation protection for crew. Docking procedures.	Will be the main point for assembly of the LPS. Will grow in importance with implementation of LSE	6	Low	TBD (ARTEMIS Lunar Gateway at NRHO)
Lunar Landing Gantry	Gantry for soft landing cargo on the lunar surface with integrated crane. Can also be used for pole to equator transportation.	Soft landing.	Reusable cryo-propellant rocket engines. Automated refuelling on lunar surface	Lunar workhorse until implementation of LSE. Later for heavy and large loads. Also for polar-equator transports.	5	Medium	TBD (robotic, disposable landing gantries on Mars and Moon)
LSE	The Lunar Space Elevator LSE will directly connect the prime meridian on the lunar equator with EM-L1 and will allow to continuously deliver cargo to/from the lunar surface.	Deployment of large-scale space structure with multi-thousand km tether.	Materials do exist in industrial scale (e.g., Zylon). Elevators are well established. Challenge is to scale up and create a viable test environment and demonstrator.	Will further lower transportation costs and establish a logistic bridge to EM-L1 and further to GEO.	2	High	TBD (Pearson, Eubanks, Radley and Sandford)
GEO Cargo Hub	Will be the end point of the fully deployed LSE and also the release point for Moon fabricated SPS	See LEO-CRS Radiation Protection.	Radiation protection for crew. Docking procedures.	Arrival and departure point for LSE cargo to/from the Moon	6	Low	TBD (ARTEMIS Lunar Gateway Station)

Table 11: TRL: Transportation System

11.8.3. GE⊕-LPS Lunar Surface Facilities

Subsystem element	Subsystem function	Critical technology	Development Challenges	GE⊕-LPS Implementation	TRL	Development Degree of Difficulty	Data Source
Energy Supply	1. Heat collection by solar concentrators 2. Underground heat storage 3. Electricity by photovoltaics 4. Battery storage	1. Glass fibre/Mirrors 2. Heat pump, Insulation 3. Hi-efficiency, thin-film PV 4. Li-Ion batteries	1. Tracking, lunar production 2. Robotic construction 3. Unfolding, dust-protection 4. Weight, efficiency	1. Heat collection by solar concentrators 2. Underground heat storage 3. Electricity by photovoltaics 4. Battery storage	1. - 4 – 2. - 4 - 3. - 8 - 4. - 8 -	1. Low 2. Medium 3. Low 4. Low	TBD
Road construction robots	Earth movement and surface sintering robots	Hi-power drives and traction Sintering technology	Economy of scale	Various tasks	5	Low	TBD (Mars and Moon rovers, starting automation in mining and constructio n industries)

Subsystem element	Subsystem function	Critical technology	Development Challenges	GE⊕-LPS Implementation	TRL	Development Degree of Difficulty	Data Source
Launch/Landing Facilities	Dust free launch and Landing pads with blast walls and automated refuelling facilities.	Automated refueling	Robotic loading and unloading Robotic refueling	Lunar surface launch facilities	4	medium	TBD
Foundations	Foundations for pre-fab modules	Regolith sintering, basalt casting	Create solid foundations		5	low	TBD
Habitat	Habitat with ECLSS and docking port for spacesuit ports and rovers	Robust ECLSS, Radiation protection micro meteorites	Stable resource recycling, minimizing radiation exposure Psychological well-being	Habitat for maintenance engineers and early-phase tourists.	5	medium	TBD (Apollo, ISS, various simulators)
Mining Robots	Robot for collection and transportation of lunar soil	Traction and stability	Large volume per time unit with light weight and low energy consumption	All Mining robots will be RASSOR type.	6	low	TBD (NASA RASSOR, starting automation in mining and construction industries)
Beneficiation Plant	Plant to separate and process main components of lunar soil	Separation, roasting and purification	Efficient process flow for automated separation of elements with high purity	Gain of basalt, pyrite, metal powders etc for fabrication	4	high	TBD (various laboratory experiments)
Fabrication	Highly automated fabrication process to build main elements of LPS	Robotic fabrication, Industry 4.0, additive manufacturing	Automated process flow form supply, pre-processing, fabrication, quality control to delivery	Modular factories for LPS component production	3	high	TBD (First micro factories)
Transportation Robots	Robots for transportation of material and component containers	Traction, positioning	Economy of scale, cargo containers	Transportation robots between beneficiation, manufacturing and the LSE base station	6	medium	TBD (many logistic robots in operation)
LSE Surface Station	Base station of Lunar Space Elevator with loading and unloading capabilities	Robotic loading	Optimizing mass and volume restrictions of climbers	Main transportation hub to and from EM-L1	2	medium	TBD (Pearson and Radley)
Rectenna	Receive the energy from LPS and feed electricity into lunar grid.	Hi-efficiency RF diodes and pilot beam	Large size deployment on difficult ground, optimized configuration	Main source of power to build SPSs for Earth	4	low	TBD

Table 12: TRL: Lunar Surface Facilities

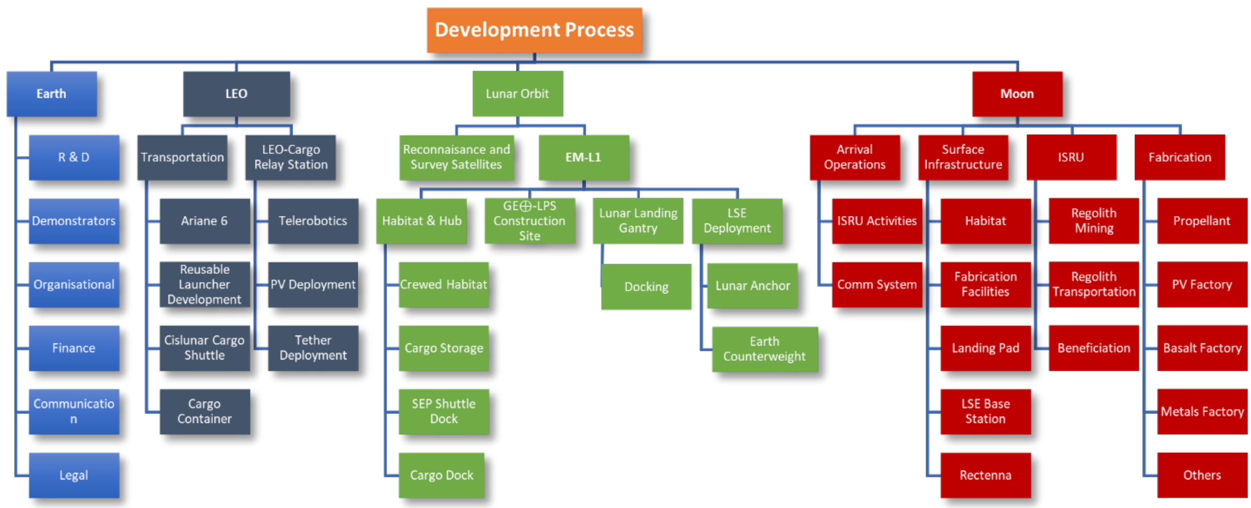
11.8.4. Cislunar Space Facilities

Subsystem element	Subsystem function	Critical technology	Development Challenges	GE⊕-LPS Implementation	TRL	Development Degree of Difficulty	Data Source
LSE EM-L1 Hub Station	The Lunar Space Elevator EM-L1 station serves the main transshipment port for cislunar cargo	Robotic cargo handling, standard interfaces	Development for growth, docking ports for LLG and CCS	Busiest spaceport in cis-lunar space. Arrival of Components for LPS and departure of supplies to Moon.	2	high	TBD
LPS Construction Site	Controlled large area in EM-L1 where robotic construction of SPS can take place	Robotic construction, geometry, positioning	Highly autonomous component handling and assembly	Construction site for LPS and later SPS for Earth export	3	high	TBD (ISS experiences)
Construction Robots	0-g construction robots to assemble large scale SPS	Autonomous space robots, connection technologies	The connection technology of assembly and deployment structure has been widely studied. the connection method of electron beam welding and composite materials is the hotspot of current research	Two main robot types for structural assembly and for deployment of hybrid PV-antenna elements	4	medium	Xue, Z. *et al.* (2021) 'Review of in-space assembly technologies', *Chinese Journal of Aeronautics*, 34(11), pp. 21–47. Available at: https://doi.org/10.1016/j.cja.2020.09.043.
LPS	Lunar Power Satellite to deliver continuous baseload power	DC-RF conversion, WPT, attitude control of large space structure	Solid-state beam steering, high efficiency conversion	Power source to double SPS component fabrication also through lunar night.	3	medium	TBD (ESA Solaris programme)

Table 13: TRL: Cislunar Space Facilities

12. Development Path Outline

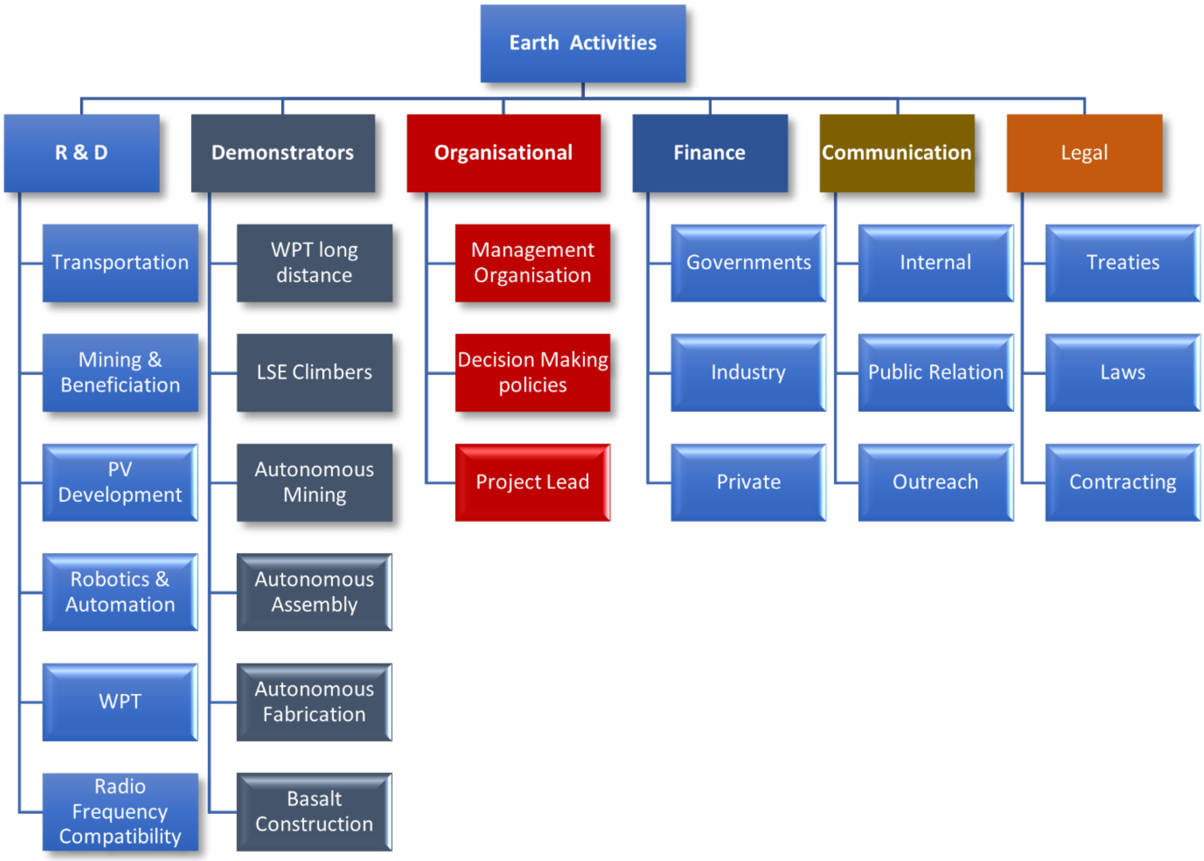
The GE⊕-LPS development entails more than technology development. For it to move forward a rationale and a consensus needs to be established that acknowledges that the approach to realising terrestrially produced and Earth-launched SPS systems capable of making, in the longer term, a substantial contribution to satisfying humanity's ever-growing energy needs faces an enormous launch bottleneck. Not only is the uncertain availability of yet-to-be-developed and deployed heavy-lift launch-systems from dedicated service providers a risk factor, but also the cadence which these launch systems can eventually provide will be challenged to meet what would be required. Additionally, it will be more sustainable as well to largely avoid the emissions related to launch if much of the needed hardware and propellant could be manufactured on the Moon. Therefore, due to the urgency of supplying society with an alternative to carbon-based fossil fuels, innovative approaches that promise to mitigate this complex situation need high-priority evaluation. The results of this study and the recommended follow-up studies should be discussed at the highest levels to determine the implications for providing clean energy to Earth in sufficiently vast quantities. Ideally, this will lead to a phased, international collaborative effort that would combine know-how, experience, and financial resources to make the large-scale implementation of SBSP technically feasible and environmentally sustainable in a reasonable timeframe.



An international space energy organization, established for the purpose of implementing SBSP globally, could become the most efficient approach. This could provide an appropriate framework for effective administration, management, and financial collaboration necessary for implementing such a large-scale, macro-engineering enterprise. Additionally, wide international cooperation of many interested nations would streamline the legal and regulatory issues that must be cleared.

In November 2022, the ESA ministerial meeting CM22 approved funding for accelerated technology development of Space-based Solar Power within a new R&D initiative called SOLARIS. As the GE⊕-LPS offers a novel approach to the realization of SBSP which addresses the anticipated launch bottleneck threatening any currently proposed Earth-launched SBSP system, early R & D efforts on such a lunar-supported approach should commence in parallel. Obviously, some of these initial activities are not unique to the GE⨁-LPS concept and will equally benefit any approach to the ultimate realization of a viable European SBSP system.

12.1. Earth Activities



12.1.1. Research and Development

The Lunar Space Elevator (GE⨁-LSE) is considered a key component of the GE⨁-LPS concept and could lead to a cislunar transportation system that would enable a two-planet economy. Lunar space elevators (LSE) can be made with existing materials available today such as: T1000 TM, Dyneema TM, Magellan-M5 TM, and Zylon TM *(Radley, C. 2017)*. These materials need special attention for how they can be produced and deployed in the required mass and dimensions. In addition, basalt fibres which could be produced on the Moon and potentially used to enhance the LSE should be tested and developed in conjunction. High-power, high-thrust, Solar Electric Propulsion (SEP) systems also need research in order to make the cislunar region easily accessible before the LSE becomes operational. Mining and beneficiation facilities will need to be lightweight, low-power and fully autonomous.

- 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. It is anticipated that the efficiency of current MGL solar cell technology under development by crystalsol GmbH can exceed 20% (Off Grid, 2021). This would be developed in parallel with the current research by the Tallinn Technical University to use lunar-derived pyrite for MGL production on the Moon.

- Robotic assembly and autonomous manufacturing production is widely in use. The engineering TRL of adapting these to in-orbit and lunar surface operations should be quickly achieved through adequate testing. Likewise, mining robots should be developed and tested in simulated lunar terrains and then on the lunar surface.
- In September 2022, the first European ground demonstration of Wireless Power Transmission (WPT) was carried out at the Airbus Central Research and Technology and BlueSky facilities near Munich, Germany. The demonstration saw electrical power sourced from photovoltaic panels, transmitted with very high efficiency in the form of microwaves to a receiver some 36 meters away. The beamed energy lit up a model city and powered a hydrogen generator and a fridge containing beer that the audience later enjoyed. While a useful demonstration to convince high-level decision makers that wireless power transmission is a reality already today, there is a long way to go to develop and demonstrate the scaling up necessary to beam MWs and GWs of power across thousands of km.
- On the terrestrial side of SBSP, Radio Frequency (RF) bandwidth compatibility needs much review, experimentation, and demonstration.

12.1.2. Demonstrators

There will be a need for a fast development by demonstrators. For these demonstrators also prizes could be launched internationally. Such demonstrators or competitions could be in the area of:

- WPT long distance and long-term demonstrations
- LSE Climbers
- Autonomous Mining and Beneficiation
- Autonomous Assembly of construction elements
- Autonomous Fabrication
- Basalt fibre constructions

The above mentioned first European ground demonstration of WPT that was performed at the Airbus Central Research and Technology and BlueSky facilities near Munich, Germany in September 2022 is a good example. As delivering power from GEO requires beaming electricity a million times this distance and a million times the power of the Airbus experiment, additional ground demonstrations over larger distances and at higher power must be performed successively to perfect the technology. WPT needs to be developed to longer distances and power levels.

Astrostrom has proposed the development of a travelling WPT demonstration that could be carried out in museums and/or stadiums. Additionally, it is considering the development of a larger scale WPT demonstration delivering 100s of kilowatt power spanning several kilometres over a valley between two mountain peaks in Switzerland. Such proposed demonstrations of WPT technology would raise the level of awareness and demonstrate the growing maturity of the technology among the public, energy industry and investors.

12.1.3. Organisational Activities

On its own the GE⊕-LPS concept is a major space undertaking requiring substantial upfront investment. With its potential to ultimately mitigate the launch bottleneck that affects SBSP deployment on a significant scale, an international consortium of nations could collaborate to provide the initial investment security, pool resources, manage the development and administer the ever-growing power available for world-wide distribution as SBSP capacity increases with low environmental impact. This would help to ensure that legal issues are amicability resolved and clean energy is provided to national economies in an equitable manner that profits their populations and their governments.

12.1.4. Financial Considerations

Funding of such a programme will need international collaboration such as is found with the EURATOM programme or the ITER organisation for fusion energy. Funding models on governmental and industrial and private investments need to be formed.

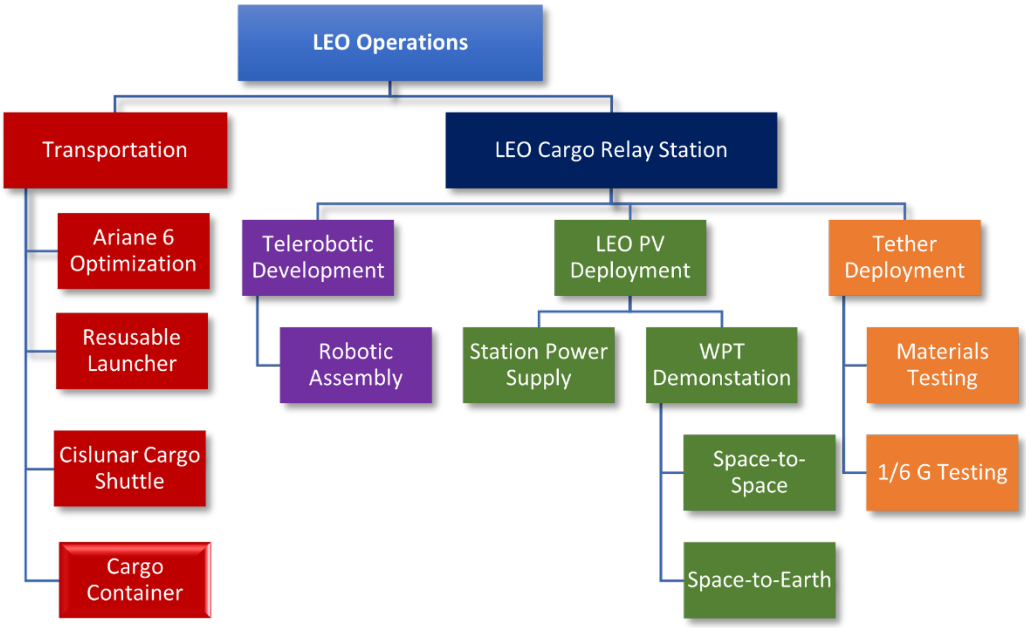
12.1.5. Communication

Communication will play a crucial part in such a programme to maintain governmental and public interest and also to let the public be part of the development. It will also help to attract the best-of-the best and to mitigate the potential concerns. Standards for the modular interfaces need to be developed and agreed on and communicated as a standard.

12.1.6. Legal

Legal aspects include international treaties like the Outer Space Treaty, international agreements such as the Artemis Accords and new national legislation such as the legal framework of the Luxembourg laws on space resources, but also contracts addressing energy distribution, liability, space debris interference and spectrum allocation.

12.2. LEO Operations



12.2.1. Transportation

- **Ariane 6 Deployment and Optimization**

The first segment of the GE⊕-CTS will be deployed in LEO and, in the initial phase between 2023 and 2028, will rely on existing launch technology. As this is a predominantly European system, and until a European reusable launch system becomes operational, in the earliest phases GE⊕-CTS will most likely utilize the Ariane 6 launch system, which has been under development since 2014 and is due to make its maiden flight in 2023. ArianeGroup has announced that it plans to make the Ariane 6 partially reusable by adding liquid fuelled boosters using liquid oxygen and liquid methane derived from the Themis reusable launcher concept which is also under development. Additionally, the ESA spaceport at Kourou, French Guiana will be an advantageous staging location due to its being near the equator. However, it may also be practical and economically advantageous to utilize other launch systems such as those from SpaceX or those from other launch providers during this phase if they are available.

Ariane 6 currently comes in two configurations with the following characteristics:

- A62: up to 10.3 t into LEO, 1.7 t into MEO, 4.5-5 t into GEO, 2.8–3 t into LTO
  A62 cost per launch: €75 million.
- A64: up to 20 t into LEO, up to 12 t into GEO, 8.2.–8.5 t into LTO, 1.7 t to the Moon
  A64 cost per launch: €115 million.

A partially reusable upgrade and a fully reusable crew and cargo stage are planned.

- **Reusable Launcher Development**

With an accelerated development program, and once the core infrastructure of the LEO-Cargo Relay Station has been constructed, crew and cargo flow can be handled economically with small reusable rockets such as the planned Themis reusable or enhanced Ariane 64 which should become operational by the end of the decade. Similar to the Falcon 9, these launchers would have the capacity to deliver 15-20 metric tonnes (MT) payloads to LEO and have short turn-around times. As seen with SpaceX's Falcon 9 launch system, launch costs can be reduced very significantly in this way. can be reduced very significantly in this way. A heavy lift reusable launcher with capabilities and payload capacities similar to SpaceX's Starship is under study by ESA *(ESA ITT 1-11440).*

- **Cislunar Cargo Shuttle Deployment**

The 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 Gateway Station and vice versa. The Cislunar Cargo Shuttle is foreseen to be powered with an ionic drive utilizing solar electric propulsion (SEP). However, depending on technological development and the cargo protection requirements when traversing the dense radiation environment of the Van Allen belts, this vehicle could also be a hybrid drive - a liquid propellant stage which could achieve high velocity when navigating the Van Allen belts to reduce the exposure time to particle events, and an ionic drive which would be used for the remainder of the flight. Cargo docking interfaces need to be developed and agreed on.

12.2.2. LEO Cargo Relay Station

Building infrastructure in LEO is an important and obvious early step in the GE⊕-CTS development. The LEO Cargo Relay Station (LEO-CRS) will be a multi-use orbital platform that serves to decouple the logistical differences of flying through Earth atmosphere and flying through space. From the Earth side, Ariane 6 and eventually reusable launchers can deliver cargo, supplies and people to the LEO-CRS where they can be deposited and carry out experiments, demonstrations, and technology testing. Eventually, cargo delivered to the LEO-CRS may be picked up by chemical and/or ionic drive shuttles which will transport them directly to a storage hub located near EM-L1. From EM-L1 the cargo can be transferred to a Lunar Landing Gantry (LLG), which will allow soft-landing on the lunar surface and/or lowering the cargo/habitat onto transportation robots for final positioning at the lunar base. Later this relay station can be used for storage of Moon-produced supplies (oxygen, propellant etc) for non-lunar space missions.

In the initial phase, the LEO Cargo Relay Station's main purpose and advantage will be as a test and demonstration platform for the technologies enabling the ultimate realization of the GE⊕-LPS. This will begin with the construction of the platform which will explore and perfect the materials and techniques that will be necessary for the construction of the GE⊕-LPS in lunar orbit. Structural elements of the platform will be pre-formed elements of extruded basalt and metal composites that are considered to be available on the Moon. Autonomous and tele-operated robots will assemble the platform. Storage and habitat facilities can be integrated. Photovoltaics manufactured in factories on Earth that have been designed for lunar operations will build out the power generating aspects. Tethers made from materials expected to be used on the Lunar Space Elevator can be deployed and tested for material strength and viability. Rotating equipment can provide a test facility for 1/6 gravity experiments.

Launching into an equatorial orbit from the ESA spaceport in Kourou, with Ariane 6 launches or later with a European reusable rocket will enable efficient and regular access to the platform which could also be used to demonstrate wireless power beaming to locations under the orbital path of the LEO-CRS. Habitable modules such as Orbital Reef being developed by Sierra Space, Starlab by Voyager Space, Lockheed Martin, Nanoracks and the Hilton hotel chain, or I-HAB from the European Space Agency in collaboration with the Japanese Space Agency, JAXA, could be connected to a rotating tether to simulate lunar gravity and also serve as a tourist location.

- **Telerobotic Technology Development**

Terrestrial industrial processes relying on robotics are very advanced and applying these practices to the specifics of orbital construction process needs to be carried out. Launched into a uniquely accessible equatorial orbit, the LEO Cargo Relay Station (LEO-CRS) could become the main in-space platform to deploy and perfect robotic assembly technologies needed for construction the GE⨁-LPS in lunar orbit. Cargo docking interfaces need to be developed and agreed on.

- **LEO PV Deployment and Testing**

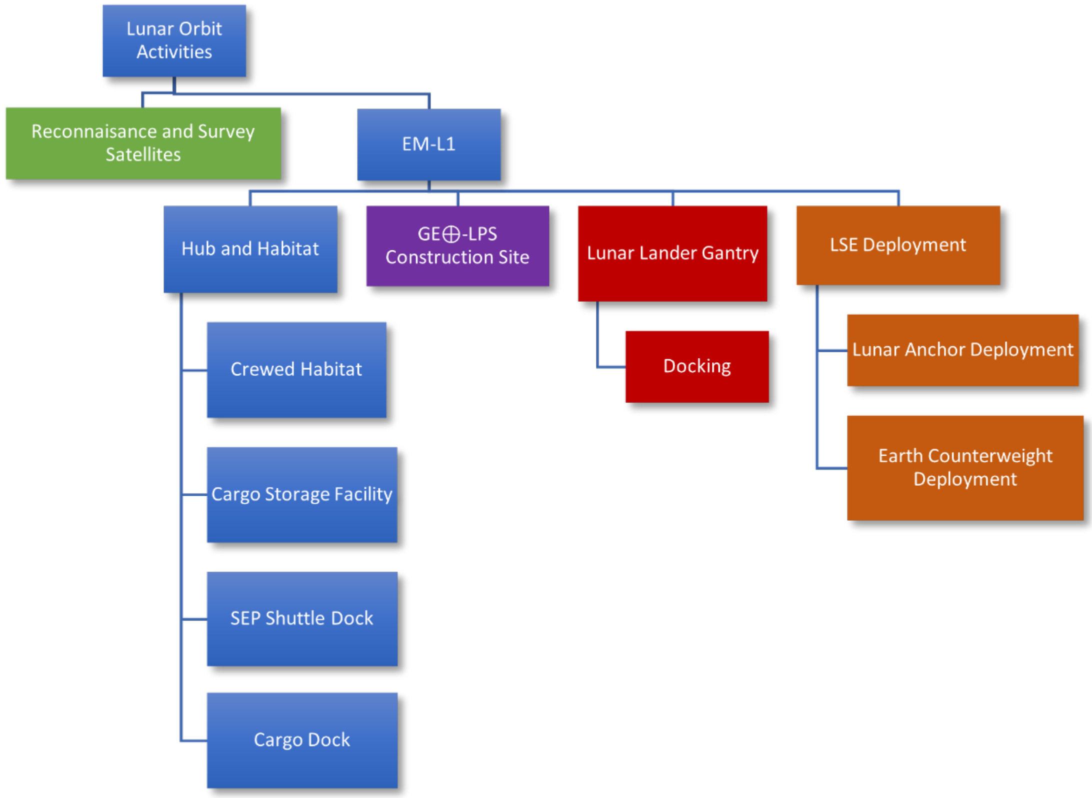
The LEO Cargo Relay Station (LEO-CRS) will also require power and as such, it will be an orbital platform for deploying and perfecting photovoltaic technologies under consideration for the GE⨁-LPS. Terrestrial versions of MGL solar cells can be integrated into containers that would unfold into solar arrays. This would lead to an optimization of the robotic deployment process as well as enhancing and upgrading the power efficiency of the solar arrays.

- **WPT Demonstrations**
  - **Space-to-Space**
    One of the most immediate tasks would be to develop and deploy space-to-space demonstrations of WPT. This needs to be done to demonstrate the proof-of-concept for potential investors and backers of SBSP. WPT demonstrations could be realized in space capsules, with nano satellites and/or with larger scale orbital satellites such as the proposed S.O.S. Space Option Star, which could have a high PR effect and provide a useful tests of various RF frequencies.
  - **Space-to-Earth**
    Space-to-Earth WPT demonstrations, first in LEO and then in GEO are needed to solidify the technical validity of the SPS concept. The LEO-CRS placed in an equatorial orbit may be utilized for this purpose.

- **Tether Demonstrations and Testing**

The LEO-CRS may be utilized as a demonstrator of a rotating tether system deployed to evaluate tether material properties and as an artificial gravity unit that can be used to test hardware for the 1/6 G lunar environment. Tethers built from materials expected to be used on the Lunar Space Elevator can be deployed and tested for material strength and viability as well as exploring potential LSE assembly and deployment techniques.

12.3. Lunar Orbit Activities



12.3.1. Reconnaissance and Survey Satellite(s)

Building upon the data received from prior lunar reconnaissance satellites such as the Lunar Prospector (1998-1999) and the Lunar Reconnaissance Orbiter (LRO) (2009-present) as well as the data expected from the upcoming Artemis missions, additional satellite surveys will focus on lunar resources. Specifically, missions to locate and analyse the availability and location of lunar resource materials that would enable the production of photovoltaics and structural elements of the GE⊕-LPS. Astrostrom is in contact and collaborating with organizations that share similar interests.

12.3.2. EM-L1 Activities

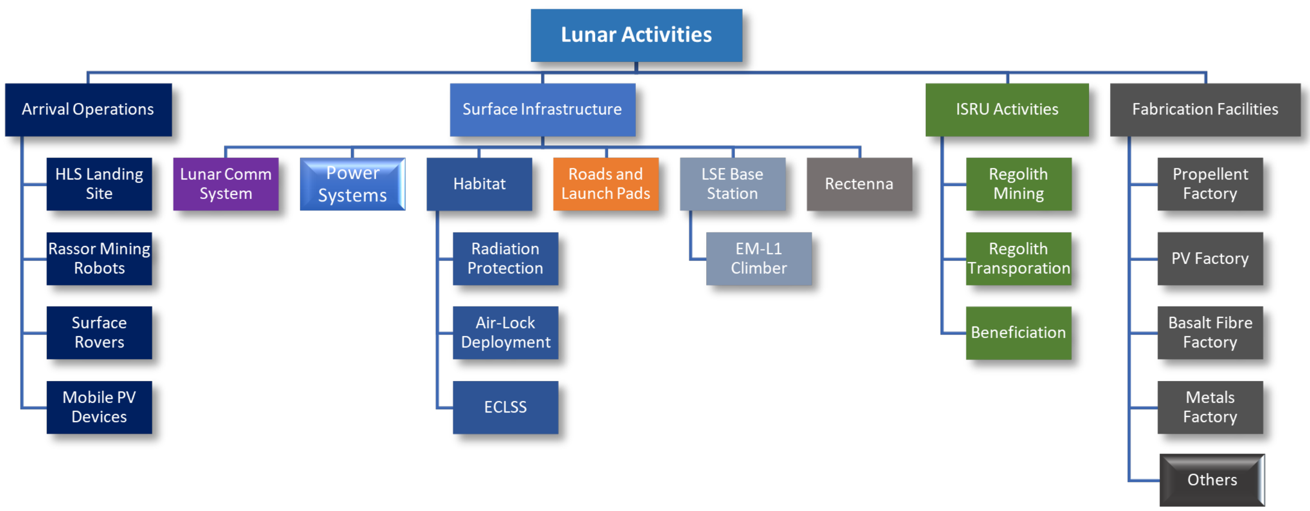
- **Hub and Habitat**
  The EM-L1 Hub will initially be setup with a habitat and cargo docks. It will have docking possibility for the Cislunar Cargo Shuttle CCS, the lunar landing gantry LLG as well as for other international spaceships. It is planned to grow over the time. Cargo can be docked and stored by a robot arm.

- **GE⨁-LPS Construction Site**
  The GE⨁-LPS Construction will be located in vicinity of the EM-L1 hub. Cargo shuttle will continuously pick up cargo from the hub and bring it to the construction site, where robots are assembly the LPS and later SPS.

- **Lunar Lander Gantry**
  The LLG is also described in more detail in section 11.2.10. Its primary function will be to transport and softly land large cargo on the lunar surface and then return to and dock with the EM-L1 hub station.

- **LSE Deployment**
  The Lunar Space Elevator deployment is described in more detail in section 11.2.11 detailing the Cislunar Transportation System and in other previous Work Packages. It includes the following elements.
  - EM-L1 Hub
  - Lunar Anchor Deployment
  - Earth Counterweight Deployment
  - SEP Shuttle Dock
  - Cargo Dock
  - Crewed Habitat
  - Cargo Storage Facility
  - Robotic Assembly Staging Hub

12.4. Lunar Surface Activities



- **Arrival Operations**
  - Initial HLS Landing
  - Deployment of RASSOR Mining Robots
  - Deployment of Surface Rovers
  - Deployment of Mobile PV Devices
- **Surface Infrastructure**
  - Lunar Communication Infrastructure

- Power Systems
- Habitat
  - HLS Habitat Burial with Radiation Protection
  - Air-Lock Deployment
  - Ecological Closed Life Support System Set-Up
- Roads and Landing Platforms
- LSE Base Station and Climber cargo handling
- Rectenna

- **ISRU Activities**
  - Regolith Mining
  - Regolith Transportation
  - Beneficiation Facilities
- **Fabrication Facilities**
  - Propellant Manufacture
  - PV Manufacture
  - Basalt Manufacture
  - Metal Manufacture
  - Other

13. Economic Parameters

Once the GE⊕-LPS concept has been technically appreciated and its potential established, a committed program leading to its implementation must be developed and initiated. This will require early substantial investment in research and development and in-space technology demonstrations predominantly carried out by national space agencies. Once these activities have commenced, the financial parameters of the initial implementation must be detailed. An accelerated economic development program securing the needed initial investments should have the same priority as the technical development program. It is important to recognise that, in the end, the economic dimensions of implementing the GE⊕-LPS concept may lead to the creation of a new space energy industry and vast potential rewards, similar to the earlier inventions of the coal, oil, natural gas and nuclear power industries.

13.1. Research and Development

The economic requirements and risk during the R & D phase will be relatively modest in relation to the overall costs of implementation. However, it is crucial and critical that the investment in this phase begins immediately and with sufficient vigour to ensure an efficient development process that will lead to early on-Earth and off-Earth demonstrations of the various technical components.

13.2. Initial Implementation Investment

The initial investment in the GE⊕-LPS concept, while comparable to other space missions, is nevertheless substantial and must be considered as an investment into its potential to address energy markets on Earth. Viewed in this context, the size of the initial investment can be considered modest, being only about 2% of the estimated cost of Europe's planned energy transition *(BloombergNEF, Path to Clean Energy, 2022).*

13.3. Economic Considerations

The implementation of the GE⊕-LPS concept will require an initial investment by international stakeholders that will be needed to develop and deploy an Earth-Moon transportation and industrial infrastructure. Economic trade-offs between using Earth delivered materials or lunar produced materials will be made at each phase of the GE⊕-LPS development and deployment.

The GE⊕-LPS concept proposes to establish a highly-automatised lunar facility to mine and process lunar material for the manufacture of the SPS components which would then be sent into a robotic assembly point at the Earth-Moon Lagrange point EM-L1. Once a lunar SPS factory becomes operational and optimized, the costs of producing SPS units for use in GEO will become a small fraction of the costs of a terrestrial manufacturing and an Earth-to orbit launch scenario. In addition to reducing the cost and the environmental impact of launching the hardware necessary for many SPSs, each weighing thousands of tonnes, the GE⊕-LPS concept mitigates the anticipated launch bottleneck for terrestrially produced SPSs.

As a one-off mission, the GE⊕-LPS concept would likely be too expensive to reasonably develop and fund. However, as an operational prototype and proof-of-concept project leading to the eventual large-scale production of Solar Power Satellite components manufactured from lunar materials, the GE⨁-LPS offers unique and potentially very substantial economic advantages when compared with manufacturing and launching SPS from the surface of Earth.

The learning curve to develop GE⨁-LPS is comparable to those in the 2022 ESA-funded Cost Benefit Analysis of Space-Based Solar Power, which include manufacturing of SPS units, reusable launch vehicles and autonomous robotic systems for satellite assembly in orbit. In addition to these three systems, the GE⨁-LPS scenario requires an Earth-Moon transportation system, preferably including a lunar space elevator, and lunar surface mining and manufacturing facilities.

13.4. Organization

Once the GE⨁-LPS concept has achieved an acceptable technological readiness level resulting from initial research and development and technology demonstrations, a multinational organizational structure to administer, finance and manage the implementation process will become necessary. Previous multinational organizations with fair return and geographical distribution procurement policies may serve as models for such an organization, such as Intelsat and Inmarsat before these were privatised. Industrial policy and geographical distribution play an important role in ESA procurement procedures. *(ESA, Business, 2023).*

13.5. Benefits

As the GE⨁-LPS concept develops, each component will be subject to a cost/benefit analysis to ascertain its contribution to the system. Overall benefits deriving from the GE⨁-LPS concept will be continuously evaluated against competing scenarios and technological developments.

13.6. Lunar Business Case

The construction of GE⨁-LPS with lunar materials requires the establishment of industrial-scale automatized mining and manufacturing processes on the lunar surface. The materials needed for GE⨁-LPS are mainly cast basalt and basalt fibre for the structural elements; silicon, ilmenite and especially pyrite are considered for semiconductors and photovoltaics; whereas metals such as iron and aluminium will serve for the electrical connections. Setting up an industrial-scale beneficiation plant will provide access to several other materials, which become valuable to other users in the cislunar region. In addition to tiny amounts of Helium-3, a vast amount of oxygen will be produced as a by-product which can be used in life support systems and in the production of rocket propellant and thereby creating business cases for new cislunar enterprises. In addition to providing plentiful power for lunar surface activities, the GE⨁-LPS may serve as a gateway between Earth and Moon operations, becoming an attractive tourist destination, and possibly, as a prototype for future space settlements in cislunar space. Each of these activities could develop into specific entrepreneurial endeavours.

13.7. Terrestrial Business Case

As it is foreseen that the energy production functions of the GE⨁-LPS concept can be scaled to any dimension, larger versions could be positioned in Earth orbit and help provide much needed clean, continuous solar energy for terrestrial purposes. Faced with a climate emergency, a developing energy dilemma and an increasingly unstable geopolitical situation, European society has entered into an uncertain phase of energy security and economic sustainability. Having sufficient energy would also contribute to restoring the environment, solving the water crisis, create new transportation fuels, reduce poverty, stimulate progress in the developing countries, sustain the world economy and end conflict over finite energy resources. Harvesting inexhaustible energy in space and distributing it to all people of all nations would enable the entire population of Earth to have a prosperous and hopeful future in contrast to current policies and measures being implemented to permanently downsize society in order that humanity may continue to live within the confines of a planet defined by the limits of its atmosphere.

As noted above, BloombergNEF's Energy Transition Investment Trends 2022, global investment in the energy transition was a total of $755 billion in 2021 due to climate ambition and policy action from countries around the world *(BloombergNEF, Energy Transition Investment Trends, 2022),* which is about 10 times the total funding of space agencies around the world. Also, BloombergNEF's European Energy Transition Outlook 2022, projects that decarbonizing Europe's energy system creates a $5.3 trillion (4.9 trillion euros) investment opportunity in new electricity generating and green hydrogen production capacity between now and the year 2050 *(BloombergNEF, Path to Clean Energy, 2022).*

By implementing the GE⊕-LPS concept, an Earth-Moon energy and transportation infrastructure will evolve leading to the creation of a two-planet economy that addresses not only the climate and energy security crises currently challenging Europe and the world but also provide a business case for starting economic development of the Moon and beyond. While addressing the critical energy and environmental needs of human civilization on Earth, the GE⊕-LPS integrates the aims of lunar development with widely shared aspirations of spaceflight, as discussed positively for decades by engineers and writers.

13.8. The Big Picture

In recent decades, technological innovations, which have been a major driver of economic growth and societal change worldwide for the past few centuries, have accelerated. As more and more engineers and scientists are trained and working in more and more countries, this acceleration is likely to continue, leading to further major changes in the world economy and international society. One deep trend is the ever-growing demand for energy in both rich and poor countries.

It is a structural feature of the European economy as a whole that it is dependent on large-scale imports of energy, to pay for which Europe must export manufactured goods and other services. This puts European industries in direct competition with other countries which export similar products and services. With the end of the "Cold War" some 30 years ago, this competition has become fiercer - and will continue to do so as more and more countries develop industrially. An important example of this is the rapid growth of the Chinese economy, which continues to develop ambitious projects such as the "Belt & Road Initiative" (BRI), and recently announced the "Space Silk Road" for which it is also researching SBSP.

It is a major aspect of economic growth that as poorer countries develop, their lower costs attract older industries which move away from richer countries with higher costs. In response to this, new industries need to be developed in richer countries in order to employ people released from industries which relocate abroad. The space industry is a candidate to become a major new industry, but commercial space activities have not to date grown into an industry commensurate with the approximately 2 trillion Euro-equivalents of public investment that it has received world-wide. Supplying electricity via SBSP would enable the space industry to contribute to a major commercial industry while enabling Europe to not only reduce its dependence on imported energy, but to also become an exporter of environmentally benign energy worldwide. As the inventor of rocket propulsion, and with decades of experience of operating a wide range of ever-advancing space equipment and facilities, European industry is well placed to play a major role in developing a SBSP industry.

Now that Europe's energy supply situation has become critical for political, environmental and geopolitical reasons, with the potential for repeated crises at short notice, there are potentially very large economic and security benefits for Europe from making the investment needed to evaluate the feasibility of SBSP.

At the present stage of development, it is not possible to predict the future cost of SPS-delivered electricity with confidence. More demonstrations of various aspects of the overall system, including the WPT subsystem, on at least Megawatt scale are needed to enable this. However, it is clear from the present study that the potentially unique contribution that SBSP could make to European and worldwide electricity supply is sufficiently large that SBSP should be urgently researched in more detail. This is particularly clear by comparison with the very large amounts of funding that has been and continues to be provided to investigate a range of other "alternative" energy sources.

Forbes writes that a bare minimum of US$30 trillion to US$40 trillion of investment is needed to put the world on a 2 °C or lower pathway *(Forbes, 2020).* The recent US Inflation Reduction Act is the largest investment to combat climate change to date — roughly $370 billion worth of incentives to slash CO_2 emissions in the U.S *(Forbes, 2022).* According to the IEA, clean energy transitions offer major opportunities for growth and employment in new and expanding industries. There is a global market opportunity for key mass-manufactured clean energy technologies worth around USD 650 billion a year by 2030 — more than three times today's level." *(IEA, January 12, 2023).* In their 'World Energy Transitions Outlook *2023: 1.5° Pathway'* report, the International Renewable Energy Agency (IRENA) writes *"Although global investment across all energy transition technologies reached a record high of USD 1.3 trillion in 2022, annual investment must more than quadruple to remain on the 1.5°C pathway….Cumulative investments between now and 2030 need to total USD 44 trillion, with energy transition technologies representing 80% of the investment, or USD 35 trillion" (IRENA, 2023).*

To date there has been a technological, commercial, and cultural gap between the space and electricity industries: the space industry knows little-to-nothing about electricity supply, while the electricity industry knows little-to-nothing about space technology. Consequently, in order for investment in this project to have the best chance of economic success there is a need for collaboration between the EU, ESA, EURELECTRIC (the organisation representing the European electricity industry as a whole, employing roughly 1 million people in the European Union, and with an annual turnover of more than €600 billion), ENTSOE (the European Network of Transmission System Operators for Electricity) and other related organisations. Through its ever-growing use of solar electricity generation, the electricity industry has already learned a great deal about photovoltaic technology, including on multi-100's of MW scale- much larger than space systems. Learning about wireless power transmission (WPT) by building MW scale demonstrators would facilitate further collaboration.

14. The Business Case

Most space programs are evaluated in terms of cost. However, by enabling cost-effective Space-Based Solar Power on a large scale, the impact of developing a GE⨁-SPS system for the terrestrial electricity market needs to also be considered in terms of economic opportunity.

14.1. Initial Infrastructure Investment

According to BloombergNEF's Energy Transition Investment Trends 2022, global investment in the energy transition was a total of $755 billion in 2021 due to rising climate ambition and policy action from countries around the world *(BloombergNEF, Energy Transition Investment Trends, 2022).* This is about 10 times the total annual funding of all space agencies combined.

BloombergNEF's European Energy Transition Outlook 2022, projects that decarbonizing Europe's energy system creates a $5.3 trillion (4.9 trillion euros) investment opportunity in new electricity generating and green hydrogen production capacity between now and the year 2050 (*BloombergNEF, Path to Clean Energy, 2022)*, or some 200 billion euros per year.

As shown below, implementing the GE⨁-LPS concept is estimated to cost less than €100 billion over 10 years, or less than 2% of the European energy transition budget. 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.

As references for the initial cost of the GE⨁-LPS, the following examples are relevant:

1. The International Space Station (ISS) which has been the most expensive single object ever constructed in space, with a mass of approximately 444 metric tonnes. As of 2010, the total cost was US$150 billion. This includes NASA's budget of $58.7 billion ($89.73 billion in 2021 dollars) for the station from 1985 to 2015, Russia's $12 billion, Europe's $5 billion, Japan's $5 billion, Canada's $2 billion, and the cost of 36 shuttle flights to build the station, estimated at $1.4 billion each, or $50.4 billion in total. *(Wikipedia, ISS, 2023)*
2. The total costs for Artemis missions through fiscal year (FY) 2025 are projected to reach $93 billion according *to* NASA Office of Inspector General *(NASA, IG-22, 2021).*
3. NASA awarded SpaceX US2.89 billion for two Starship HLS missions to the Moon. *(NASA, Artemis, IG-21 2021)*
4. In 2010 and 2011, Paul Spudis and Tony Lavoie published two papers that detailed a 31 mission, 16-year plan to establish a fully functioning lunar base capable of producing ~150 tonnes of water per year and roughly 100 tonnes of propellents. Their plan relied on sending robotic systems to the Moon which are teleoperated from Earth to prospect and qualify local lunar resources and produce water. These robots would be launched separately over several years, allowing the program to be implemented under varied funding conditions. In total 96 tonnes would be delivered to the lunar surface for an aggregate cost of approximately $88 billion *(Spudis, Lavoie, 2011 and 2016).*

5. In 2022, Frazer-Nash Consultancy projected a R&D investment cost of €15,765 million over four phases resulting in the first GW-scale SPS in-orbit prototype. The costs to develop a reusable launcher capability were not included *(FNC/LE, (2022)*.
6. In January 2023, the International Energy Agency published its Energy Technology Perspectives 2023 which provides an analysis of the risks and opportunities surrounding the development and scale-up of clean energy and technology supply chains in the years ahead, viewed through the lenses of energy security, resilience and sustainability. The analysis states: *"Clean energy transitions offer major opportunities for growth and employment in new and expanding industries. There is a global market opportunity for key mass-manufactured clean energy technologies worth around USD 650 billion a year by 2030 – more than three times today's level." (IEA, January 12, 2023)*

The overall implementation cost of the GE⊕-LPS includes the research and development of a SSP system (€15 billion), a European Reusable Heavy Launch System (ERHLS) with a similar design and capacity as the Starship heavy launch System (€10 billion), and a Lunar Space Elevator (€11 billion). These three items constitute €36 billion of the proposed budget and could be developed independently of the GE⊕-LPS initial infrastructure investment, in which case the incremental cost of GE⊕-LPS would be reduced to €63 billion instead of the €99 billion mentioned below.

	Cost	**MT**	**Launches**
Management and Operations	€100 million		
10 years GEEO Administration	€1 billion		
SPS Research & Development	€15 billion		
Ground WPT Demonstration	€1 million		
LEO Space-to-Space Demonstration	€50 million		1
LEO Space-to-Earth Demonstration	€1 billion		1
LEO Cargo Transit Station	€8 billion	200	2
Cislunar Transport Shuttle	€2 billion		1
ERHLS Development Cost	€10 billion		
Initial Lunar Base	€2.1 billion	300	21
Delivery of RASSOR and mobile PV system	€700 million	100	7
Delivery of PV Factory	€2.1 billion	300	21

Delivery of Basalt Fibre Factory	€2.1 billion	300	21
Delivery of Oxygen/Propellant Factory	€2.1 billion	300	21
Delivery of Metals Processing Factory	€2.1 billion	300	21
Delivery of Addition Infrastructure	€2.1 billion	300	21
Lunar Space Elevator R & D	€ 2 billion		
Delivery of Lunar Space Elevator to EM-L1	€2.1 billion	100	7
Enhancement of Lunar Space Elevator	€7 billion	700	70
Lunar Rectenna Construction	€1.4 billion	200	14
Scaling up Lunar Production and Infrastructure	€14 billion	2,000	140
Lunar Transportation System	€1.4 billion	200	14
Cost of Factory Hardware to the Moon (5,500 MT @ €2 million/MT)	€11 billion		
GEO-LPS Parts from Earth	€1.4 billion	200	14
6 Person Crew & Life Support / 10 years	€1 billion		
Yearly Earth-Moon Crew Exchange / 10 years	€7 billion		70
	Cost	MT	Launches
Totals	**€98.75 billion**	**5,500**	**467**

Table 1: Overall breakdown of initial lunar infrastructure investment

Note: Each ERHLS mission to the Moon represents 6 fuelling launches and 1 cargo/crew ERHLS rocket, or 7 launches in total, with a payload capacity to the lunar surface of 100 MT similar to SpaceX's Starship Human Landing System (HLS). As such, each mission is estimated to cost €700 million, i.e. €100 million per launch based upon current (2023) estimates of the cost of a Starship launch. As launch costs are projected to decrease in the expected timeframe, this estimate is a conservative assumption of the expected future costs of implementing the GE⨁-LPS concept.

Total projected cost of GE⨁-LPS implementation: **€98.75 billion**

Estimated ERHLS launch costs (2023 estimate): €46.7 billion
Number of ERHLS launches: 467

Mass to be launched from Earth (metric tonnes) 5,500 MT
Hardware costs for Infrastructure: 5,500 MT @ €2 million/MT €11 billion

Concerning the 7 rocket launches per mission used in these calculations, accurate data does not exist as the Starship refuelling tanker variant is still under development and a European alternative such as ERHLS has not been technically defined. In Figure 85, NASA appears to indicate 6 launches in total when depicting the Artemis III concept of operations *(NASA, Chojnacki, 2020).* However, Elon Musk stated on Twitter (Musk, 2021)*:*

"16 flights is extremely unlikely. Starship payload to orbit is ~150 tons, so max of 8 to fill 1,200 ton tanks of lunar Starship. Without flaps & heat shield, Starship is much lighter. Lunar landing legs don't add much (1/6 gravity). May only need 1/2 full, i.e. 4 tanker flights"

Thus, one could speculate that the cost of launching to the Moon or EM-L1 will be less than what we are projecting.

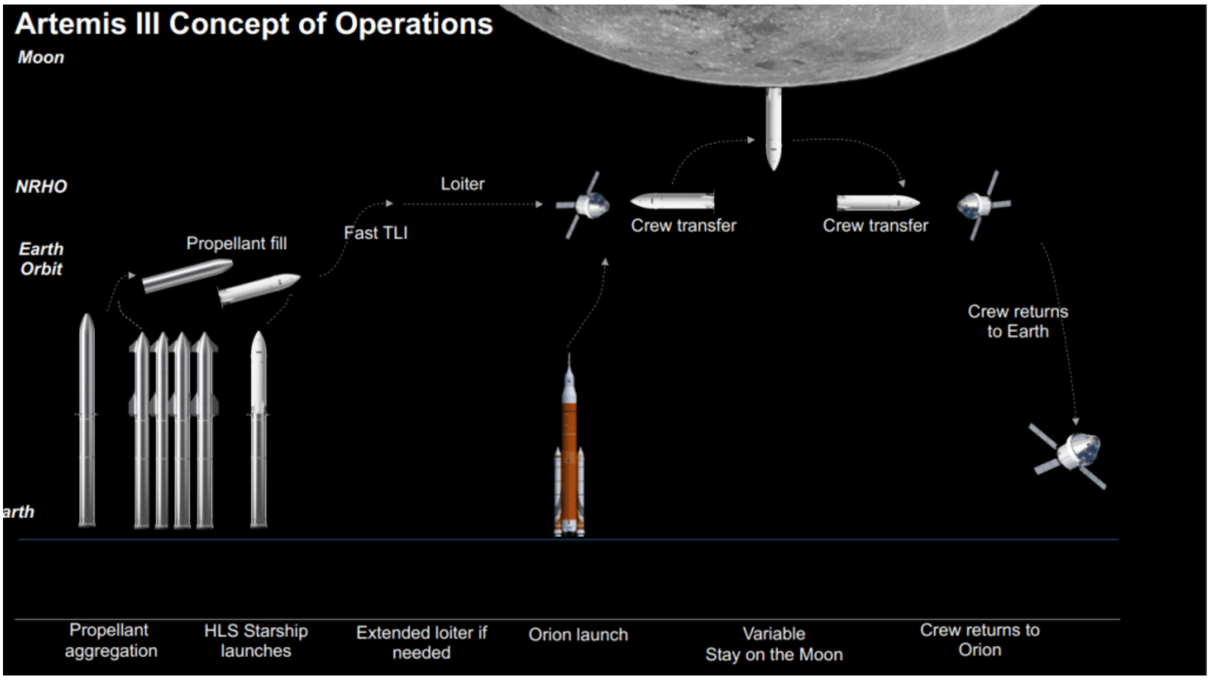


Figure 85: Conceptual plan of how HLS will be utilized. (Credit: NASA)

With the above initial investment calculations, we are projecting 100 tonnes delivered to the lunar surface would cost €700 million (7 Starships or 7 ERHLS @ €100 million each) as today's published prices. This is €7 million per metric tonne. Thus, launching 5,500 MT would cost €38.5 billion.

Figure 86 indicates a simplified breakdown of the initial lunar infrastructure investment. As mentioned above, included in this estimate is €15 billion for the research and development of a SSP system, the development cost of a European Reusable Heavy Launch System (ERHLS) at €10 billion with a similar design and capacity as the proposed Starship Heavy Launch System, and a Lunar Space Elevator (LSE) at €11 billion. The delivery and implementation of the lunar mining and processing infrastructure is estimated to cost €43 billion including €14 billion for scaling up the initial processing and manufacturing facilities, roads and launch pads, transportation, fuel production communications, and CLLS systems, each requiring additional materials from Earth. Initial administration and R&D including LEO demonstrations is targeted at €16 billion. Human crew costs over a ten-year period are approximately €8 billion.

The total initial investment cost is thus estimated to be approximately €99 billion.

Figure 86: GE⊕-LPS System Initial Infrastructure Investment. (Credit: Astrostrom)

The cost estimates for developing the lunar industrial capabilities needed for the GE⊕-LPS concept are not based on detailed analysis of each part, but on approximate comparison with other space technology development projects – some of which have been referenced above. However, 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.

Although it is easy to criticise such projections by saying that development costs are always underestimated, there are several reasons for optimism rather than pessimism in the present case. These include the preparatory work in related technical fields already supported by ESA (as discussed above); ongoing ESA work on lunar activities as part of the Artemis project; major efforts being made by Chinese, Russian and Indian space industries to start lunar activities, including crewed visits, within the next few years, which will develop useful technological knowhow and/or stimulate geopolitical competition; and the rapid progress being made in many terrestrial technologies which are related to those needed for GE⊕-LPS, which include intelligent robots and multi-robot systems, additive manufacturing, reusable launch vehicles, semiconductor technology, basalt engineering, and AI. These promising ongoing developments suggest that the costs and risks of an early, phased development project designed to de-risk the path to GE⊕-LPS are well justified by the unique potential benefit of creating an economically profitable basis for the development of a lunar industrial base – due to the huge, growing and unsolved demand for clean electricity on Earth - with all the potential spin-offs that this would generate.

Furthermore, to offset the remaining risks, it is assumed that this initial investment could be provided by a consortium of countries that would essentially become anchor stakeholders such as in the proposed Greater Earth Energy Organization (GEEO) described in section 14 Organisational Aspects. The member countries which will have co-financed the development costs would then have the right to purchase the energy produced from the operational GE⊕-SPSs at the most favourable rate. Not only would this provide the citizens of the respective countries with access to a perpetual supply of clean energy, but the savings from lower electricity costs could be used by the respective governments to contribute to their national budgets.

The €16 billion development cost cited by Frazer-Nash does not include the development of a reusable launch system whereas the Astrostrom initial investment budget does include this item (€10 billion), as well as the R&D cost for SPS technologies (€15 billion) and the Lunar Space Elevator (€11 billion). If SPSs are developed and initially launched from the surface of the Earth, this will pay for the development and prototyping of SPSs, for the development of the ERHLS and of in-orbit robotic assembly systems, estimated to cost some €27 billion in this study. If these systems are developed for that purpose, the incremental cost of developing the additional capability to manufacture the majority of the mass of SPS units from lunar materials and deliver them to GEO is estimated at approximately €72 billion.

This economic objective of GE⊕-LPS makes it strikingly different and economical than other space programmes. For a roughly comparable initial investment, developing the ability to make and deliver much of the mass of GE⊕-SPS units from lunar materials would more than repay the entire initial investment, thereby eliminating the initial burden on taxpayers, and creating substantial employment in a major new industry. Indeed, the economic benefits could eventually even repay the cost of ESA's participation in Artemis, particularly if this is designed to contribute as much as possible to developing the knowhow and infrastructure needed for lunar industrialisation, rather than solely government objectives, such as geopolitical or scientific goals.

14.2. From GE⊕-LPS to GE⊕-SPS

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

The ESA SBSP Cost/Benefit studies described the deployment of two possible SPS systems for Europe.

- Frazer Nash/London Economics: *(FNC/LE, (2022)*
- €7.6 billion per deployed 1.44-GW CASSIOPeiA (10th system)
- 54 SPSs = €418 billion delivering 70 GWe (7.6% of 8,000 TWh/yr)

- 2,491 MT per SPS = 134,514 MT for 54 SPSs launched to GEO

- Roland Berger/OHB: *(Roland Berger - OHB 2022)*
- €10 billion-€33.4 billion per deployed 2.0-GW SPS-ALPHA system
- 20-25 SPSs = €200 to €835 billion delivering between 36 GWe-45 GWe
- 7,600 MT per SPS = 152,000-190,000 MT launched to GEO

Astrostrom has used a 1.44 GW GE⊕-SPS LCoE calculation to make a direct comparison with the Frazer Nash/London Economics proposed SPS system. The results described below are:

- €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 for 54 GE⊕-SPSs
- 78 GE⊕-SPSs = €277 billion delivering 101 GWe (11% of EU electricity in 2050)

Levelised Cost of Electricity (LCoE) is the most commonly used metric to assess cost competitiveness of power generation technologies. It distils all direct technology costs into a single metric and represents the revenue generated that would be required to recover the costs of financing, building and operating the system during its life. LCOE is the average net present cost of producing energy for a specific system which considers all the costs over the lifetime of the energy-producing system. It is an important metric for assessing energy projects' practical applicability, cost-effectiveness, and economic soundness.

The cost of energy production depends on costs during the expected lifetime of the plant and the amount of energy it is expected to generate over its lifetime. The LCoE is the average cost in currency per energy unit, for example, EUR per kilowatt-hour or EUR per megawatt-hour. The LCoE is an estimation of the cost of production of energy, thus it tells nothing about the price for consumers and is most meaningful from the investor's point of view.

We have used the online Levelized Cost of Energy Calculator from the National Renewable Energy Laboratory *(NREL, 2023)*, to give a metric that allows the comparison of the combination of capital costs, operation and maintenance costs and performance costs between a GE⊕-SPS and a similar capacity SPS system as described in the Frazer Nash study. Note: this simple LCoE Calculator does not include financing issues, discount issues, future replacement or degradation costs, etc. which would need to be included for a more comprehensive analysis.

https://www.nrel.gov/analysis/tech-lcoe.html

The cost breakdown of a tenth generation 1.44 GW GE⊕-SPS production unit (90% availability = 1.296 GW) manufactured from lunar materials is shown below. We assume that 20% of the GE⊕-SPS or 400 MT will be delivered to EM-L1 from Earth. Also, a crew of six persons will be necessary to manage the construction process. The electricity provided and all the other costs are based on the results contained in the ESA Cost Benefit study conducted by Frazer Nash Consultancy. As they reported, a 10th production SPS unit would have a CAPEX (Capital Expenditure) of approximately €7.6 billion and an OPEX (Operating Expenses) of approximately €1.3 billion. Thus, the main difference between the two systems are the costs of deployment which is directly related to required number of launches needed to deploy one SPS system. In the Frazer Nash study this number is between 86 and 119 launches or more precisely €2,702 per kg which is the cost per kg we have used in our calculations although the cost to launch to EM-L1 are slightly less than to GEO, depending in high or low thrust scenarios. In the GE⨁-SPS scenario we require 35 launches to deliver the 400 MT and the 6-member crew to EM-L1.

For both scenarios the future price per kg is expected to decrease substantially once reusable heavy-lift launchers become widely available. Likewise, the seven launches needed to deliver 100 MT to EM-L1 or to the Moon is a conservative estimate which was discussed in section 13.1.

Cost Breakdown of a tenth generation 1.44 GW GE⨁-SPS

400 MT to EM-L1 @ €2,702/kg = 28 launches @ €38,600,000:	€1,080,800,000
400 MT of space hardware @ €300/kg:	€120,000,000
6-person crew @ €100 million each:	€600,000,000
Crew transport to EM-L1 = 7 launches at €38,600,000:	€270,200,000
Total Space Cost:	€2,071,000,000
Rectenna + Land:	€765,965,214
Ground Facilities:	€444,427,000
Insurance + Connection Costs:	€284,506,002
Total Ground Costs:	€1,485,898,216
CAPEX: Capital Cost of a Deployed GEO-SPS:	**€3,556,898,216**
Cost of Money 20% / 2 years:	€787,850,335
OPEX: Operations and Maintenance / 30/years:	**€1,256,639,640**
Total Cost of one GE⨁-SPS over 30 years:	**€5,601,388,191**

CAPEX ÷ 1.296 GW = 2,744.5 €/kW
OPEX ÷ 1,296 GW = 32.3 €/kW/year

Thus, using the NREL LCoE calculator in Figure 87, a 1.44 GW GE⨁-SPS 10th production unit would have a LCoE of €7.4/kWh or €74/MWh. It uses a Discount Rate of 20% referred to as the 'hurdle rate' by Frazer Nash. As a comparison, this LCoE calculator for the Frazer Nash SPS system returned a LCoE of €15.6/kWh or €156/MWh which is consistent with their own report for a 10th production SPS unit (P90, 10 OAK).

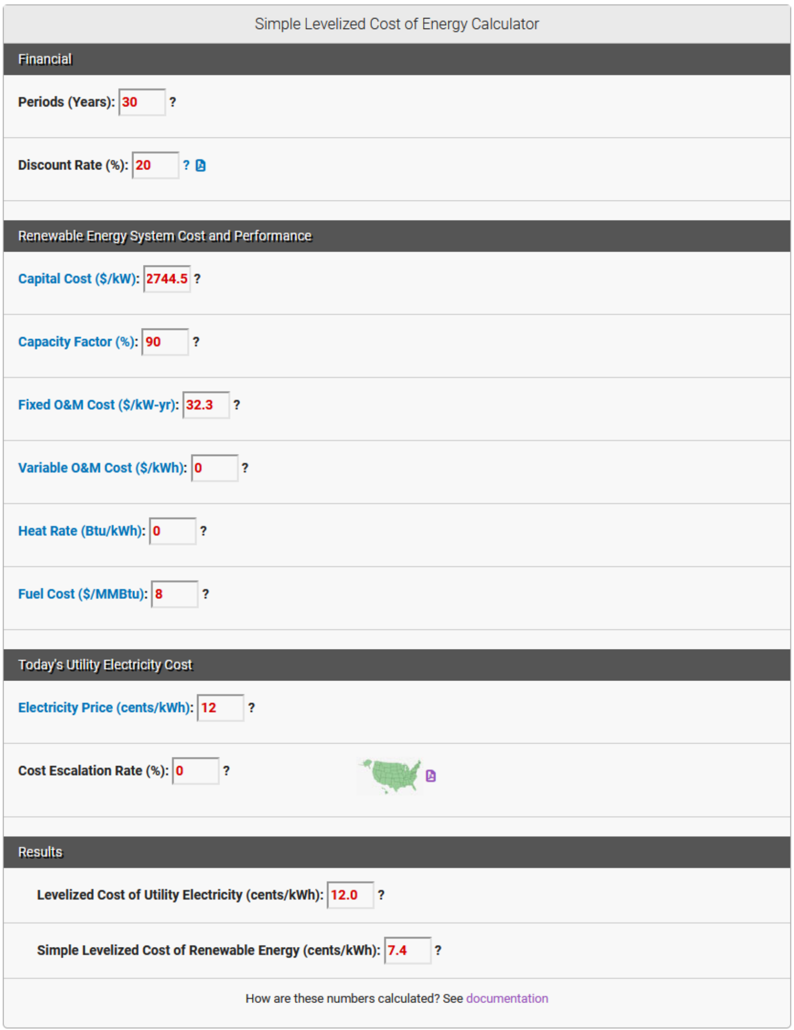


Figure 87: LCoE Calculation for a 10th generation GE⊕-SPS *(NREL Online LCoE Calculator)*

The Frazer Nash cost/benefit analysis states *(FNC/LE, (2022)*:

"At a 10% hurdle rate, the LCoE of the first SBSP system is comparable with a nuclear new build programme (€109/MWh versus €108/MWh respectively). At a 5% hurdle rate, the LCoE of the first system would be €69/MWh, making it more cost-competitive than all alternatives."

Using a Hurdle Rate (Discount Rate) of 10% instead of 20% for GE⊕-SPS, results in a LCoE of: €4.5/kWh or €45/MWh and as such, not only would GE⊕-SPS be more economically attractive than a comparable Earth-launched SPS, but it is also cost-competitive with any terrestrial energy alternative.

1.44-GW GEO-SPS	10th GEO-SPS Unit		1.44	GW	Profit / Loss Calculation		30 Years Operations	
Wholesale Price of Electricity								
€0.12/kWh + 25% = €0.15/kWh	€ 0.15	€/kWh			LCOE	€ 0.0740	€/kWh	
							€ 5’601’388’191	CoE/30years
Yearly Revenues			€ 1’702’944’000				€ 840’119’040	CoE/year
Total Revenues 30 years			€ 51’088’320’000				€ 862’824’960	Gross Yearly Profit
Revenues minus Costs			€ 45’486’931’809			Minus 10% Overhead:	€ 776’542’464	Adjusted Yearly Profit
Output/year	11’352’960	MWh				30 Year Gross Profit:	€ 23’296’273’920	
Total Output: 30 years	340’588’800	MWh				Minus Total Costs:	-5’601’388’191	
						Net Profit 1 SPS:	€ 589’829’524	1/year
						Net Profit 1 SPS:	€ 17’694’885’729	30/years
						Net Profit 78 SPSs:	€ 1’380’201’086’894	30/years

Figure 88: Profit Loss Calculation for a GE⊕-SPS

With the total cost per GE⊕-SPS of Euros €5,601,388,191 including hardware, launch, financing, operations, and maintenance, while supplying 11,352,960 MWh of electricity per year at a LCoE of €74/MWh results in the profit/loss calculations shown in Figure 88.

To highlight the information in the above chart:

Electricity delivered per year:	11,352,960 MWh
LCoE (€0.074/kWh):	€74/MWh
WPoE (€0.15/kWh):	€150/MWh
Yearly revenues:	€1,702,944,000
10% overhead costs per year:	€776,542,464
Yearly net profit:	€589,829,524
Net profit 30 years:	€17,694,885,729

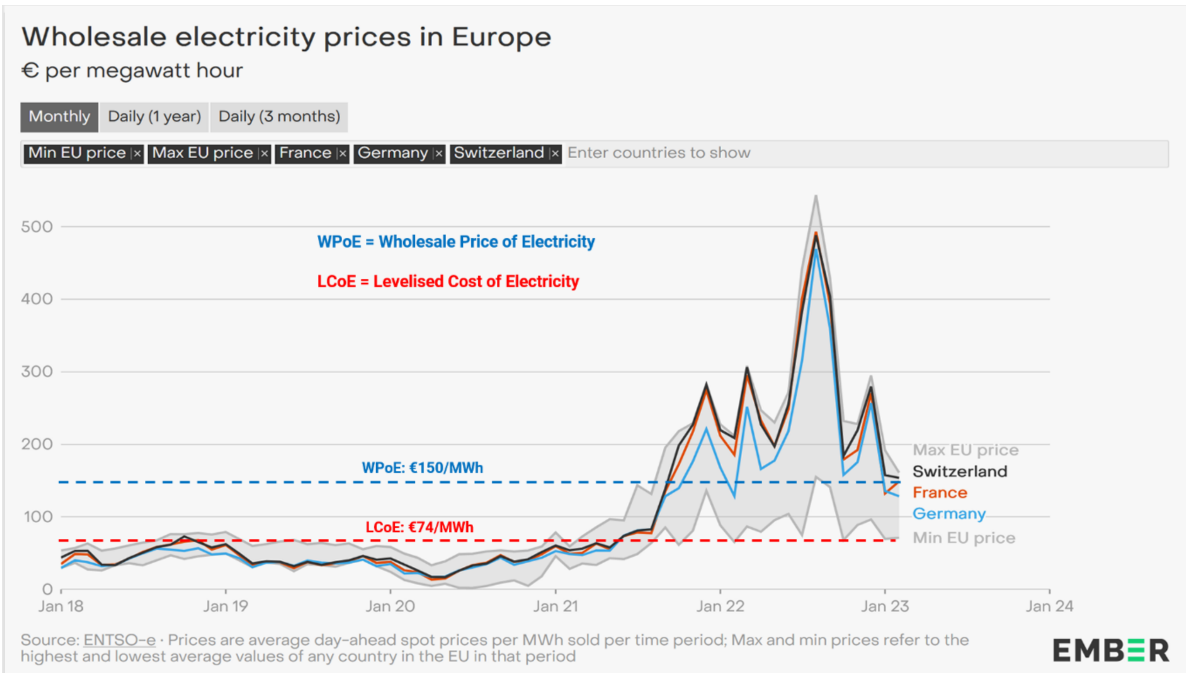


Figure 89: WPoE in Europe: January 2018 - January 2023 (Source: Ember, 2023)

As seen in Figure 89, in practice the WPoE varies in different countries and in recent years has become very volatile in Europe. In our calculations, the profit of delivering electricity from a GE⊕-SPS is based on a reference Wholesale Price of Electricity (WPoE) of €0.15 kWh or €150/MWh and the difference between this and a LCoE of €74/MWh.

One 1.44-GW GE⊕-SPS operating with a 90% availability would deliver 341 TWh of electricity over its 30-years of operation. Delivering the same amount of baseload power that was supplied by nuclear energy in 2021 (882.8 TWh see Section 4.6), approximately 78 of these GE⊕-SPS systems could supply 101 GWe of power providing 886 TWh/year of clean electricity (Figure 90) or 11% of Europe's 2050 projected electricity needs of 8,065 TWh. With a wholesale electricity price of €0.15 one 10th generation 1.44-GW GE⊕-SPS would generate a yearly profit of €589,829,524 million and the potential net profit from 78 operational GE⊕-SPSs would be approximately €1.4 trillion. The estimated approximate breakdown of the other energy sources are: Fossil Fuels 1,600 TWh (20%), Nuclear 809 TWH (10%), Hydroelectric 680 TWh (8%), Renewables 3,929 TWh (49%) and Other 161 TWh (2%).

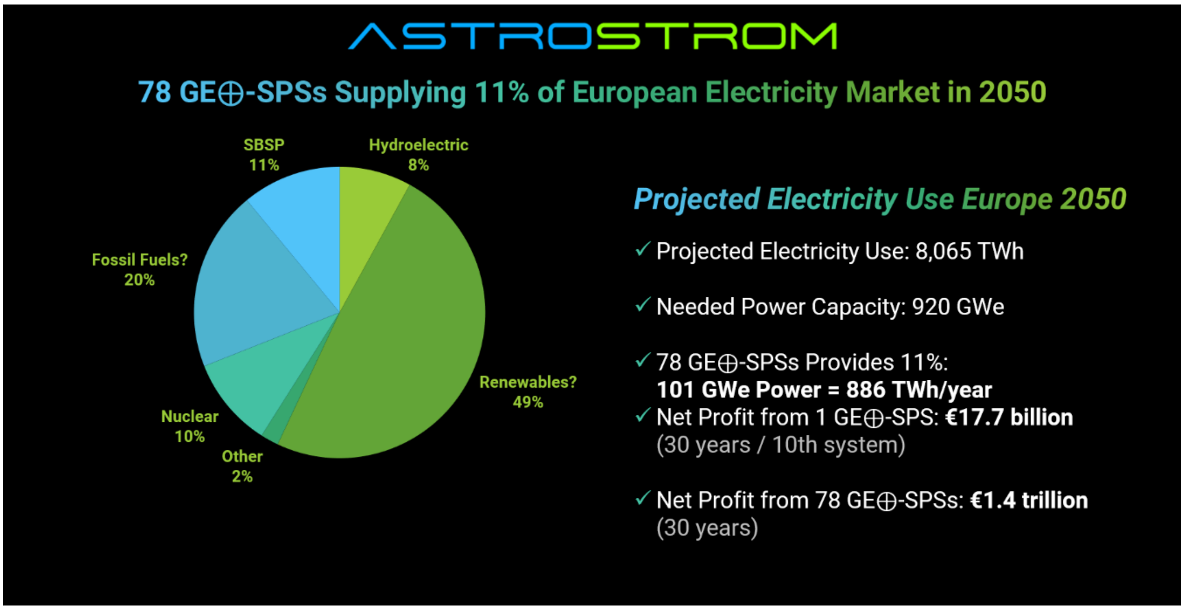


Figure 90: Supplying 11% of the European Electricity Market in 2050. (Credit: Astrostrom)

14.3. Dual Earth and Moon SPS Production Strategy

Over the years, the main discussion concerning SBSP has been about cost, i.e., will SBSP be competitive with terrestrial alternative energy sources when launch costs decrease as is expected. We now know that terrestrial renewable energy alternatives are not suitable for providing the scale of environmentally sustainable baseload power that will be needed. We also know that fossil fuel and uranium reserves are limited for a growing world economy that is heavily dependent on energy and especially, clean energy to address the climate crisis. However, now that programmes like ESA's Solaris are bringing the attention to the contribution that SBSP could make to the global energy mix, the community is becoming aware of the logistical launch capacity bottleneck confronting all Earth built and launched SPS systems. The discussion of this bottleneck issue often rests on the unbridled confidence that SpaceX will solve this problem when its Starship heavy lift launch system becomes operational, and that it will be mass-produced to offer unprecedented low-cost and frequent access to orbit. Due to the potential market for SBSP, it is assumed other launch providers will emerge with similar technology and launch capacity to satisfy the market demand for the thousands of rocket launches that will be needed to deploy Earth-built SPS systems at a significant rate.

The Frazer Nash brochure makes this evident (*FNC/LE, (2022).*

"Availability of space launch capacity will be a key constraint to the timing and speed of SBSP deployment. Using projected near-term space lift capability, such as SpaceX's Starship, and current launch constraints (based on the number of permitted launches and existing demand for space-lift capacity) delivering one satellite into orbit would take between 4 and 6 years. Providing the number of satellites to satisfy the maximum contribution that SBSP could make to the energy mix in 2050 would require a 200-fold increase over current space-lift capacity. By doubling the number of suitable launch sites and lift cadence, a 16-fold capacity increase can be achieved. Significant investment in new space-lift sites and launch vehicles will be needed."

"A European space-port and one reusable heavy launch vehicle could support around 77 SBSP launches per year, sufficient for an additional satellite per year to be delivered, taking global systems to between 1.5 and 2 per year. At that cadence, by 2050 there could be no more than 20 SBSP satellites, less than half the theoretical maximum."

ESA's on-going PROTEIN reusable launcher studies specifies a need for providing 10,000 tonnes to orbit per year. At a notional payload mass of 100 tonnes per launch to GEO, this cadence would be 100 launches per year to LEO which is only 21-29 tonnes to GEO per launch if PROTEIN proves to be as capable as the proposed Starship heavy lift launcher *(ESA ITT 1-11440).*

Additionally, there is the issue of launching 100 GW of capacity that would require perhaps 10,000 launches, burning more than 1 million tonnes of propellants, of which the environmental impact would probably be prohibitive. Surely this will become a public perception issue that will need to be addressed.

The lunar production of SPS components will not solve this launch bottleneck problem in its initial deployment phase which foresees the production of one SPS per year. Lunar surface production must be sufficiently scaled and transport from the surface of the Moon to EM-L1 significantly enhanced to increase this production cadence. This is only the first phase of an Earth-Moon energy driven economy which will surely continue to develop if the first phase proves to be successful.

As such, in the next decades a dual approach - Earth produced SPS and Moon produced SPS - to providing clean energy to Earth would seem to be the best strategy, even if this only doubles the expected capacity. Astrostrom's lunar GE⊕-SPS system and an Earth-launched SPS system such as the one baselined in the Frazer Nash study should be pursued in parallel simultaneously. Developed and deployed diligently, together these two approaches could provide at least 100 GWe or 10% of Europe's projected electricity demand for the year 2050, and then be expanded further as required. As a comparison, 10% is equivalent to electricity that could be provided by 111 new 1-GW nuclear power plants which, at €10 billion per GW, would cost more than €1 trillion if these could be built *(Flamanville, 2019) (Hinkley Point, 2019).*

Figure 91 shows a break-even cost comparison with a terrestrially produced and launched 1.44 GW SPS as described in the Frazer-Nash study brochure and a lunar-built 1.44 GW GE⊕-SPS as described in this study. According to Frazer-Nash the initial development cost will be ca. €16 billion, and the cost of a 10th SPS production unit will be €7.7 billion *(FNC/LE, (2022).* This is compared with an initial investment cost of €99 billion for the GE⊕-LPS lunar infrastructure and a production cost of €3.6 billion per GE⊕-SPS for a 10th production unit. The result is a typical break-even scenario comparing a high up-front investment cost, but lower operating costs once set up - versus a lower investment but higher operating-cost system. Calculated like this the break-even point would be hit at about 20 SPSs built.

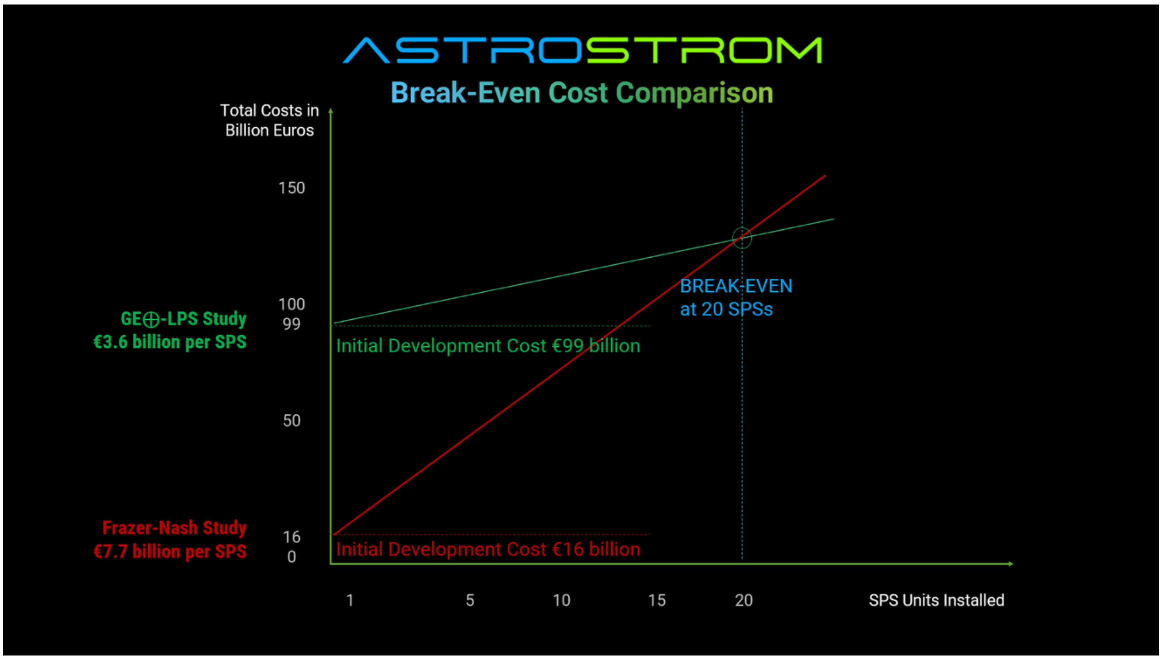


Figure 91: Break-Even Cost Comparison. (Credit: Astrostrom)

14.4. Additional Advantages of the GE⊕-SPS Approach

The GE⊕-SPS baseline system includes hardware sent from Earth (20% of the mass, 400 MT) and the human crew. The comparison of manufacturing satellite components on the lunar surface with terrestrial manufacturing is essentially a standard case of break-even analysis, except that the comparison between lunar production and terrestrial production can be usefully measured with three different parameters:

1. mass that needs to be launched from Earth which results in atmospheric pollution,
2. terrestrial energy resources used which cause pollution within the biosphere, and
3. monetary cost.

As in typical break-even analyses, the initial cost (as well as energy used and mass launched) to make things on the lunar surface will be higher than making them on Earth. However, as experience accumulates and the scale of production increases, the cost per unit will fall, due primarily to the lower energy needed to launch to GEO from the lunar surface than from the Earth - about 83% less. For simplicity, the present study considers only SPS units operating in GEO. The advantage of the much lower energy needed for transportation from the lunar surface than from Earth may be offset to some extent by the higher mass per unit and lower efficiency of SPS components that may be achieved, at least in the earlier phases of the project. A "mature" system should be able to manufacture products equivalent to those manufactured on Earth. As data become available, cost modelling should enable estimates of after how much investment and how many years lunar sourced SPS components could reach break-even and become cheaper than terrestrial components in GEO. This will depend on the rate at which lunar launch costs fall, and so on the development of the non-rocket launch systems such as a lunar space elevator (and/or a mass-driver).

For the foreseeable future, launches from Earth will use chemical-propellant rockets, which use terrestrial energy resources and cause atmospheric pollution. The effect on the ozone layer is also a major concern by experts *(Larson et al, AGU, 2016).* The development and implementation of various lunar-surface facilities, including particularly a range of materials-processing and manufacturing systems, will use terrestrial energy, rocket launch systems, and other terrestrial resources in the initial phases. However, as operations on the lunar surface lead to increasing lunar surface capabilities, there will be less and less need for resources delivered from Earth, both to the lunar surface and to GEO, leading to advantages of lunar over terrestrial manufacturing by reducing both energy that is used within the biosphere and the atmospheric pollution caused.

ESA's existing and prospective contributions to the NASA-led Artemis project provide a very timely opportunity for ESA to develop expertise in the lunar surface operations needed to make and launch SPS components, as proposed in this study. In the absence of the Artemis project, every piece of hardware needed, including a range of reusable manned vehicles, lunar landers and other vehicles would all have to be developed *de novo*. However, as a participant in Artemis, it seems probable that ESA will be able to use such systems developed by partners in Artemis in exchange for their use of systems developed by ESA. By careful planning of related technology development for "dual use" - that is, both for Artemis and for GE⊕-SPS - the hardware and know-how needed to realise GE⊕-SPS could be obtained at far lower cost than if it was a purely standalone ESA project.

Moreover, by developing GE⊕-SPS, ESA's contribution to Artemis, and other projects that contribute to GE⊕-LPS, will also be able to be repaid later from commercial revenues earned by SPS electricity sales to Earth. This is an example of the transformative influence of using space technology and knowhow to help solve humans' energy problem: space agencies' costs related to this will cease to be a burden on taxpayers, and will contribute directly to enabling sustainable, world-wide economic growth. Consequently, further investigation of the feasibility and optimisation of GE⊕-LPS and GE⊕-SPS concepts would be very timely inputs for planning ESA's participation in Artemis to have the greatest possible economic value.

14.5. Flywheel Effects

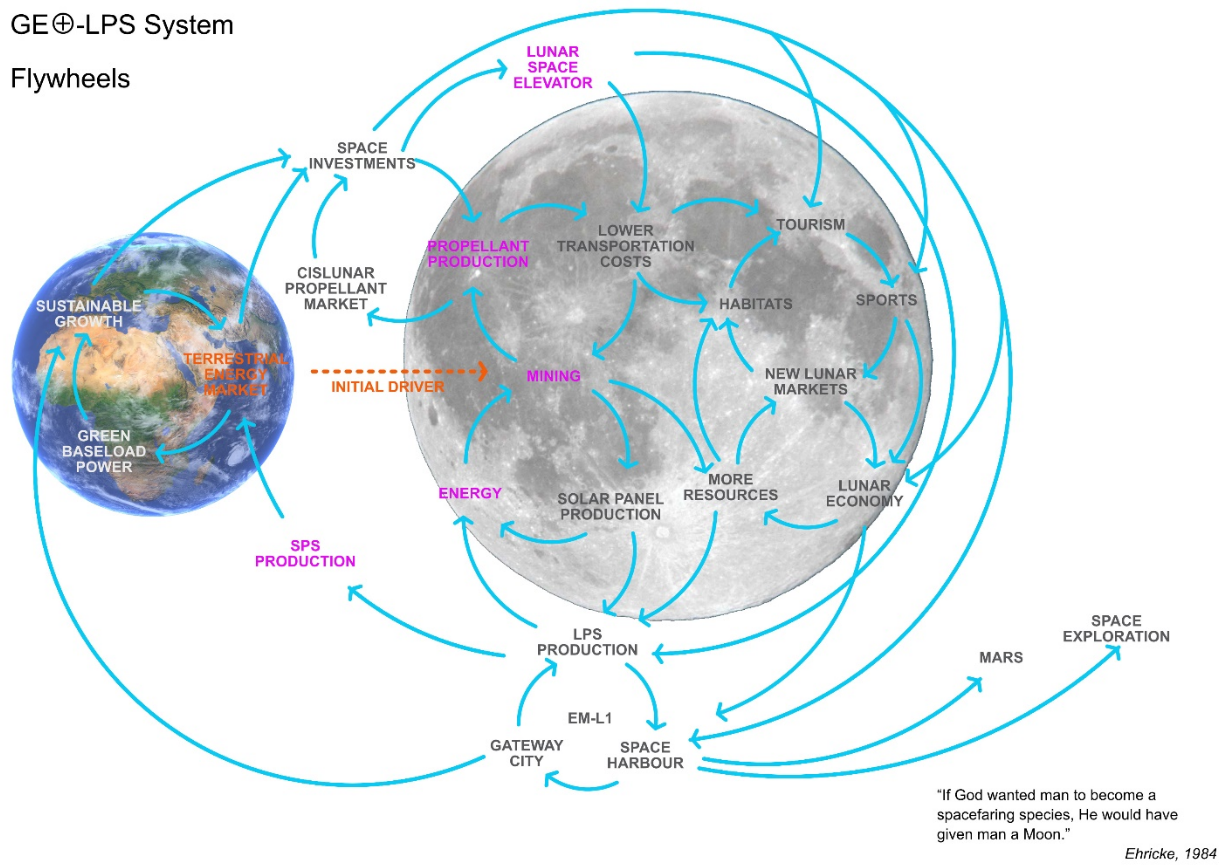


Figure 92: The GE⊕-LPS System Flywheel Effects. (Credit: Astrostrom)

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. The flywheel effect has often been used to describe the growth dynamics of companies that grow rapidly to large-scale, such as Amazon Inc, which is reported to have invested $300 billion before earning a profit. For the GE⊕-LPS system, it is very clear that the initial investment needed will be large. However, the benefits of establishing an industrial base on the Moon will be commensurately large, and may well grow to have significant benefits for future generations which have not yet been anticipated.

As shown in Figure 92, the initial driver is the need for a green baseload energy source supplying the terrestrial electricity market, which can be realized by developing SPS. However, a bottleneck is created by the large number of heavy-lift launches needed to transport the massive, GW-scale SPS units from Earth to GEO.

This raises the question: What if the systems to be located in space were actually built in space and not on Earth? In this context the Moon offers unique possibilities which have been discussed theoretically for decades. Mining the Moon to build SPSs for Earth will lead to the production of photovoltaic systems and propellants on the lunar surface, which in turn will supply more and cheaper energy to Earth, which will lead to increasing space investment, new space businesses, and other opportunities, in a virtuous circle of economic growth. Also, most importantly, the initial driver is not a specific, small and uncertain market like that for Helium-3, but the whole world's trillion-dollar electricity market, which is growing even faster than the overall energy market as electrification spreads - as well as contributing to the growing need for energy security. In this way, many new markets will be not only expanded, but created from scratch. These include a cislunar transportation and logistics market, a lunar mining and beneficiation market, a propellant market in cislunar space, a market in GEO for numerous SPS components and related services, an energy market on the Moon, tourism and entertainment markets in cislunar space, and others.

14.6. Cooperation Among Nations

Another important driver is the geopolitical aspect. Cooperation among nations is turning into competition for scarce resources and economic advantages. In short, the world needs to become more united in order to address the many issues humanity currently faces. The International Space Station has been a remarkable example of peaceful cooperation in space and is the most politically and legally complex space exploration programme in history involving five space programmes and fifteen countries. In the 1998 Space Station Intergovernmental Agreement set forth the primary framework for international cooperation among the parties. A series of subsequent agreements govern other aspects of the station, ranging from jurisdictional issues to a code of conduct among visiting astronauts which continues today even after the Russian-Ukraine conflict. Cooperation in a multi-national "macro-engineering" project such as GE⊕-LPS could contribute even more to improving global security and de-escalating already dangerous tensions benefitting all nations in numerous ways.

14.7. Creating a Lunar Industrial Base

It is of particular importance that development of the ability to construct much of the mass of the GE⊕-LPS from components produced on the lunar surface will create the ability to make components that could be used in SPS units supplying electrical power to the Earth. As such, GE⊕-LPS can be considered as a prototype for developing and maturing the systems needed to eventually make SPS units for operation in GEO, providing environmentally benign, clean electric power to Earth. Evaluation of additional potential benefits arising from other uses of the lunar-surface manufacturing capabilities developed for GE⊕-LPS will depend on scenarios for the development of other commercial uses of the lunar surface, as discussed below.

It will require considerable initial investment to develop manufacturing and launch facilities on the lunar surface. However, the demand for electrical power on Earth is going to grow continually for decades to come, enabling energy-related lunar operations to reach very large scale, sufficient to repay even large investments – on the condition that the cost of lunar-produced components and sub-systems delivered to GEO, including environmental costs, will become lower than Earth-produced sub-systems in GEO. Part of the revenue stream paid by electricity companies for microwave power supplies delivered from SPS satellites in GEO to rectennas on Earth, will pay for the costs of the lunar-produced components of the satellites. How far they may also repay the initial investment required to develop the needed manufacturing and launch facilities remains to be seen, but initial estimates seem positive. Once the technology and systems developed reach a sufficient level of maturity for companies, including insurance companies and banks, to have confidence in them, lunar-based production of SPS parts for power supply to Earth and other uses should become a largely commercial activity.

14.8. Creating a Lunar Economy

The process of implementing the GE⊕-CTS concept will develop a range of technologies for operation on the lunar surface and at EM-L1. This will thereby "de-risk" a range of activities that are not feasible today. Among others, the technology and know-how to construct buildings on the lunar surface needed for GE⊕-LPS will create particularly valuable technology and know-how of vital importance for all companies planning lunar surface activities. In this way the GE⊕-LPS operations will become both the anchor customer and the economic driver for future lunar activities.

There is a range of companies with no experience of space engineering which may choose to participate in lunar activities once they are possible for people other than professional astronauts. This will notably include companies already involved in orbital tourism services. This creates a potentially exponential business opportunity for the initial operators of the GE⊕-LPS mining, processing, manufacturing, and construction activities as other players become customers for these products and services.

14.9. Creating a Cislunar Economy

Implementing the GE⊕-CTS leads to the possibility of upscaling the lunar operations to serve different economic sectors that would benefit from an Earth-Moon cislunar economic development scenario.

14.9.1. Energy for Earth

Once the GE⊕-LPS becomes operational as a 'proof-of-concept' it is foreseen that the installed lunar operations will be upscaled to begin production of SPSs for the multi-trillion Euro terrestrial energy market. This will be a gradual process, but eventually energy from space might even become one of the main sources of energy for powering civilization on Earth and beyond.

14.9.2. Propellant Production

One of the first industrial processes on the lunar surface will be the production of propellants to serve lunar and cislunar transportation and Earth-bound return vehicles. Regolith is rich in oxygen which has many obvious uses from life-support to industrial production. Oxygen will be a by-product of many lunar material utilization processes. Hydrogen may be obtained from the water ice that is claimed to be present in the shadowed craters in the polar regions.

14.9.3. Helium-3

Helium-3 (He-3) is very rare in the terrestrial environment but found in significant concentrations in the lunar regolith. The Helium-3 isotope has a wide range of applications on Earth, including quantum computing and modern cryogenics research to achieve extremely low temperatures. As a medical isotope, He-3 is used as a non-toxic inhalant to scan for lung function. He-3 is used in neutron research in colliders to study the "shadow world" of anti-matter, helping to uncover some of the deepest mysteries of the universe. Helium-3 has also been identified as a promising fuel for realising nuclear fusion as an energy source.

14.9.4. Transportation

The implementation of the GE⨁-LPS will require from its early phase, the development of reusable European launch systems, a reusable Earth-to-LEO human transport system and a LEO cargo transit station. The next phase will develop the Greater Earth Lunar Space Elevator (GE⨁-LSE) to enable lunar-sourced SPS components to be sent to the EM-L1 assembly location. As the GE⨁-LSE becomes more robust to handle greater cargo loads from the Moon, it will also extend Earthwards as its capacity increases. This will result in an Earth-Moon transportation system with an economic hub located at or adjacent to the EM-L1 hub of the GE⨁-LSE. Due to their uniqueness, EM-L1 and EM-L2 will become important pieces of a cislunar space infrastructure, used by many countries, similar to the Suez and Panama canals. Orbital assembly operations in or near GEO may develop as the cislunar transportation system matures and a demand for lunar-sourced components develops - not only for GE⨁-SPS - but for other SPS designs as well.

14.9.5. Tourism

The GE⨁-LPS design incorporates a central habitat that is intended for human management of the satellite and as a waystation for crew transport operations. The system design also includes a lunar base station for managing surface operations. Both aspects require the development of secure Closed-Loop Life Support Systems (CLLSS) suitable for sustaining and protecting the human crew during the performance of their missions. Developing a lunar industrial complex will require the construction of extensive buildings, including manufacturing facilities from lunar materials. These are core capabilities for future tourism activities, and so once they are in place and functioning reliably and safely, there will be an immense motivation for companies in several countries to develop lunar tourism destinations.

New forms of tourism and entertainment, such as sport and dance in low gravity will also become possible and attractive for broadcasting to worldwide audiences as well as to visitors from Earth seeking a 'once-in-a-lifetime' experience. Such possibilities are already being considered by the French Zenon company in a collaboration with the Moonshot Institute with the support of CNES and ANRT *(Parabolic Arc, 2021)*.

14.9.6. Security

2022 became the year of global insecurity. Extreme weather abnormalities affecting food production point to an acceleration in the changing climate. Geopolitical conflicts, including the destruction of massive energy infrastructure, have already impacted the reliable delivery of energy resources which are forcing countries to rethink their energy policies and their future energy security. For the security of humanity's future well-being on Earth, it seems that the time has come to extend human civilization beyond the home planet and establish it on its closest celestial neighbour. The GE⊕-LPS concept is a visionary opportunity to refocus humanity's popular perception of its place and purpose in the cosmos. If successful, eventually providing clean and plentiful energy from space not only to Europe, but also to countries throughout the world, it will lead to solving both the climate and the energy crises confronting humanity. To be successful, this will require a united global cooperative effort which may be manifested and facilitated in the creation of an intergovernmental space energy industrial organization.

14.10. Possible Synergies

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.

14.10.1. Reusable Launcher Development

There is obvious synergy between this transportation system, which will be valuable for many other projects, and implementing GE⊕-LPS. €10 billion for the development of a reusable heavy-lift launcher has been included in the GE⊕-LPS initial investment budget of €99 billion which is considerably more than the cost of Ariane 6 development.

14.10.2. Cislunar Space Elevator

€11 billion for the development of a Lunar Space Elevator (LSE) has also been included in the GE⊕-LPS €99 billion initial investment sum outlined in Section 13.1. This is several times the cost estimate of $2 billion for a prototype LSE proposed by Charles Radley and Marshall Eubanks *(C. Radley, 2017) (T. M. Eubanks, C. Radley, 2016*). There will be many advantages from creating such a transformative Earth-Moon transportation infrastructure beyond the implementation of GE⊕-LPS, including those for many countries beyond Europe. Earlier concepts of large-scale Moon production systems (mainly from the 1970s) relied on the "mass driver" technological concept to launch material to the Earth-Moon Lagrange point 2 (EM-L2) to be captured by a "mass catcher" and then processed into useful elements in zero-g conditions. However, alone the strong weight and volume restriction of such payloads makes a mass driver a very inflexible device, in addition to many other unsolved problems. The presence of lunar gravity simplifies many production techniques compared to microgravity in orbit. By comparison, the LSE offers much more flexibility and a higher potential for a future cislunar economy. However, research and engineering studies are scarce and should be intensified as the LSE has the potential to become a key infrastructure element in cislunar space.

14.10.3. Greater Earth Energy Organization - GEEO

A new dedicated international organization comprised of nation stakeholders would have many advantages beyond providing and guaranteeing the initial financial investment. These include: enabling a just return on the investment to all stakeholders, fair distribution of geographically weighted industrial return contracts, establishing necessary laws and regulations, and ensuring compliance in adherence to the provisions of the Outer Space Treaty.

14.10.4. Mining Industry

The terrestrial mining industry is very experienced in resource extraction using autonomous robotic equipment. This industry is also dependent on finding new sources of resources to mine and process. Cislunar resource utilization could become a major new market for this industry, both in terms of engineering and in access to valuable resources.

14.10.5. Construction Industry

Establishing a lunar base will require in-situ mining and processing of lunar regolith into construction elements for buildings, roads, factories, and storage facilities. The main priority will be obtaining the specific materials necessary to construct the GE⊕-LPS, but once developed these construction processes will be available to be applied to other lunar surface projects requiring such infrastructure. The spin-offs from the development of automation and robotics will be beneficial for the terrestrial construction industry as well as for future solar system industrial activities.

14.10.6. Energy Industry

Energy powers civilization. Providing sufficient, reliable, secure and environmentally neutral sources of energy is necessary for the transition to a carbon neutral future for developed societies while ensuring access to plentiful sources of energy for developing countries. As shown in section 5, scaling terrestrial energy sources to meet the growing energy needs of humanity on Earth would be extremely challenging due to various restraints. However, the region of "Greater Earth" has 13 million times the volume of the physical Earth and through it passes more than 55,000 times the amount of solar energy which is available on the surface of the planet. The amount of sunlight passing through the cislunar region alone is 6,400 times the amount that reaches the surface of Earth. This is a natural resource potentially available for supplying terrestrial energy use, which is already a multi-trillion-Euro market and is perpetually growing.

14.11. Parallel Lunar Industrial Development

GE⊕-LPS represents a significant industrial development program that spans cislunar space. To date there have been mostly exploratory activities in this region and any major effort to initiate ISRU for commercial purposes will automatically attract industrial players to consider potentially commercial projects in line with their area of expertise. The GE⊕-LPS project would involve the development of a range of activities and infrastructure on the lunar surface. These include facilities for mining, materials processing, and manufacturing, as well as water and propellant production.

There is already a very considerable research literature on the subject of industrial processing on the lunar surface. Unfortunately, none of this work has yet been tested in the lunar environment, although a small number of possibilities has been tested on Earth with lunar regolith simulants. Although the GE⊕-LPS project is carefully planned to require as few different industrial processes as possible, its activities will create an initial industrial base on the lunar surface, making it increasingly easy for other entities to initiate other activities involving a wider range of new and even experimental processes.

The industrialisation of the lunar surface will thus involve incremental growth of successful capabilities such as solar panel production, as well as experimental development of new processes, using such techniques as a range of methods of thermal processing of materials, use of robot-clusters, electron-beams and others. In this way it can be anticipated that lunar industrialisation will create a "virtuous circle" of growth much as seen on Earth in the development and growth of industrial "clusters". The initial publicly funded activities will play the same role of de-risking the later investments which will be predominantly from the private sector.

There will also be rocket landing and launching sites made from melted basalt, as well as sintered or melted basalt roadways between the different facilities and mining sites, and for access to the base of LSE-1. There will also be a range of buildings made largely from 3-D printed basalt, with both cast and sintered basalt parts, and using complex components delivered from Earth. These will include unpressurised and pressurised doorways, with attached equipment such as airlocks, dust-traps (using static electricity, air jets and/or other methods), and air-tight electric cabling pass-throughs. Some buildings may have windows (also delivered from Earth, at least initially). There will also be water supply and wastewater treatment facilities.

These will not comprise typical systems seen in terrestrial buildings, but will be more basic, based on systems developed for and used in airliners, ISS and elsewhere, such as in orbital hotel facilities currently being developed by companies such as Bigelow Aerospace Inc, Orion Span Inc, Orbital Assembly Inc, and Axiom Space Inc.

All of these systems will be progressively developed further over time to be as convenient as, though not identical to, terrestrial systems, through the normal processes of incremental improvement, which will be faster the more people use them. Consequently, these facilities, equipment and systems will become progressively available for additional users who plan activities on the Moon.

The Exploration Company in Germany and Ispace Inc. In Japan are due to deliver several small payloads to the lunar surface. If these projects succeed, the two companies may well have a series of customers who wish to test aspects of regolith processing at small scale. This could greatly help to advance knowledge in this field.

14.12. Common Utilization of In-situ Resources

Practically all lunar development scenarios consider the following operations essential to establishing a sustainable long-term presence on the Moon. In addition to supplying energy to Earth, the following ISRU activities will be mutually beneficial.

14.12.1. Rocket Propellant Production

The apparent discovery of water-ice at the lunar poles reinforces the possibility that in-situ production of rocket propellant could realistically enhance rocket traffic to and from the lunar surface, as assumed in almost all scenarios of lunar settlement. The production of rocket propellant will be one of the first objectives of the initial GE⊕-LPS operations, with or without using hydrogen from water-ice, since oxygen is plentiful in the lunar regolith. This is probably one of the first business cases for lunar industrial development not only for transportation on the lunar surface but also for exporting propellants to LEO as, once the necessary infrastructure is developed, this could become less expensive than launching them from Earth, as estimated in the recent study Commercial Lunar Propellant Architecture: A Collaborative Study of Lunar Propellant Production *(Kornuta et al. 2019).*

14.12.2. Life Support Systems

The apparent discovery of water on the Moon is also obviously important for future life-support systems. Water and oxygen are essential for maintaining human crews and for future agricultural installations which will be important for recycling and food production. Long-term crews will rely on such systems in later phases of GE⊕-LPS operations. As lunar development progresses, such bio-science capabilities will be another potentially lucrative business case, for which accumulating early experience will be valuable. As commodities, both water and hydrogen will become a source of trade between lunar bases.

14.12.3. In-Situ Energy Production

Before a power producing system such as GE⊕-LPS becomes operational, energy production on the lunar surface will be necessary for all mining and industrial operations. Photovoltaic (PV) panels made from in-situ resources could be used for energy production on the lunar surface and can be expected to be scaled up later to supply PV systems for SPS production in GEO. Many previous studies citing future PV production from ISRU assume silicon would be the obvious material of choice due to the large presence of silicon in lunar materials.

However, the industrial processes required to manufacture clean silicon wafers on an industrial scale are considerable and require much use of liquids *(Landis, 2005).* Conventional vacuum processes and vapour-phase deposition—for the fabrication of electronic devices are also not practical on the Moon. Therefore, research on alternatives like the proposed pyrite based Monograin Layer (MGL) technology should be intensified *(Raadik, et. al 2021).* MGL lightweight solar panel technology combines the advantages of high-efficient single-crystalline material and low-cost roll-to-roll panel production, enabling the manufacture of flexible, lightweight, and cost-efficient solar panels from powders of crystalline semiconductor absorber material without involving the complicated silicon wafer production technique. In addition, these solar cells are readily recyclable, in contrast to silicon-based cells. As more entrepreneurs come to the Moon, solar panels produced from lunar materials will become a valuable product in the local lunar economy.

14.12.4. In-Situ Energy Storage

Given the long lunar night, in-situ energy storage technologies need to be developed to extend the time of production. Initially the GE⊕-LPS system will only provide energy storage for the habitat and will cease production during lunar night. This situation will persist until enough power is beamed from the LPS to continue production during the night. However, with given energy storage capabilities the lunar energy grid can be kept in balance with good safety and redundancy and this could become a commercially viable service.

15. Greater Earth Energy Organisation (GEEO)

To supply Europe (and the world) with a substantial percentage of its future electrical needs via SBSP will result in the creation of a new space energy industry. Frazer Nash's Cost/Benefit study in 2022 indicated R&D investment of €15.8 billion over four phases would be necessary to develop the first GW-scale in-orbit SPS prototype. However, the R&D of reusable spacelift capability was not included in the development programme costs they presented (*FNC/LE, (2022).* This reusable heavy lift launch system may add approximately €10 billion to the initial cost of developing SBSP. The lunar option described in this study including a cislunar transportation infrastructure would be an additional €70 billion. Thus, with projected costs on the order of one hundred billion Euros to achieve Europe's energy goals, a multi-national approach is deemed likely and necessary.

Figure 93: GEEO.earth / GEEO.space. (Credit: Astrostrom)

Using the amount of €100 billion as a baseline goal, Astrostrom proposes the creation of a *Greater Earth Energy Organisation (GEEO) (*)* based on existing and established organizational examples 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 is to provide Europe and the eventually entire world with an inexhaustible supply of environmentally clean energy in an equitable, economical, and socially just manner. The GEEO would be set up as a democratic organization composed of national entities independent of any other international organization or influence. An international consortium of national entities working together would also allow expediency in addressing the regulatory issues of spectrum allocation, orbital positioning, and energy distribution issues. *(* see section 18.2 for a definition of Greater Earth)*

As an international consortium of nations, the GEEO should be incorporated as a not-for-profit organization. The main advantage to having such a structure would be to avoid conflict and competition between nations and to provide a transparent process for the development and eventual distribution of this new space energy resource. Ideally, this organization should be based in a neutral country with a credible regulatory framework. Switzerland represents such a country and international organizations such as the IOC – the International Olympic Committee (in French, Comité International Olympique CIO) and FIFA (Fédération Internationale de Football Association) have their headquarters in Switzerland and both are registered as "associations" which, under Swiss law, allows them to have a tax-free status if requested. Both organizations manage budgets amounting to billions of dollars. Other examples are the World Health Organization (WHO) and the Bank for International Settlements (BIS) which have additional diplomatic privileges.

15.1. Precedents

There are two precedents for this type of international space related organization. The first is INTELSAT (1964-2001) – an intergovernmental consortium owning and managing a constellation of communication satellites before it became privatized in 2001. The second is the European Space Agency (ESA) – an inter-governmental organization of 22 member nations and 9 associate members dedicated to the exploration of space which was founded in 1975.

In the case of INTELSAT, the financing was shared among the participating members according to members' so-called investment shares which were proportional to each member's use of the system, as determined on an annual basis.

The European Space Agency on the other hand, has two budgetary categories: "Mandatory" which all member contributions are based on a scale related to their Gross National Product and "Optional" where members can optionally participate in special programs. It is interesting to note that not all member countries of the European Union are members of ESA and not all ESA member states are members of the European Union. This is an important aspect.

From its beginning, ESA has applied a principle of *juste retour* (fair return) in its industrial procurement policy of geographical distribution. The juste retour principle means that national contributions are distributed only to selected research teams from that particular country. Simply stated this is based on the ratio between the share of the weighted value of contracts a member country receives, and the country's contributions paid to ESA. This percentage of a member's contribution is called the "industrial return coefficient". For example, with a coefficient of 98% a member country can expect to receive 98% of its annual contribution in the value of contracts placed with its local industries. This process is constantly evolving, and each budgetary process must look at the needs and goals of the organization in order to determine how this process can be optimally applied to a system involving contractors and sub-contractors.

15.2. International Consortium - GEEO

Using these two organizations as examples and as inspiration of the kind of international organization needed, the GEEO would be set up as an international consortium of nation states. Each member state will become a member of the GEEO Assembly of Parties (GAP) with an equal vote in deciding the strategic organizational policies and the budget plans. An organizational infrastructure would be created to manage all GEEO operations. As proposed, the GEEO is designed to provide a framework for administrating, organizing, managing and financing the accelerated development of SBSP including the GE⊕-LPS option if shown to be technically feasible, or any other future energy technology that may become feasible.

Technological and economic progress are closely correlated with per capita energy consumption. There is a close fundamental correlation between the stage of development of a country and its energy consumption. Developed countries have the highest per capita consumption of energy. Poorest, least developed countries have the lowest per capita consumption. To achieve as much as possible a 100% fair and equal participatory plan reflecting the energy procurement and development process, and to stimulate energy use responsibility, each member's contribution to GEEO would be determined by an *efficiency coefficient* that is based on its population and its per capita energy consummation. A country with a high per capita consumption of energy and a small population would contribute correspondingly more to the GEEO budget than a country with a large population and a lower per capita energy consumption level calculated on a *per capita basis*.

As increased energy is usually correlated with a country's level of economic development, this formula should encourage already developed countries consuming higher levels of energy to become more energy efficient while stimulating lesser developed countries with low per capita energy use to intentionally increase their level of energy use in order to further their economic development.

The following example illustrates how this might function. As with the ESA concept of fair return and geographical distribution, an equal percentage of a country's contribution to GEEO will be returned to each country through contracts that are placed with its local industries and organizations. The GAP meets and determines its immediate development goals and associates a corresponding budget to achieve these goals. With a larger number of participating member countries, the budget can be larger while the per country contribution smaller. Figure 94 shows the funding breakdown of the ESA budget for 2021.

Using the ESA member states as an example for GEEO membership and applying the *energy coefficient*, this results in an average per capita contribution from each member state. For comparison purposes Switzerland (CH - above left in the image), one of the founding members of ESA, is highlighted in each chart. Switzerland's 2021 contribution to ESA was €172.6 million which was 3.8% of the ESA yearly budget.

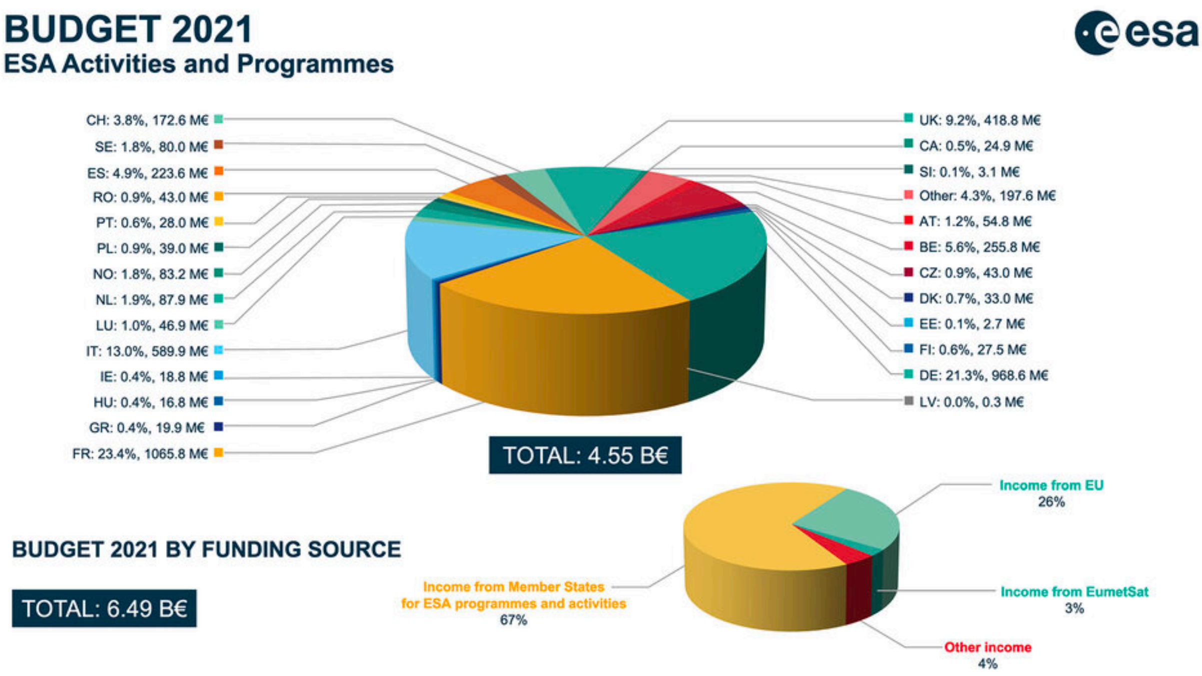


Figure 94: Breakdown of the ESA budget for 2021 (Credit: ESA)

15.2.1. GEEO Budget Scenarios

The following describes the initial budget of the GEEO which would be required to create the necessary organizational apparatus and facilities. When this organization has been established and becomes operational, the procurement of technology and services would require a substantially larger investment budget which is estimated to be between €50 and €100 billion until the year 2050. Once the first solar power satellites begin delivering power to Earth, the operational costs will be covered by the revenues from providing energy to terrestrial markets and resulting in profits to all the participating nations. Indeed, according to our calculations, SPS would be profitable, and the initial investment could be repaid if necessary. However, this initial investment is more than financial, it is an investment in the environment, in energy security, in resolving geopolitical conflicts and it is an investment in hope for a prosperous future.

15.2.2. Initial GEEO Budget: €100 Million

To begin GEEO operations, an initial yearly budget of €100 million is set. The chart in Figure 95 shows that per capita contributions from of all ESA members states is an average of 20 Euro cents. Again, as an example, Switzerland, with its population of 8,570,146 and per capita energy consumption in 2019 of 4.171 kW would contribute a total of €1,392,428 for this first-year of operations.

GEEO Budget: 100 Million Euros

Country		Population 2020	Per capita kWh 2019	Per capita kW 2019	H/year	Efficiency Coefficient	Multiplier	Total Contribution	Per capita Contribution
					8760		0.2		
Austria	FM	8’935’112	46’524	5.311		1.034		1’848’287	0.2
Belgium	FM	11’492’641	65’303	7.455		1.452		3’336’916	0.3
Czech Republic	FM	10’701’777	44’313	5.059		0.985		2’108’528	0.2
Denmark	FM	5’873’420	33’535	3.828		0.746		875’753	0.1
Estonia	FM	1’328’439	50’001	5.708		1.112		295’333	0.2
Finland	FM	5’536’146	55’118	6.292		1.225		1’356’730	0.2
France	FM	67’413’000	41’281	4.712		0.918		12’373’319	0.2
Germany	FM	83’190’556	47’703	5.446		1.060		17’644’610	0.2
Greece	FM	10’678’632	30’384	3.468		0.675		1’442’623	0.1
Hungary	FM	9’730’000	28’489	3.252		0.633		1’232’487	0.1
Ireland	FM	5’001’500	37’739	4.308		0.839		839’234	0.2
Italy	FM	60’317’116	29’239	3.338		0.650		7’841’433	0.1
Luxembourg	FM	633’622	76’658	8.751		1.704		215’963	0.3
Netherlands	FM	17’694’600	57’047	6.512		1.268		4’488’135	0.3
Norway	FM	5’425’270	91’240	10.416		2.028		2’200’893	0.4
Poland	FM	38’179’800	31’355	3.579		0.697		5’322’710	0.1
Portugal	FM	10’344’802	28’328	3.234		0.630		1’302’958	0.1
Romania	FM	19’186’201	19’665	2.245		0.437		1’677’549	0.1
Spain	FM	47’540’795	34’004	3.882		0.756		7’187’681	0.2
Sweden	FM	10’402’070	62’047	7.083		1.379		2’869’676	0.3
Switzerland	FM	8’570’146	36’542	4.171		0.812		**1’392’428**	0.2
United Kingdom	FM	67’081’000	32’250	3.682		0.717		9’618’816	0.1
Canada	N-FM	38’436’447	105’540	12.048		2.346		18’036’517	0.5
Latvia	N-FM	1’907’675	23’137	2.641		0.514		196’247	0.1
Lithuania	N-FM	2’795’680	24’641	2.813		0.548		306’294	0.1
Slovenia	N-FM	2’108’708	37’446	4.275		0.832		351’087	0.2
		POPULATION		**Avg. per capita kW**				**BUDGET**	AVG.
Totals		**550’505’155**		**5.135**		**1.000**		**106’362’209**	**0.2**

FM=Full ESA Member
N-FM= Non Full Member

Population: Wikipedia
Per capita kWh 2019
https://ourworldindata.org/grapher/per-capita-energy-use

Figure 95: GEEO € 100 million budget. (Credit: Astrostrom)

15.2.3. Implementation Budget: €10 Billion/Year

As shown in Figure 96, once the GEEO organization is set-up and running, a yearly development budget of €10 billion may be considered realistic for technology development and procurement of space services and hardware. In this budget phase, an average per capita contribution of €19 from each member country would be necessary to reach the €10 billion budget. Switzerland's contribution in this scenario is about €132.3 million, and its per capita contribution would be €15.4. Note: countries which are large energy producers such as Canada (12.048 kW) and Norway (10.416 kW) consume substantially more energy per capita than countries without large energy production such as Switzerland (4.171 kW) or Austria (5.311 kW). The yearly administration budget is estimated to remain at €100 million.

GEEO Budget: 10 Billion Euros

Country		Population 2020	Per capita kWh 2019	Per capita kW 2019	H/year	Efficiency Coefficient		Multiplier	Total Contribution	Per capita Contribution
					8760			19.0		
Austria	FM	8'935'112	46'524	5.311		1.034			175'587'260	19.7
Belgium	FM	11'492'641	65'303	7.455		1.452			317'007'055	27.6
Czech Republic	FM	10'701'777	44'313	5.059		0.985			200'310'172	18.7
Denmark	FM	5'873'420	33'535	3.828		0.746			83'196'551	14.2
Estonia	FM	1'328'439	50'001	5.708		1.112			28'056'679	21.1
Finland	FM	5'536'146	55'118	6.292		1.225			128'889'322	23.3
France	FM	67'413'000	41'281	4.712		0.918			1'175'465'311	17.4
Germany	FM	83'190'556	47'703	5.446		1.060			1'676'237'966	20.1
Greece	FM	10'678'632	30'384	3.468		0.675			137'049'205	12.8
Hungary	FM	9'730'000	28'489	3.252		0.633			117'086'278	12.0
Ireland	FM	5'001'500	37'739	4.308		0.839			79'727'219	15.9
Italy	FM	60'317'116	29'239	3.338		0.650			744'936'128	12.4
Luxembourg	FM	633'622	76'658	8.751		1.704			20'516'519	32.4
Netherlands	FM	17'694'600	57'047	6.512		1.268			426'372'822	24.1
Norway	FM	5'425'270	91'240	10.416		2.028			209'084'860	38.5
Poland	FM	38'179'800	31'355	3.579		0.697			505'657'447	13.2
Portugal	FM	10'344'802	28'328	3.234		0.630			123'781'018	12.0
Romania	FM	19'186'201	19'665	2.245		0.437			159'367'182	8.3
Spain	FM	47'540'795	34'004	3.882		0.756			682'829'698	14.4
Sweden	FM	10'402'070	62'047	7.083		1.379			272'619'247	26.2
Switzerland	FM	8'570'146	36'542	4.171		0.812			**132'280'701**	15.4
United Kingdom	FM	67'081'000	32'250	3.682		0.717			913'787'475	13.6
Canada	N-FM	38'436'447	105'540	12.048		2.346			1'713'469'108	44.6
Latvia	N-FM	1'907'675	23'137	2.641		0.514			18'643'497	9.8
Lithuania	N-FM	2'795'680	24'641	2.813		0.548			29'097'906	10.4
Slovenia	N-FM	2'108'708	37'446	4.275		0.832			33'353'225	15.8
		POPULATION		**Avg. per capita kW**					**BUDGET**	AVG.
Totals		**550'505'155**		**5.135**		**1.000**			**10'104'409'852**	**19.0**

FM=Full ESA Member
N-FM= Non Full Member

Population: Wikipedia
Per capita kWh 2019
https://ourworldindata.org/grapher/per-capita-energy-use

Figure 96: GEEO Budget €10 billion all ESA member states. (Credit: Astrostrom)

Figure 97 shows the impact on the member contributions if, for example, four ESA countries decide not to participate in the space energy program. In this scenario Canada, Norway, France and the United Kingdom have declined to participate. In this example, the average per capita contribution increases to €29 to meet the €10 billion budget. In the case of Switzerland, its contribution increases to €222.2 million.

GEEO Budget: 10 Billion Euros									
Country		Population 2020	Per capita kWh 2019	Per capita kW 2019	H/year	Efficiency Coefficient	Multiplier	Total Contribution	Per capita Contribution
					8760		29.0		
Austria	FM	8'935'112	46'524	5.311		1.138		294'939'361	33.0
Belgium	FM	11'492'641	65'303	7.455		1.598		532'486'572	46.3
Czech Republic	FM	10'701'777	44'313	5.059		1.084		336'467'202	31.4
Denmark	FM	5'873'420	33'535	3.828		0.820		139'747'824	23.8
Estonia	FM	1'328'439	50'001	5.708		1.223		47'127'673	35.5
Finland	FM	5'536'146	55'118	6.292		1.349		216'499'388	39.1
France	FM								
Germany	FM	83'190'556	47'703	5.446		1.167		2'815'628'848	33.8
Greece	FM	10'678'632	30'384	3.468		0.743		230'205'796	21.6
Hungary	FM	9'730'000	28'489	3.252		0.697		196'673'448	20.2
Ireland	FM	5'001'500	37'739	4.308		0.923		133'920'280	26.8
Italy	FM	60'317'116	29'239	3.338		0.715		1'251'292'295	20.7
Luxembourg	FM	633'622	76'658	8.751		1.875		34'462'233	54.4
Netherlands	FM	17'694'600	57'047	6.512		1.396		716'191'640	40.5
Norway	FM								
Poland	FM	38'179'800	31'355	3.579		0.767		849'368'482	22.2
Portugal	FM	10'344'802	28'328	3.234		0.693		207'918'811	20.1
Romania	FM	19'186'201	19'665	2.245		0.481		267'693'994	14.0
Spain	FM	47'540'795	34'004	3.882		0.832		1'146'970'200	24.1
Sweden	FM	10'402'070	62'047	7.083		1.518		457'926'996	44.0
Switzerland	FM	8'570'146	36'542	4.171		0.894		**222'195'992**	25.9
United Kingdom	FM								
Canada	N-FM								
Latvia	N-FM	1'907'675	23'137	2.641		0.566		31'316'060	16.4
Lithuania	N-FM	2'795'680	24'641	2.813		0.603		48'876'655	17.5
Slovenia	N-FM	2'108'708	37'446	4.275		0.916		56'024'445	26.6
		POPULATION		**Avg. per capita kW**				**BUDGET**	AVG.
Totals		**372'149'438**		**4.666**		**1.000**		**10'233'934'196**	**29.0**

FM=Full ESA Member
N-FM= Non Full Member

Population: Wikipedia
Per capita kWh 2019
https://ourworldindata.org/grapher/per-capita-energy-use

Figure 97: GEEO Budget €10 billion minus 4 ESA Members. (Credit: Astrostrom)

15.2.4. Beyond Europe

GEEO Budget: 10 Billion Euros									
Country		Population 2020	Per capita kWh 2019	Per capita kW 2019	H/year	Efficiency Coefficient	Multiplier	Total Contribution	Per capita Contribution
					8760		11.5		
Austria		8'935'112	46'524	5.311		1.224		125'720'501	14.1
Belgium		11'492'641	65'303	7.455		1.717		226'977'094	19.7
Czech Republic		10'701'777	44'313	5.059		1.165		143'422'110	13.4
Denmark		5'873'420	33'535	3.828		0.882		59'568'742	10.1
Estonia		1'328'439	50'001	5.708		1.315		20'088'586	15.1
Finland		5'536'146	55'118	6.292		1.450		92'284'772	16.7
India		1'366'417'754	6'942	0.792		0.183		2'868'779'458	2.1
Germany		83'190'556	47'703	5.446		1.255		1'200'186'607	14.4
Greece		10'678'632	30'384	3.468		0.799		98'127'249	9.2
Hungary		9'730'000	28'489	3.252		0.749		83'833'790	8.6
Ireland		5'001'500	37'739	4.308		0.992		57'084'699	11.4
Italy		60'317'116	29'239	3.338		0.769		533'374'367	8.8
Luxembourg		633'622	76'658	8.751		2.016		14'689'831	23.2
Netherlands		17'694'600	57'047	6.512		1.500		305'282'997	17.3
Japan		126'860'301	40'524	4.626		1.066		1'554'773'397	12.3
Poland		38'179'800	31'355	3.579		0.825		362'050'800	9.5
Portugal		10'344'802	28'328	3.234		0.745		88'627'225	8.6
Romania		19'186'201	19'665	2.245		0.517		114'106'924	5.9
Spain		47'540'795	34'004	3.882		0.894		488'906'155	10.3
Sweden		10'402'070	62'047	7.083		1.632		195'195'417	18.8
Switzerland		8'570'146	36'542	4.171		0.961		**94'713'000**	11.1
Brazil		211'049'527	16'525	1.886		0.435		1'054'763'052	5.0
South Africa		58'558'270	25'440	2.904		0.669		450'541'086	7.7
Latvia		1'907'675	23'137	2.641		0.608		13'348'747	7.0
Lithuania		2'795'680	24'641	2.813		0.648		20'834'105	7.5
Slovenia		2'108'708	37'446	4.275		0.985		23'880'913	11.3
		POPULATION		**Avg. per capita kW**				**BUDGET**	AVG.
Totals		**2'135'035'290**		**4.341**		**1.000**		**10'291'161'623**	**11.5**

FM=Full ESA Member
N-FM= Non Full Member

Population: Wikipedia
Per capita kWh 2019
https://ourworldindata.org/grapher/per-capita-energy-use

Figure 98: GEEO €10 billion budget with international members. (Credit: Astrostrom)

As it may be advantageous to look beyond Europe and to give an example of an international mix of countries, in Figure 98, Canada, Norway, France, and the UK have been replaced with India, Japan, Brazil, and South Africa. To meet the budget of €10 billion in this scenario, the average per capita contribution from each country is €11.5 with India €2.1, Japan €17.3, Brazil €5.0, and South Africa €7.7. Switzerland's total annual contribution would be €94.7 million, and its per capita contribution would be €11.1 in this scenario. The total population of the countries represented is more than 2 billion people.

An initial investment of €100 billion does not seem unreasonable if it can generate an increasing amount of profits, while creating new economic opportunities, stimulating peaceful cooperation, providing energy security and restoring the environment.

16. Legal Aspects

The legal framework for the eventual use of extraterrestrial resources rests with the Outer Space Treaty (OST) which forms the basis of international space law. More recently, the Artemis Accords were initiated by NASA with the aim to establish a common set of principles to ensure missions that fall under the Artemis mission umbrella are undertaken responsibly. Co-led by NASA and the U.S. Department of State, the Artemis Accords are signed at a national level rather than on an organizational level, and countries that sign the accord do so on a voluntary basis. One of the key principles is to adhere to the provisions of the Outer Space Treaty.

16.1. The Outer Space Treaty

The Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies (OST) entered into force on October 10, 1967, and, as of April 2023, 113 nations are parties to the treaty including all major spacefaring nations and another 23 signatories *(OST, 2023).*

The Outer Space Treaty provides the basic framework on international space law, including the following principles:

- the exploration and use of outer space shall be carried out for the benefit and in the interests of all countries and shall be the province of all mankind,
- outer space shall be free for exploration and use by all States,
- outer space is not subject to national appropriation by claim of sovereignty, by means of use or occupation, or by any other means,
- States shall not place nuclear weapons or other weapons of mass destruction in orbit or on celestial bodies or station them in outer space in any other manner,
- the Moon and other celestial bodies shall be used exclusively for peaceful purposes,
- astronauts shall be regarded as the envoys of mankind,
- States shall be responsible for national space activities whether carried out by governmental or non-governmental entities,
- States shall be liable for damage caused by their space objects, and,
- States shall avoid harmful contamination of space and celestial bodies.

With regards to the development of the GE⊕-LPS concept, several specific articles are of particular importance which further gives credence to having an international approach. These include Articles I, II, III, IV, VI, IX and XIII.

16.2. Artemis Accords

With NASA leading the Artemis missions, international partnerships will play a key role in achieving a sustainable and robust presence on the Moon while preparing to conduct a historic human mission to Mars. The Artemis accords are all bilateral agreement between on one side the US government and on the other side governments participating in the Artemis program.

With numerous countries and private sector players conducting missions and operations in cislunar space, it will be critical to establish a common set of principles to govern the civil exploration and use of outer space.

The Artemis Accords describe a shared vision for principles, grounded in the Outer Space Treaty of 1967, to create a safe and transparent environment which facilitates exploration, science, and commercial activities for all of humanity to enjoy. As of 2023, the following countries have signed the Artemis Accords Australia, Bahrain, Brazil, Canada, Columbia, France, Israel, Italy, Japan, Luxembourg, Mexico, New Zealand, Poland, Romania, Saudi Arabia, Singapore, South Korea, United Arab Emirates, and the United *Kingdom.* One of the key principles of the Artemis Accords is to affirm the importance of countries complying with 1967's Outer Space Treaty. *(Artemis Accords, NASA 2023).*

16.3. Additional Legal Issues

The GE⊕-LPS concept introduces new and unchartered areas of legal issues due to its relevance to the terrestrial energy market. Investigation and definition of the legal issues related to accessing and utilizing space resources are already underway. In particular, international treaties and new inter-governmental agreements will be needed to create an acceptable legal framework for the extraction, exploitation and ownership of extraterrestrial resources and commercial operations in cislunar space. These issues are being addressed by the United Nations Office for Outer Space Affairs (UNOOSA) and its Committee on the Peaceful Uses of Outer Space (COPUOS) which was set up by the General Assembly in 1959 to govern the exploration and use of space for the benefit of all humanity: for peace, security and development. Specific issues associated with SBSP energy production such as spectrum allocation, RF interference with communication signals, and management of the wireless power transmission could be resolved by the International Telecommunications Union (ITU) in collaboration with other national and international organisations such as the European Electronic Communications Code (EECC) or the US Federal Communications Commission (FCC).

The activities in cislunar space and on the lunar surface proposed for GE⊕-LPS will involve considerable communications traffic as well as Megawatt-level WPT. These will need regulation in order to preserve their efficiency and fairness. It would seem reasonable to expect international agreement via the UN that the authority of the ITU could be expanded to cover these activities beyond the Earth itself. Energy security issues apply to all forms of energy production which needs international agreements and enforcement. As only one Lunar Space Elevator can be built between the Earth and the Moon; access, ownership, maintenance, and operation of this vital cislunar infrastructure will require additional legal examination at an international level.

To ensure safety and security of SPS units, related orbital facilities, and other space-based facilities such as hotels and sports centres, three new international government services will be needed.

i) Space Police
As the number of human-tended facilities in orbit increase, “daily life” in orbit will include crimes, for which police services will be needed. From the start, such “space police” work will be fundamentally international, requiring detailed international cooperation to be effective.

Interpol has 192 members, an annual budget of more than 100 million Euros and a long history of international cooperation. To extend its abilities to include the role of space police, a range of new technological capabilities will be needed, including Interpol facilities in orbit, with ability for intra-orbital travel and EVA, communications with every country, and communications with all orbiting facilities.

ii) Orbital Traffic Rules

A second government service that will be needed is a system of traffic rules for all vehicles and facilities in cis-lunar space, to prevent collisions at as low cost as possible. An example of a potential rule is that similar facilities such as SPS units, factories and hotels may use the same orbit in order to avoid collisions. In order to implement this, all orbital facilities will be required to maintain their positions within certain parameters. However, activities to maintain the orbital position of a facility such as the ISS are complex: because of air resistance, their altitude continually falls slowly, and so propulsion is needed to raise them from time-to-time. Existing rules governing vehicles approaching and leaving ISS may also be used as the basis of new orbital traffic rules needed for commercial facilities in various Earth and lunar orbits. It is said that both the US Federal Aviation Administration (FAA) and UK's Civil Aviation Authority (CAA) are already working to develop space travel regulations. Perhaps, following the satisfactory international role of the International Air Transport Association (I.A.T.A.), a new space organisation I.S.T.A. should be established soon to prepare space traffic rules that are acceptable to all countries?

iii) Space Coastguard

Third, by analogy with the role of coastguard services in countries with a coastline, a new function is needed to protect Earth's external security. Specific activities needed include protection of orbiting assets against space debris, against threats between facilities in space, against threats to space facilities from Earth, and against threats to Earth from space facilities. To ensure this, detailed inspections will be required. As examples of systems that could be used to contribute to this function, Lockheed-Martin Inc. is developing its "Space Fence" project in collaboration with other countries, while Roscosmos Precision Systems is developing laser cannons for de-orbiting space debris. Later, a space coastguard service might also operate pilot services to safely bring non-terrestrial materials into defined Earth orbits. The International Association for the Advancement of Space Safety (IAASS), established in 2004, may be able to contribute to this activity. Direct collaboration between different countries' existing coastguard services may also be effective in developing a new international system.

These three new international space security services, if successful, should have a great influence towards preserving world peace. Consequently, a diplomatic initiative in this direction may receive strong international support. Military budgets today are so large that even if peace treaties were achieved, reducing military budgets sharply would cause recession. In order to reduce military spending without causing recession, the aerospace industry needs some other large project in which to invest. Establishing the above space security services would require considerable investment in space-based facilities but would be a peace-keeping influence – and so internationally popular. Civil aviation today supports about 100 million jobs worldwide, both directly and indirectly. If they receive investment, both SBSP and space tourism services could grow to similar scale within a few decades, thereby contributing greatly to peaceful economic growth worldwide.

17. Cultural Aspects

Civilization is defined by its culture and the cultural dimension of space development is extremely important. Most people are probably not aware that the idea of space exploration began in the mind of the artist or that artists have been intimately involved in space exploration from the beginning. Yet long before the first rocket penetrated the atmosphere, artists were making the concept of humanity traveling beyond Earth's atmosphere a reality. They have also been responsible for keeping the dream of spaceflight alive in the public's imagination. The best example are the cinematic productions about space which are among the most successful artworks of all time in terms of audience size, popularity, and financial return and these artistic expressions have played a major role in stimulating and maintaining the public's ongoing interest in space exploration. Indeed, the idea of space exploration first appeared in literature and in illustration. These works inspired many to choose career paths as space scientists and engineers. New artistic concepts and creations in all media will surely be one result of extending civilization into cislunar space.

Thus, of particular importance to the study - next to the economic and the supply of green energy aspects - are the activities which GE⊕-LPS will initiate on the Moon that will be not only science and exploration, as has been the objective of lunar activities to date, but one of imagination, inspiration, and hope. The infrastructure established by GE⊕-LPS in terms of transportation, logistics, energy and ISRU will undoubtably lower the entry level for all sorts of start-ups and will be especially favourable for the considerable economic potential of culture and sports.

The unique 1/6 gravity environment on the Moon will become a magnet for travellers and tourists, which could grow into a major new field of the tourism industry, and hence lead to many new types of cultural activity, of great fascination for all peoples on Earth. For this reason, by starting a commercially self-sustaining industrial park on the lunar surface, GE⊕-LPS will also be a highly significant new cultural departure. For example, developing lunar surface construction methods will enable companies which have played no role in space development to date to invest in preparing commercial facilities and activities on the lunar surface.

17.1. The Overview Effect

More than 30 years ago, 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, 1987). 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. For example:

- Chris Hadfield revealed that his realization came when he wrote "*There are six million of us living in Pakistan.*" He didn't write, there are six million people living in Pakistan, he wrote, of us.
- Nicole Stott described her moment in this way: "*Finally, we were flying over Florida. I wanted to fly to the window and see it, and then realized somewhere down the line that I wasn't looking at Florida that same way anymore. I still wanted to see Florida,*

but Florida had just become this special part of home, which is Earth. I don't know when that happened. Was that two days after I got there? I mean, it wasn't like one day I woke up and was like, 'Oh yeah, Earth's my home."

- Perhaps Michael Collins captured it best when he explained: *"The Earth must become as it appears; blue and white, not capitalist or communist; blue and white, not rich or poor; blue and white, not envious or envied."*

Human expansion into space 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, not the least of which is a stronger impetus for peace and care for the environment. At the least, permanent human presence on the Moon will serve as a reminder that we are all more alike than we are different.

Interestingly, White's original concept of the Overview Effect focused on people who lived permanently off the home planet, settlers who would always see the Earth as a whole system, without borders or boundaries. Lacking space settlers to confirm his hypothesis, he turned to astronauts as proxies. A human presence on the Moon will offer an opportunity to test the hypothesis more accurately. In addition, it literally removes the boundaries of our horizons. But that is just the beginning. The opportunity to experience the 'Overview Effect' will also be a prime motivation for the development of lunar tourism.

17.2. Lunar Tourism

The possibility of visiting the lunar surface has been discussed both in fiction and in scientific terms, over more than a century. Twelve Americans walked on the lunar surface between 1969 and 1973, proving that it is physically possible, and within the scope of human engineering. In view of the immense progress that has been achieved in every field of engineering during the half-century since the early 1970s, it is clear that enabling people to visit the lunar surface could be achieved today at far lower cost than 50 years ago, if appropriate investments are made.

In recent years there has been growing interest in several leading countries in sending astronauts (and cosmonauts and taikonauts) to the lunar surface for various purposes. Government space agencies are considering projects that fulfil important goals in their specialized fields of space science and space technology development. Military organisations are apparently interested in defensive activities, in order to avoid other countries gaining a lead in developing potentially threatening new military capabilities. A third activity which is attracting attention is tourism. Plans already exist for trips from Earth to beyond the Moon and back: having first been proposed by Russian engineers using the Soyuz system, plans are progressing for such a trip on board SpaceX's "Starship": initially planned for 2023 it is now expected to be delayed. However, the major potential of lunar tourism will be for visits to the lunar surface.

Robotic exploration of the lunar surface started in the 1960s and is currently under way by the Chinese space agency, as well as being in detailed planning in the USA, Russia, Japan and India, and including private companies such as Ispace Inc (*ISPACE, 2020).* However, passenger travel to the Moon will require a great deal more preparatory investment in a range of infrastructure than robotic missions. A small number of very wealthy people may possibly visit the lunar surface as risk-sharing explorers at an early phase of currently planned lunar activities. However, for lunar tourism to become a significant commercial activity on a promising growth path, there will be a need for investment of some billions of Euro-equivalents in a number of essential technological systems, notably transportation and accommodation, in order to reduce the costs and increase the safety of lunar travel to a level at which demand can grow to large scale *(Collins, 2003).*

The most important of the systems needed to enable the growth of a commercial lunar tourism industry is the development of safe, low-cost, fully-reusable, passenger-carrying transportation systems, the first phase of which is passenger vehicles which operate between spaceports on the Earth's surface and accommodation facilities in LEO. Although the reusable "Starship" vehicle currently being developed by SpaceX is expected to substantially reduce the cost of delivering cargo to LEO, it is optimized for carrying heavy cargoes to LEO, other orbits and to the Moon, and so is far from optimal for carrying passengers. Although several companies, both in the USA and in other countries, are developing new space vehicles, only Sierra Space in the US has publicly announced plans to develop and deploy an orbital passenger-carrying vehicle – the *Dream Chaser* – which is scheduled to make its maiden flight in 2023 *(Sierra Space, 2022).* In addition, several companies are developing orbital stations for hotel accommodation, among other services *(Bigelow, 2022) (CNN Travel, 2021).* However, developing economical passenger launch services to LEO is on the critical path of any plan to develop space tourism services either in LEO or on the Moon.

With 5 new heavy launch vehicles originally planned to start test flights in the near future – Starship, SLS, New Glenn, Ariane 6 and Long March 7 - developing another competitor would not be commercially promising. Currently, the major commercial launch market is launching satellite constellations, but it seems possible that their growth may be limited by market saturation and/or regulation: SpaceX's plan to launch 20,000 satellites into orbits between 300 and 500 km altitude would make LEO almost a no-go zone for passenger vehicles! Successful growth of the LEO hotel business will also increase the market for heavy lift - but passenger vehicles are key to growing the market for orbital accommodation: the components of an orbital hotel need to be launched only once, but many passenger flights will be made carrying guests to and from each hotel. Thus, subject to detailed analysis, investment in passenger vehicles seems likely to be more commercially successful, and subject to growth of demand to a larger scale than other launch markets. Developing such vehicles will require deep, innovative collaboration between space engineers and aviation engineers, combining detailed knowledge of designing equipment to operate in vacuum and weightlessness with relentless focus on passenger experience and economy.

It is worth noting that the technology used by SpaceX to achieve partial reusability of its launch vehicles is not new: commercial companies' focus on reducing costs has led SpaceX to implement technological capabilities that have existed already for several decades but have been ignored by space agencies. The speed with which this has enabled a new company to take a large share of the launch market and thereby make expendable launch vehicles uncompetitive is a lesson in how quickly technologies that are considered "futuristic" can become "normal" *(Collins, 2006).*

An example of a fully reusable passenger launch system that could reduce the cost of passenger travel to LEO very substantially is the 2-stage "Spacecab" prototype spaceplane, which was the subject of a study funded by ESA in the 1980s *(Ashford, 1994).* The larger successor spaceplane "Spacebus" is expected to reach maturity of operations within 15 years of starting development *(Ashford, 2009).*

Development of lunar hotel accommodation and other tourist facilities will depend on lunar construction and manufacturing capabilities reaching a level considerably beyond that needed for GE⊕-LPS. This would particularly involve developing interior equipment for convenient and comfortable accommodation, including water supply, kitchens, and equipment for sightseeing, which will require corresponding investment. The role which private investment could play in this depends on many factors that are not predictable today.

An example which can be foreseen is the use of the "Lunar Cruiser" which is being developed by JAXA and Toyota for initial use in the late 2020s. The basic model is to be able to carry two people for six weeks on the lunar surface (Toyota, 2020). However, in order to sell as many units as possible, Toyota is surely likely to develop variants of the basic model as soon as there is demand. One such variant is likely to be a truck for carrying equipment short distances, rather than being a lunar "camper". Another likely variant will be a tourist bus to carry several passengers in a pressurized cabin on sight-seeing tours. Other facilities that are likely to be built for tourists are gymnasia / stadia in order to enable sports and other entertainments in low gravity, which could be broadcast to Earth, due to their uniqueness.

17.3. The Societal Dimension – Humanity's Cosmic Choice

On Earth, human civilization has reached such a point in its development where it has evolved the means to leave its home planet and to begin operating in the environment beyond its atmosphere. Optimistically, this development would enable humanity to utilize this technological capability to harness the infinite resources located off Earth in order to improve the well-being of the population as well as improving the chances that its current civilization can continue to prosper in the decades and centuries ahead – both on Earth and eventually in other places in the solar system including the Moon. On the other hand, this same capability could also be used in a negative manner in order to exert tyrannical control over a majority of the population thereby limiting prosperity to a select few, or, in the ultimate worst case, it could be used to destroy civilization and humanity's only chance of expansion into the Cosmos.

Gerard K. O'Neill once posed the following question *(Brand, 1975):*

"Is a planetary surface the right place for an expanding technological civilization?"

This question concisely encapsulates the idea of a Cosmic Choice. An evolving technological species existing on a planet with finite resources is faced with the ultimate challenge of maintaining its development and the viability of its civilization before it reaches the threshold of unsustainability and/or the possibility of collapse. In order to meet this challenge, it will need additional resources beyond those that are available to it on its home planet as well as an expanded environment that will stimulate the further development of its technological capabilities.

Of all the options available to humanity at this moment, the Space Option *(Bernasconi and Woods, 1993)* presents our species with an unprecedented opportunity to meet the basic and anticipated needs of human civilization through the utilization of extraterrestrial resources and to apply these resources for use on Earth so that humanity and the natural world it lives within, may survive and thrive in an eventual era of peace and prosperity. The process of accessing and harnessing these resources will in turn create an infrastructure beyond the atmosphere upon which further expansion of human civilization can be anticipated. Consequently, if human civilization can be established beyond Earth, then the chances for its ultimate survival will correspondingly increase. However, by not embracing the Space Option, the possibility that humanity will be overrun by one or more of the many threats to its survival will increase and, likewise, its chances of ever becoming a spacefaring species will diminish. Therefore, today, humanity must face this critical situation – one that constitutes its Cosmic Choice.

17.4. "Earth Problems Must Have Earth Solutions ….."

Most people intuitively assume and fundamentally believe that terrestrial problems must have terrestrial solutions. This is obviously due to a lack of understanding about our interconnectedness and interdependence with the rest of the Cosmos. As a terrestrially evolved organism, it is in our genes to adapt to our immediate environment as we have over millions of years. Only recently have we begun to become aware of how celestial events affect our lives. We now know that such events have been critically important to the evolution of life on Earth. Impacts of comets most likely provided a young Earth with the necessary water and perhaps even the necessary genetic materials for life to appear. Subsequent impacts by large asteroids are believed to have resulted in mass extinctions of life at various times in the history of our planet. The gravitational influence of the Moon may have played a significant role in the Earth specific phenomena of plate tectonics and continental drift, forces that may also have been important to the evolution of life on Earth.

Most of the problems confronting humanity can be traced to the ever-expanding activities of the human species on a finite planet that has resulted in it occupying every available niche and exploiting every available earthly resource for living, working, and maintaining society. This process has not only led to the development of our technological society and its many advantages but also to the disadvantages of having such powerful technologies available to be used in an irresponsible and dangerous manner.

Expanding our civilization to the Moon and using lunar resources to address one of the most pressing issues on Earth may be the only way to insure humanity's future. This would provide humanity with a purpose, and a motivation to achieve something great. It could unite the entire world in a shared mission with a vision.

17.5. Space Solutions to Earth Problems

In recent times, human civilization has become increasingly dependent on technological assets located in space. Removing these space assets would pose dire consequences to the functioning of today's complex technological society. Thus, in all aspects, humanity's future on Earth is irrevocably linked to its future in space. Therefore, considering space options to address some of humanity's most pressing problems would appear to be a very logical and intelligent choice to make.

The list below shows a number of problems, issues and challenges currently confronting human civilization that are paired with possible solutions that can be found through the utilization of space resources and technologies. Each of these issues and the accompanying space solution could and should be addressed in much more detail. It would surely be an interesting study to take each issue and compare the terrestrial and extraterrestrial options that are proposed as solutions.

This list shows us that by considering these space options, humanity may be able solve some – if not most – of its many pressing issues by simply thinking beyond the limits of a finite planet. If it embraces and applies these solutions responsibly with commitment, then its future chances of survival will correspondingly increase.

Some of the ideas may seem enormous from today's perspective, and others we cannot even imagine. However, the gate that GE⊕-LPS is opening will be an epochal paradigm shift creating the basis for a true spacefaring species. The internet (arpanet) was invented in the same year as the first Moon landing in 1969. However, it's full impact has only emerged during the last decade.

17.5.1. The Energy Dilemma

- Meeting much of humanity's future energy needs with increasing amounts of clean CO_2 neutral energy from space with the near-term goal to supply 10% of the energy mix with Space-Based Solar Power (SBSP).
- Helium-3 mined on the Moon could be eventually used for fusion reactors on Earth.

17.5.2. Climate Change / Mitigation & Control

- SBSP increasingly replaces fossil fuel energy sources for the generation of electricity.
- SBSP augments and integrates with terrestrial energy production.
- SBSP integrates with terrestrial hydrogen fuel production.
- In the case of Global Cooling leading to a new Ice Age: Solar Thermal Power Satellites & Space Mirrors could be directed to raise the surface temperature of specific regions such as cities.
- In both warming and cooling hypotheses, Solar Power Satellites, Parasols & Space Mirrors represent productive investments, in that they not only provide mitigation devices, but that their development and realization further support – or even create – an extended infrastructure together with operational capabilities that can serve, e.g., environmental remediation and developmental projects.
- Parasols (Sun Shields) located at the Sun-Earth Lagrange (L1) point can reduce flux towards Earth and permit cooling of the planet's atmosphere. Note: this geoengineering solution is continuously controllable and, as its elements are located outside the biosphere without any direct interaction; if necessary, it could be modulated or moved away in a short time.

17.5.3. Environmental Considerations

- Ground transportation: electric & hydrogen fueled vehicles powered by clean energy from space.
- Scaling back terrestrial power plants will increase availability of water; furthermore, water desalination can be powered by energy from space (with resulting brines may serve as feedstock for co-located extractive facilities).
- Some polluting industries can be moved into space, helping the biosphere to recover.
- Sufficient clean energy will be available to address other environmental issues.
- Knowledge gained by creating sustainable artificial bio-environments off Earth can contribute to solving some of Earth's environmental problems.
- Building SPS elements on the Moon would reduce the amount of rockets needed to deploy SPSs from the surface of Earth.

17.5.4. Resource Depletion

- The lunar regolith is considered a source of Helium-3.
- Processing regolith on the Moon for the production of solar cells for SBSP giving oxygen and other minerals and metals as secondary by-products.
- Metals for industrial purposes and construction are found in the lunar regolith such as Iron, Aluminum, Calcium, Magnesium, Sodium, and Titanium.
- Platinum Group Metals (PGM) on the asteroids and the Moon that are necessary for many industrial products especially for the production of hydrogen fuel cells.
- Water on the Moon is essential for human outposts and for in situ rocket fuel production.
- Over 16,000 near-Earth asteroids that share a similar orbit to Earth which contain the essential resources that make it possible to fuel and sustain life in space. (Water, light elements and PGMs being the main objectives as well as carbon for lunar processes).
- Water scarcity in regions on Earth could be addressed by powering desalination plants with clean energy from space.

17.5.5. Planetary Protection

- SBSP systems could mitigate Global Warming or Global Cooling.
- An industrial infrastructure in cislunar space will help provide a defense from possible impacts by asteroids and comets.
- Establishing off-Earth outposts and repositories for terrestrial life will guarantee the survivability of all life.

17.5.6. Economic Growth

- Energy is the largest market on Earth and essential to all aspects of civilization. An unlimited power supply from space would drive and sustain economic development for generations to come.
- Space tourism, space mining and space power industries would create millions of qualified and productive new jobs.
- New net-wealth creation through expanding economies into cislunar space.

- Ample opportunities for entrepreneurs and new markets.
- Transitioning the skills, knowledge, and experience of the war industries into the new space industries.
- Importing resource wealth from space instead of depleting the remaining resource wealth of Earth.
- Rising prosperity would automatically have a positive influence on population pressures.
- A new territory for human endeavors leading to new knowledge, skills and technologies.
- An industrial infrastructure in cislunar space would be a stepping-stone to expanding human civilization throughout the Solar System creating exponential economies.

17.6. Educational Considerations

Another way in which benefits from the development of the systems and infrastructure needed to realise space tourism can be made available to a large proportion of the general public is through education, perhaps particularly at school level. A particularly promising approach would be to make related experiences available for educational purposes to young people – students, schoolchildren, and researchers. Such activities can start well before even sub-orbital flights become commercially available in Europe by making parabolic flight services available, which provide up to about 20 seconds of micro-gravity.

ESA currently performs a wide range of leading-edge education activities, as described on the ESA website: ESA at the forefront of space education *(ESA Education, 2020).*

However, these activities centre on STEM subjects, which involve only about 10-20% of young people in education. The coming growth of space tourism will involve essentially everyone, due to the great popularity of the idea of traveling to space. It would therefore be a valuable addition to ESA's existing educational activities to start programmes for children relating to space travel itself, rather than aimed at scientific or engineering research: such preparatory activities can be highly educational, although not specifically STEM activities.

As part of this, the opportunities for young people to experience micro-gravity during parabolic flights could be expanded by calling for proposals not only for scientific experiments, but also for making videos, micro-gravity art, sports, drama, dance, music and other themes and on any topic the proposer chooses. Some talented young people will surely make fascinating videos that will "go viral", obtaining uniquely valuable publicity for ESA and for its educational programmes, as well as strengthening popular support among young people. By also including video-making of sports activities within the permitted range of topics for micro-gravity experience flights, young people's imaginations and enthusiasm will be fired, and even micro-gravity sports contests will be able to start. Because the field of sports is popular and meritocratic, it will generate support for the development of both orbital and lunar sports.

In addition, many sports are commercially vigorous, and so space sports surely have the potential to attract commercial support for space activities that contribute to the development of sports facilities in space. A recent article shows the growing interest in the possibility of sports in space "Max Q; Sports in Space?" *(Etherington, 2022)* and pioneering organisations such as the Space Games Federation are even starting to be set up to encourage space sports *(Space Games Federation, 2022).*

Consequently, widening the scope of applications for micro-gravity flights to be decided on a competitive basis seems likely to become very popular throughout ESA member-states. The cost of preparing and operating such a service would also be very low compared to developing and performing space missions. Participating countries could hold national competitions, and such activities could expand to require the use of one or more dedicated aircraft. At a later date, such a programme of activities could lead seamlessly into making sub-orbital flights available on a similar basis, once they are in regular operation, further increasing popular support for ESA among several times more younger people than STEM students alone.

18. The Rationale

18.1. The Space Option

In the third decade of this new millennium humanity is being confronted by the consequences of its success as the dominant species on planet Earth. As its numbers have recently exceeded 8 billion, its home planet has begun to experience the effects of its overwhelming occupation resulting in environmental degradation, resource depletion, resource wars, a loss of biodiversity and unsound climatic experimentation. Every day the news is packed with alarming new statistics and dire predictions. Our civilization appears to be constantly approaching a state of chaos.

"The challenge of the great spaces between the worlds is a stupendous one, but if we fail to meet it, the story of our race will be drawing to a close. Humanity will have turned its back upon the still untrodden heights and will be descending again the long slope that stretches, across a thousand million years of time, down to the shores of the primeval sea."

Arthur C. Clarke *(Clarke, 1968)*

In the first decade of the 21st century it has become acutely obvious that the impact of an expanding human population on a finite planet is impacting the near-term sustainability of human society as we know it unless immediate and effective corrective measures are taken. To address these issues political leaders will implement either the “most innovative” or the “most repressive” solutions imaginable.

Without question, most people alive today instinctively assume that whatever humanity's fate in the years ahead, that fate will be ultimately decided and enacted here on planet Earth and surely not anywhere else. As our global problems seem to exponentially multiply, most our world leaders also seem to believe that: Earth problems must have Earth solutions.

Fortunately, space visionaries and pioneers such as Krafft Ehricke and Gerard K. O'Neill long ago recognized this dire eventuality and they and their followers have consequently developed both the scientific rationale and the technological capability to address the impending human dilemma. This has led to a concept called: The Space Option.

"While civilization is more than a high material living standard, it is nevertheless based on material abundance. It does not thrive on object poverty nor in an atmosphere of resignation and hopelessness. It needs vigour as well as vision. Therefore, the end objectives of solar system exploration are social objectives in the sense that they relate to, or are dictated by, present and future human needs."

Krafft Ehricke *(Ehricke, 1970)*

The Space Option concept is an evolutionary plan to meet the basic and anticipated needs of humanity through the utilization of near-Earth resources - not only for the in-situ support of science or exploration - but rather to apply these resources and/or their products for use on Earth at a conspicuous level. Most immediately, the harnessing of energy from space would replace humanity's dependence on the continued use of finite fossil fuels which are environmentally negative and likewise, on the widespread use of nuclear fuels which have grave environmental and political aspects. Unfortunately, it appears that alternative and renewable terrestrial energy resources, while both desirable and necessary, can never be deployed on a scale sufficient to meet the growing needs and demands of our present and future populations.

Inexhaustible amounts of clean solar energy from space, on the other hand, would significantly contribute to the restoration of the environment while avoiding the environmental and political consequences associated with the continued use of fossil fuels or nuclear power. Having an inexhaustible supply of clean energy and other natural resources would not only preserve the living standards of the developed nations but would continue to provide the basic means for further stimulating the economies of the developing countries. As such, future generations would be guaranteed a sufficient supply of energy and other material resources for their further development and today's less fortunate societies would be provided with hope that they, too, could still aspire to improve their living standard beyond their present situation.

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. Of all the options currently available to our species at this critical moment in its history, the Space Option offers humanity the most optimistic path to its long-term sustainability and survival.

"We face a choice of the type of future that we leave to posterity: a stone age or a space age. If it is to be a space age, there is a need to act now with much greater vigour than is currently being shown."

Mark Hempsell (*Hempsell, 1989)*

Civilization has reached a threshold. Humanity has the means today to implement the Space Option but not yet the commitment. However, if our species does not soon embrace this unique opportunity with sufficient commitment, it may miss its one and only chance to do so.

Humanity could soon be overwhelmed by one or more of the many challenges it now faces. The window of opportunity is closing as fast as the many crises it faces intensify. In the 21st century, the main challenge to the space community will be informing and then convincing the public of the viability of the Space Option as the most optimistic alternative to the other current approaches to human destiny.

18.2. Greater Earth - GE⊕

All celestial bodies of significant concentrated mass exert a field of gravitational attraction which extends to the point of tangential intersection with other celestial bodies' gravitational fields. Earth's gravitational influence extends 1.5 million kilometres in all directions from its centre, where it meets the gravitational influence of the Sun. This sphere, with a diameter of 3 million kilometres, has 13 million times the volume of the physical Earth, and through it passes more than 55,000 times the amount of solar energy which is available on the surface of the planet. In addition to energy, within this sphere are enormous amounts of other resources, including the Moon and occasional passing asteroids.

Like the territorial waters surrounding nations, these resources naturally belong to our planet and should be used for the ultimate benefit of humanity and all life which has originated here. As it has throughout its history, humanity must refine its perception of the planet in order to recognize and embrace the perception of a greater, richer, and more sustainable Earth.

This new perception is called *Greater Earth*. Within its boundaries, our species will find the necessary room, resources, opportunities, and inspiration that it will need to survive and prosper in the current millennium. Expanding civilisation to occupy and utilise the area of *Greater Earth* will make humanity universally conscious of its responsibility to all life sharing its home planet and of the crucial role of the human species in the evolution of life on Earth and beyond.

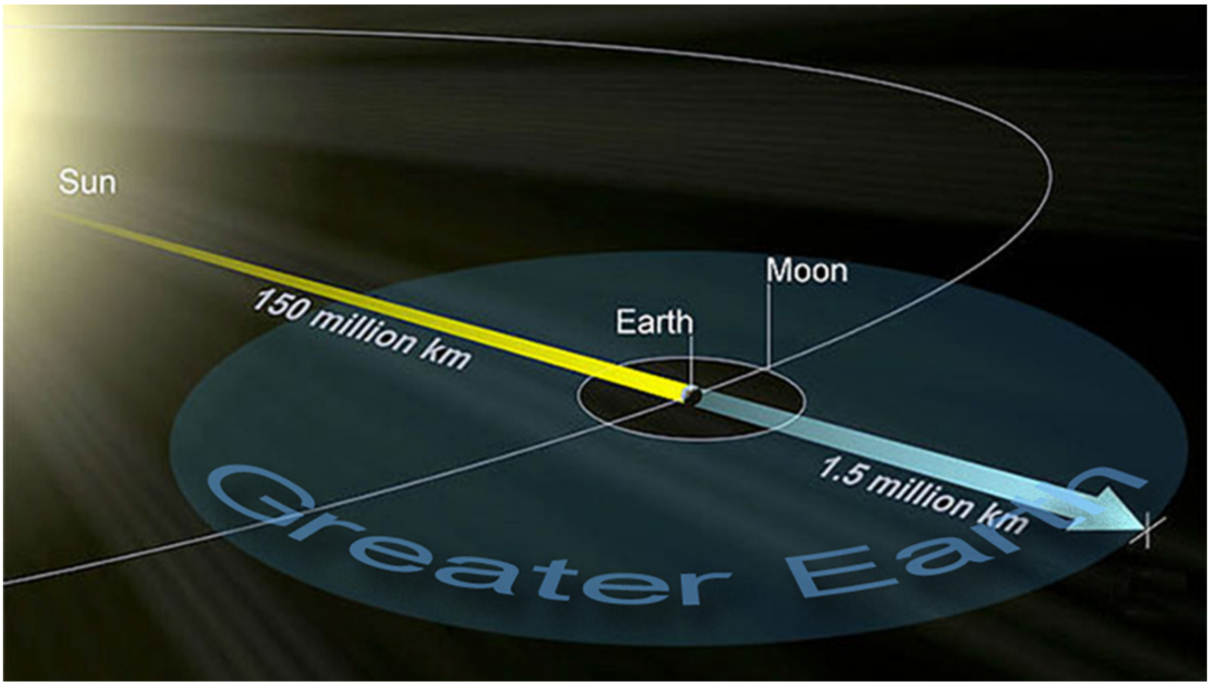


Figure 99: GE⊕ - Greater Earth Diagram. (Credit: Astrostrom)

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) and other Greater Earth system components mentioned in this study.

18.3. Energy Available in the Regions of Greater Earth and Cislunar Space

The energy available beyond the atmosphere of Earth is enormous and inexhaustible. Greater Earth is a perception of our planet that is defined by celestial mechanics and the laws of physics. Earth's gravitational influence extends 1.5 million kilometres in all directions from its centre where it meets the gravitational influence of the Sun. This sphere, with a diameter of 3 million kilometres, has 13 million times the volume of the physical Earth. The spherical area of the outer boundary of Greater Earth is 28,274,333,882,308 km^2, and the surface area of the

Earth is 510,064,472 km². Thus, more than 55,000 times the amount of solar energy passes through the area of Greater Earth than which is available on the surface of the planet.

Cislunar space encompasses the area around the Earth extending out to just beyond the Moon's orbit and including all the five Lagrangian points that are stable in position in reference to the Earth and Moon as they rotate about each other. For transport purposes, the two Earth-Moon Lagrange points close to and in line with the Moon, EM-L1 and EM-L2, are the most important. EM-L1 is always in front of the Moon and EM-L2 is always behind the Moon, each by roughly 61,350 kilometres. Being in what are essentially zero gravity locations, even large objects placed there, in gentle halo orbits, can be kept there with minimal propellant use for station-keeping.

Cislunar space is also a very large region and, like Greater Earth, cislunar space is a three-dimensional volume. The radius of Geostationary orbit is 42,164 km, extended outwards to 12 GEO Radii gives a radius 505,968 km. The outer boundary of this region has a spherical area of 3,217,036,330,140 km², through which passes some 6,400 times the amount of sunlight than reaches the surface Earth. Harnessing this inexhaustible amount of sunlight for terrestrial energy purposes is one of the goals of the GE⊕-LPS concept.

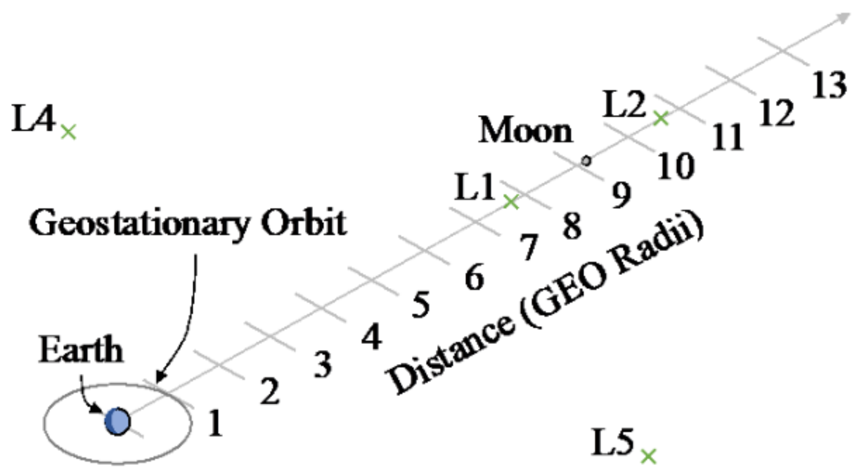


Figure 100: Spatial Scale in Cislunar Space (Source: A Primer on Cislunar Space, AFRL 2021)Energy Security

18.4. The Greater Earth System

"If God wanted man to become a spacefaring species, he would have given man a Moon."

Krafft A. Ehricke *(Ehricke, 1984)*

Greater Earth is not only a region defined by celestial mechanics and the laws of physics but is also an interdependent dynamic system that contributed to the emergence and evolution of life on Earth. Understanding the dynamic nature of this extended region of Earth and how it has functioned over time, adds insight on the future role of the human species in the evolution of life on Earth and in its relation to the Cosmos.

Greater Earth is not only a region that operates under the laws of physics and celestial mechanics which defines its true cosmic dimensions and functionality, but it is also an interactive, interconnected biological and geophysical system that for billions of years has led to the appearance, evolution, and maintenance of a living planet. This system has led to the emergence of a new bio-technological information system that has encircled the planet that enables knowledge to be created and instantly shared.

The formation of the *Greater Earth System* was a result of incredibly fortunate cosmic coincidences, including Earth being at the right distance from the right kind of star, having the right size, density and composition, then having an opportune collision with another celestial body which created the Moon which provided a gravitation influence which has helped to stabilize the climate and catalyze the evolutionary processes of life that eventually led to an intelligent technological species that has now enabled planet Earth to become both self-aware and capable of spreading its “seeds” to other places in the immediate Cosmos.

Recent astronomical discoveries indicate that Earth-like planets are common in the habitable zone of stars, and statistical research shows that planets with massive, obliquity stabilizing moons may occur only in approximately 10% of these *(Elser, S., Moore, B., et al 2011).* However, when one considers that the appearance and evolution of life on Earth over the past 3.7 billion years has not been a linear natural selection process but rather a haphazard series of fortunate circumstances with many starts and stops, including a number of mass extinctions along the way, yet resulted in the eventual appearance of an intelligent technological species that has impacted the planet’s physical environment as no other species and, in addition, has now also artificially extended the physical size of the planet beyond its atmosphere to enhance its communication capabilities; we must ask ourselves just how often similar circumstances converged, if at all, in the history of the vast universe.

As the 21st century unfolds, humanity finds that it needs more room and more resources to sustain its numbers and to maintain its thirst for further development and knowledge. The finite planetary resources that contributed immensely to its present state are being exhausted to unsustainable levels and their uncontrolled use within the biosphere is resulting in severe ecological damage as climatic and environmental changes pose a threat to future of all life. Governmental programs to address these issues with terrestrial solutions will lead to severe societal and geopolitical consequences.

Thus, humanity must take measures to consciously and intelligently intervene in Earth’s dynamic life systems in order to adapt to changes it is causing as well as adapting to a constantly expanding sun and other cosmic threats. As it is momentarily unequipped to occupy and transform a neighbouring planet to meet its growing needs, humanity’s next logical step will be to discover and inhabit the last reaches of its own planet – to expand its activities to Earth’s true boundaries as defined by the laws of physics. Within the boundaries of *Greater Earth* our species will find the necessary room, resources, opportunities, and inspiration that it will need to survive and prosper in the current millennium and, with some luck, to eventually become a spacefaring species.

Awareness of *Greater Earth* as a dynamic system unites the immense potential of space development with the critical terrestrial issues of ecological sustainability, environmental restoration, clean energy generation, global prosperity, and international security. Occupying the region of *Greater Earth* including the Moon and geolunar space will contribute to making humanity universally conscious of its responsibility to all life sharing its home planet and of the crucial role and purpose of the human species in the evolution of life on Earth and beyond. Embracing the concept of *Greater Earth* as a new perception of our planet and understanding this as a dynamic system may be a viable strategy for merging the environmental and ecological movements with the economic goals of the space development community. The GE⊕-LPS concept proposed in this study can be a meaningful first step into this system.

18.5. Energy Security

In February 2022, Dr. Angela Wilkinson, World Energy Council Secretary General and CEO wrote:

"The use of public-private partnership (PPP) mechanisms in addressing global sustainable development challenges has grown since the early 1990s. These partnerships have sought to resolve the growing tensions between global market forces and sovereign states, fuelled by the forces of globalisation and digitalisation.

Recently, the flurry of global ESG (Environmental, Social and Governance) frameworks and voluntary corporate reporting requirements, however, has exposed societies to new risks of corporate greenwashing and capital market arbitrage. Meanwhile the challenge of effectively coordinating global civic society has triggered a return of nationalism and populism. It has always been easier for diverse interests to unite against change rather than build forward together.

In this context, it is perhaps unsurprising that conversations around energy are siloed and polarising, ridden with conflict-laden language and overtone. Good vs. bad energy, 'zero fossil' vs 'net zero' policy pathways, 'clean' vs. 'green' taxonomies and even "the weaponisation of energy" has crept back into parlance.

The role of energy systems as leveller and peace maker in globally connected and interdependent societies is at risk of being overlooked, or worse still forgotten altogether.

Energy is too important to the future of humanity to fight over, yet the fragmentation of responsibility for managing energy systems as enablers of peace and prosperity presents a considerable risk to global order.

National governments cannot deliver energy security or meet their commitments for clean and just energy transitions through hard power. Nor can they deliver without partnership with integrated energy networks and increasingly diverse place-based communities. Global markets cannot continue to extract value and accelerate the flows of new ideas, goods and services without attention to matters of co-custody, co-benefits, energy justice and de-colonisation.

The achievability and affordability of global ambitions is currently gridlocked by global power struggles. It's time for a new kind of energy diplomacy – one which involves soft power and polycentricism; one that puts the 'P' for people, into Public Private Partnerships.

Today, around two billion people worldwide – or 25 per cent of the world's population – still don't have access the benefits of clean, affordable, reliable energy products and services. Yet few of us appreciate the scale and scope of the invisible energy systems – the connections and interactions which deliver convenient and reliable heating and cooling, power, fuel, and storage solutions on which our modern lives depend.

For those households recently noticing the rising costs of their petrol, gas and/or electricity bills, the uncomfortable truth is that the energy use represented in these bills is only a small part of the real cost. The basic access gap – measured as one billion or so people across the world who lack access to any source of electricity – highlights the divide between the "haves" and the "have nots". Digitalisation has created an ever expanding "digital divide" and a new risk of market power monopoly which is coined by the question 'Is Big Data the new oil?'.

Billions more people are now at risk from a combination of energy market failures, the return of nationalist agendas and a growing shortfall in productive energy access for decent jobs, human wellbeing and a healthy planet. New global civil society movements include demand for radical transparency – using integrated and forward-looking assessment frameworks, science-based metrics and Big Data analytics – to engender trust and enable more effective coordination and collaboration." (Wilkinson, WEC, 2022)

18.6. Geopolitics and the Moon

A growing number of nations are developing programmes to return to the Moon and begin ISRU activities there especially at the lunar poles where water ice is expected. These countries are approaching the legal parameters associated with these activities from different perspectives with different interpretations of the Outer Space Treaty provisions. Indeed, Europe has joined the U.S. and is a partner in the Artemis Accords. To date, European companies have made a central component of the Artemis 1 vehicle that successfully travelled beyond the Moon and back. Once lunar surface activities start, a politically central question will be: "What benefits will European taxpayers receive from European space companies participating at taxpayers' expense?"

Working to definitively solving Europe's energy problem, while also developing a major, new, strategic industry that could eventually employ millions of Europeans, would be a politically popular and persuasive reply. To achieve this, ESA should design their share of the ongoing project to contribute as much as possible to developing lunar industrial capabilities needed for GE⊕-LPS implementation. This can be seen as a necessary backup strategy for plans to develop SPS as a major energy source for Earth.

"If not now, when?" It is surely reasonable to assume that the technologies which need to be developed in order 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 serious international friction.

Furthermore, as the GE⊕-LPS concept represents a significant industrial development program that spans cislunar space, envisions erecting a Lunar Space Elevator and establishing lunar mining operations at the Moon's equator, in order to service the terrestrial energy market, international legal cooperative arrangements and agreements will be a prerequisite for its eventual success. As there can only be 'one' LSE between the Earth and the Moon, surely this will be disputed if only one nation or even a group of 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 this operation. In many ways this could contribute to easing some of the geopolitical tensions currently associated with control of resources on Earth.

The following is a description of current plans by other nations to return to the Moon.

18.6.1. The Artemis Program

Artemis is the twin sister of Apollo and goddess of the Moon in Greek mythology. Now, she personifies NASA's efforts to return astronauts and a new wave of science payloads and technology demonstrations to the lunar surface. NASA's Artemis website lists their reasons for going back to the Moon (NASA, Artemis, 2022).

In addition to the social signalling goals of sending the first woman and the first person of colour to the lunar surface, NASA mentions standard objectives such as going back to the Moon for scientific discovery, economic benefits, and inspiration for a new generation of explorers which they call the Artemis Generation. As always, a fundamental rationale is maintaining American leadership in space exploration, while building a global alliance to explore deep space for the benefit of all.

Discovery: With Artemis, NASA is building on more than 50 years of exploration experience to reignite America's passion for discovery.

Economic Opportunity: Artemis missions enable a growing lunar economy by fuelling new industries, supporting job growth, and furthering the development and demand for a skilled workforce.

Inspiration for a New Generation: NASA will explore more of the Moon than ever before with its commercial and international partners. Along the way, the NASA Artemis program will engage and inspire new audiences – the Artemis Generation.

The Artemis Program began with the successful launch of Space Launch System (SLS) on November 16, 2022 carrying the Orion spacecraft which is designed to carry astronauts from Earth to lunar orbit and back. The Orion capsule splashed down on December 11, 2022 with a mission duration of 25 days, 10 hours, 53 minutes.

The SLS will be able to send cargo and astronauts to the Moon in a single mission. The SLS is a super heavy-lift expendable launch vehicle that comes in various configurations including crew and cargo only versions. According to the Planetary Society, it was developed at a cost of $23 billion and cost per launch is estimated to be between $2 billion and $4 billion. The Orion capsule was developed at a cost of $20.4 billion. Related ground infrastructure has cost over $5 billion since 2012. Cost per year of the SLS is estimated to be $2.55 billion (The Cost of SLS and Orion, 2022). In 2021, the NASA Office of Inspector General (2021) estimated that total costs for Artemis missions through fiscal year (FY) 2025 are projected to reach $86 billion. (NASA-OIG, 2021)

Once at the Moon, specific objectives include building the Gateway in lunar orbit and an Artemis Base Camp on the lunar surface. The Gateway spaceship in lunar orbit is where astronauts will transfer between Orion and the lunar lander on regular Artemis missions. Gateway will be a small space station in lunar orbit intended to serve as a solar-powered communication hub, science laboratory, short-term habitation module for government-agency astronauts, as well as a holding area for rovers and other robots. It is a multinational collaborative project involving four of the International Space Station partner agencies: NASA, European Space Agency (ESA), Japan Aerospace Exploration Agency (JAXA), and Canadian Space Agency (CSA). It is planned to be both the first space station beyond low Earth orbit and the first space station to orbit the Moon. Gateway will remain in orbit for more than a decade, providing a place for astronauts to live and work, and supporting long-term science and human exploration on and around the Moon.

The Human Landing System (HLS) will be built by commercial space companies and will provide transportation from Gateway to and from the lunar surface. NASA has selected Blue Origin, Dynetics, and SpaceX to develop a HLS.

The Artemis Base Camp (ABC) will give astronauts a place to live and work on the Moon. It includes an unpressurized rover to transport suited astronauts around the site; a pressurized rover to enable long-duration treks away from the outpost; and the surface habitat itself, which will be capable of housing four humans at a time. These elements will allow robots and astronauts to explore and conduct science activities on and around the Moon. The ABC is home-away-from-home and demands a lot of infrastructure such as communications, power, radiation shielding, waste disposal and storage space These are requirements for a sustained human presence on the Moon that can be revisited and built upon over the coming decades. Though not yet officially decided, a possible and likely location will be at the Moon's south polar region.

18.6.2. China and Russian Plans for an International Lunar Research Station

China and Russia are promoting their own International Lunar Research Station (ILRS) as an alternative to the US-led Artemis program. This joint Sino-Russian mission also aims to build a Moon base and install a space station in lunar orbit. The station is planned to be a state-of-art experimental research facility created on the surface or in the orbit of the Moon. In June 2021, Roscosmos of Russia, and the China National Space Administration (CNSA) presented a roadmap for the ILRS divided into three phases, five facilities and nine modules which are planned for the station to support long and short missions to the Moon's surface and orbit. The construction of the station is expected to be completed by 2035. These facilities include a Cislunar Transport Facility to support round-trip transfer between Earth and the Moon, lunar orbiting, soft landing, a take-off on the lunar surface, and re-entry to Earth.

On the surface, a long-term support facility will feature a command centre, energy and supply modules, and thermal management. The lunar transport and operation facility will help modules move over the surface and support excavation or sampling. The other two are the lunar scientific facility for in-orbit and surface experiments and the ground support and application facility. As for the modules, the designs reportedly include a “hopping robot” and smart mini rovers that would move around the Moon’s surface.

18.6.3. First Phase of ILRS Construction

The station is planned to be built in three phases, with the first phase involving six missions, including China’s Chang’e-4, 6, and 7 missions and Russia’s Luna 25, 26, and 27. The first phase involves gathering data and verifying high-precision soft-landings which is supposed to last until 2025. The Chang’e-4 (CE-4) mission delivered a landing platform and a rover named Yutu-2 to the Moon’s far side in January 2019, marking the first soft landing on the far side of the Moon by any country. Yutu-2 landed in Von Kármán crater, in the Moon’s South Pole-Aitken basin, in January 2019. The CE-4’s purpose is to explore the area’s geology. The CE-6 and CE-7 are expected to be launched around 2025.

The CE-6 is supposed to bring back to Earth lunar samples with a mass of up to 2 kilograms, and CE-7 will be tasked with landing on the lunar South Pole and detecting local natural resources. CE-7 is comprised of five separate spacecraft, namely an orbiter, lander, rover, hopping probe, and a polar relay satellite.

Russia also plans to launch its Luna-25 mission in 2023, thereby reactivating the Soviet-era series of robotic lunar missions that ended decades ago. The last in the series was Luna 24, which sent about 6 ounces (170 grams) of moon material back to Earth in 1976. The Luna-25 moon probe will launch atop a Soyuz-2.1b rocket with a Fregat upper stage from the Vostochny spaceport in the far eastern region of Amur. The probe’s primary destination for landing is the Moon’s South Polar region, specifically, a spot north of the Boguslavsky Crater.

According to Russia’s rocket design bureau, NPO Lavochkin has constructed the Luna 25’s lander. There are three main tasks for this mission: to develop soft-landing technology; study the internal structure and exploration of natural resources, including water, in the circumpolar region of the Moon; and investigate the effects of cosmic rays and electromagnetic radiation on the Moon’s surface (Kadam, 2022).

The development of a lunar base has been identified by the Beijing Declaration as the ideal next project for international collaboration on space exploration. CSIS Space Initiatives has made an estimate, based on available literature, that the likely costs of developing such a base would be about $35 billion, and operating the base would run about $7.35 billion per year (Costs of an International Lunar Base, 2009). As this information is quite dated, it may be assumed the projected costs have substantially increased since then.

18.6.4. China and Helium-3

Chinese nuclear scientists are studying lunar surface material samples brought back by its Chang'e 5 lunar exploration mission late in 2021. One sample is believed to contain a helium-3 isotope. This particular isotope is very rare on Earth but thought to be relatively abundant in lunar surface material in comparison. Verification of the presence of helium-3 could be very important, because helium-3 has many industrial uses and is thought to be the ideal future fuel for fusion reactors. Helium-3 fusion energy for terrestrial energy markets could be a rival to Space-Based Solar Power (SBSP) concepts.

In order to supply 10% of the global energy demand by 2040, roughly 200 tons of Helium-3 would be required annually. To do this would require a regolith mining rate of about 630 tons per second. This number is based on an optimistic concentration of 20 ppb helium-3 in the lunar regolith. All this translates to a requirement of between 1,700 to 2,000 helium-3 mining vehicles. To support the mining operation, a fleet of three lunar ascent/descent vehicles and 22 continuous-thrust orbit-transfer vehicles would be needed.

Based on these numbers, the required power for mining operations would be as high as 39 GW, with a resulting power system mass of the order of 60,000 to 200,000 tons which would probably be a SBSP system. The expected annual costs of such a program would be in the trillion-dollar range and could not begin seriously until fusion energy has been shown to be technically feasible and economically viable (Space Daily, (2021).

18.6.5. China and SBSP

In the field of SBSP, China has shown interest in developing its own SBSP system and has been developing a research facility in Bishan and conducting Wireless Power Transmission (WPT) demonstrations. The Bishan testing site will be a dual-use facility for military and civilian researchers.

Despite the many controversies, space solar power technology plays an important role in China's space development plan because it will stimulate the development of a wide range of cutting-edge technologies, including a superheavy rocket, a hypersonic space plane for low-cost transport, construction of massive orbital infrastructure and directed energy weapons (South China Morning Post, (2021).

18.6.6. China's Space Silk Road

China has grown from a stage of seeking self-sufficiency in spacefaring to one that is capable of exporting its services to a growing space market. China's space services, especially launches to the geostationary orbit and manufacture of communication satellites, together with its financing options, have proved to be highly attractive to the developing countries. China has penetrated an emerging market for space services among these nations, which are increasingly aspiring to utilise the benefits from satellite technology. These include countries like Bolivia, Nigeria, Pakistan, Belarus, Laos, Sri Lanka, and Venezuela. China's recent Silk Road initiatives on the ground too reflect a similar engagement with a focus on infrastructure creation with developing and less advanced countries of Eurasia, especially Pakistan and Central Asia, as well as Central and Eastern Europe. Developing a presence on the Moon would add yet another dimension to China's Silk Road ambitions (Anand, 2016).

18.6.7. China and Space Elevator Development

In recent years, Chinese researchers have been working to develop ultra-strong fibres that would be sufficiently strong to be used in a terrestrial space elevator. As further "circumstantial evidence" for optimism about the cost benefit of a lunar space elevator, researchers at Tsingtao University claimed that they had produced the strongest fibres in the world in 2018 (Chen, 2018). The same report quotes estimated costs of launch with a terrestrial space elevator of $500/kg by contrast to $10,000$/kg for normal launch.

18.6.8. Rationale of the Artemis and China/Russian Lunar Programs

NASA's Artemis Accords and the China-Russia proposal to build the International Lunar Research Station (ILRS) are two recent programs that are expected to impact the long-term vision of human activities on the Moon. History shows that reaching the Moon is not only a demonstration of technological dominance but also of the larger geopolitical logic associated behind it. New projects for the Moon also need study regarding any possible influence of these projects on the future of space security. These projects offer an opportunity to start (or restart) a debate about the need for the development of a rule-based mechanism for the management of planetary resources.

NASA's Artemis program is about returning humans to the Moon, and going beyond, with commercial and international partners. The first major step in this program would be to undertake the landing of humans on the Moon as soon as 2024. As the twin sister, Artemis looks very much like a re-do of the Apollo mission. Many of the goals are similar: demonstrating US leadership in space, exploration, discovery, and expected economic spin-offs, yet without a defined commercial program. Beyond sending the first woman and the first person of colour to the Moon, as inspirational justification, a main selling point appears to be using the Moon and Artemis program as a stepping-stone to a human Mars mission. With the first SLS mission having been successfully completed in November 2022, the Artemis program has already cost over $50 billion. The $2-4 billion price per launch and the $2 billion per year operating costs may not be sustainable in the anticipated period of economic recession.

The second project involves proposals by China and Russia to build a Lunar Research Station, either on the Moon's surface or in lunar orbit. The idea is to develop this station as a scientific base with the capability for conducting long-term autonomous operations, where lunar-based observations and various scientific experimentations would be undertaken. China and Russia have not yet announced any definitive timeline for this project, which still appears to be at its earliest phases. As a member of BRICS (Brazil, Russia, India, China, and South Africa), India could be invited as the next partner. This multilateral mechanism has arrangements for satellite data sharing. Thus, there is an opportunity for India, Brazil, and South Africa to join the Lunar Research Station.

Developing multilateral mechanisms for undertaking major projects in the space domain is not a new idea. In the post-Cold War period, one of the most successful space collaboration initiatives has been the construction of International Space Station. This effort has, until recently, managed two decades of continuous human presence in space. NASA's Artemis program is a multilateral mechanism for going to the Moon and beyond; while the China-Russia Lunar Research Station is currently a bilateral mechanism, they are keen to have more partners associated with it.

"Nations like India need to take the initiative to ensure fairness in the arena of distribution of planetary resources. The Artemis Accords and the China-Russia Lunar Research Station program clearly indicate that the US and China/Russia are interested in space hegemony and are keen to control the management of planetary resources in the future. Such collaborations are likely to ensure that technologically savvy and wealthier states would dominate the process of future rulemaking in the space domain, which could become a source of conflict." (Lele, 2021)

Using lunar resources for the development of SBSP does not appear to be a main priority of either China or Russia. As an alternative to SBSP, harvesting lunar helium-3 for terrestrial fusion energy production requires major technological and logistical developments making this commercial enterprise unrealistic in the near-term. However, as an expansion of China's Space Silk Road plans, and with Russia and maybe India as a partners, the Moon is an attractive destination.

18.7. A Spacefaring Species?

In 1987, in his book *The Overview Effect,* Frank White wrote:

"War and space exploration are alternative uses of the assertive, exploratory energies that are so characteristic of human beings. They may also be mutually exclusive because if one occurs on a massive scale, the other probably will not." (White, The Overview Effect, 1987)

In this context, the primary contribution of the Space Option to end our species' propensity to engage in war resides in the fact that it carries with it an authentic hope, a challenge and a potential which may be able to compensate for the confusion, the despair, and the misery of the philosophy of a finite world expressed in the practice of war which is humanity's main obstacle to becoming a spacefaring species.

Whatever the justifications for war – the victor in most such conflicts is usually the one with the superior technological advantage and space technology is deeply embedded in today's military arsenals.

Extending civilization into cislunar could redirect the aggressive aspects of human nature towards conquering the space frontier instead of the pursuit of war on itself and with its home planet This tension-reducing potential is perhaps the greatest potential contribution of the GE⊕-LPS project to peace and security on Earth.

By embracing and committing to the GE⊕-LPS project, the aggressive aspects of human nature could be channelled towards conquering the space frontier instead of being nurtured in the pursuit of war. Indeed, the International Space Station has been and still is a remarkable example of peaceful cooperation in space.

Having an inexhaustible supply of clean energy and other natural resources would not only perpetuate the lifestyle of the developed nations but could provide the basic means for further stimulating the economies of the developing countries. As such, future generations would be guaranteed a sufficient supply of energy and other material resources for their further development and today's less fortunate societies would be provided with hope that they, too, could still aspire to improve their living standard beyond their present situation.

If human civilization can be established beyond Earth beginning with the Moon, then the chances for its ultimate survival on Earth will correspondingly increase. A truly international effort dedicated to providing clean energy from space and to settle the Moon would be extraordinary opportunities to inspire and unite humanity to achieve its ultimate potential while addressing the critical issues related to the climate, the environment, economics, and energy security. 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.

19. Outstanding Challenges

The challenges to implementing the GEO-LPS concept can be grouped in three categories:

1. Technical
2. Financial
3. Political

19.1. 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 e.g. 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 in this list can be deployed and tested on Earth and then packaged as modules for lunar operations.

19.1.1. 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 ™ *(Radley, C. 2017).* These materials need special attention for how they can be produced and deployed in the required mass and dimensions. In addition, basalt fibres which could be produced on the Moon and potentially used to enhance the LSE should be tested and developed in conjunction with the terrestrial materials. The LSE materials and their suitability for space application, need in-space testing and development. Additionally, the deployment of a tether that extends from the surface of the Moon to almost the region of GEO needs extensive engineering research and development. As a key component of the Cislunar Transportation System, the LSE should have a high priority, not only for the technical aspects, but also in view of the economic and political implications. €11 billion for the development and deployment of a Lunar Space Elevator (LSE) has been included in the GE⊕-LPS €99 billion initial investment budget outlined in Section 13.

19.1.2. 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. It is anticipated that the efficiency of current MGL solar cell technology under development by crystalsol GmbH in Austria can exceed 20%. This would be developed in parallel with the current research by the Tallinn Technical University to use lunar-derived pyrite for MGL production on the Moon.

The recent announcement by Blue Origin *(Blue Origin, 2023)* about the development of 'Blue Alchemist' lunar solar cell technology which produces iron, silicon, and aluminium through molten regolith and purifies silicon to more than 99.999% to make solar cells, may become an additional option, either for development of similar technology in Europe or as a commercial provider of PV technology for GE⊕-LPS purposes.

19.1.3. Lunar Material 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 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. All the technologies related to basalt products applicable to the GE⊕-LPS system should be researched initially using terrestrial resources. Such industrial applications from basalt mining and processing are well established on Earth. Applications most appropriate for implementing the GE⊕-LPS concept should be optimized as potential lunar applications and the fabrication facilities should be designed and optimized for lunar operations. These include the extrusion of basalt for structural elements and the production of high-tensile strength fibres.

19.1.4. Electronics and Semiconductors

Semi-conducting materials such as silicon, ilmenite and pyrite are available on the Moon. The challenge will be to use them for electronic component production. Especially power semiconductors will be useful. There are numerous studies about how to make concrete and oxygen out of regolith, but only few on how to produce semiconductors.

19.1.5. 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 to be manufactured on the Moon. Glass is relatively easy to produce on the Moon, however it is only considerable for surface solar panels. Research should be intensified how to thin lightweight substrates for the PV panels like the polyimide Kapton, which is one of the few space-graded film materials.

19.1.6. 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. The need for propellant may decrease somewhat once the GE⊕-LSE is in operation. As oxygen is plentiful in regolith it can contribute a good part to propellant production. Since the proportion of oxygen in rocket propellant can be up to 80%, the option to import hydrogen et al. from the pole regions or from Earth can make sense. With the beneficiation of lunar-soil a considerable amount of oxygen will be produced, which can already reduce propellant shipments from Earth. Before there are roads or railroads established between the lunar poles and at the equator (Latitude/Longitude 0°/0°) the LLG can easily transport LOH from the poles to GE⊕-LPS production site. While descending from EM-L1 the LLG can deliver supplies to the station at the poles and pick up LOH and deliver it in a ballistic flight to Sinus Medii. This would be the most immediate and practical approach. Another option would be to construct a pipeline from the poles to the GE⊕-LPS operations at the equator such as the Lunar South Pole Oxygen Pipeline proposed to NASA by Lunar Resources, Inc. *(Curreri, 2023).* However, the mining of water ice at the poles and the extraction of water and hydrogen must be demonstrated first.

19.1.7. European Reusable Heavy Lift Launcher

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. As such, the ERHLS is a key component of the Cislunar Transport System essential for the implementation of the GE⊕-LPS concept. While it is assumed this launch system will be developed independently, €10 billion of the initial investment budget has been allocated towards its development. The challenge for Europe will be to make its system capable and competitive.

19.2. 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. In January 2023, the IEA wrote: *"Clean energy transitions offer major opportunities for growth and employment in new and expanding industries. There is a global market opportunity for key mass-manufactured clean energy technologies worth around USD 650 billion a year by 2030 – more than three times today's level." (IEA, January 12, 2023).* BloombergNEF's European Energy Transition Outlook 2022, projects that decarbonizing Europe's energy system creates a $5.3 trillion (4.9 trillion euros) investment opportunity in new electricity generating and green hydrogen production capacity between now and the year 2050 *(BloombergNEF, Path to Clean Energy, 2022).* €100 billion would only be just 2% of that amount.

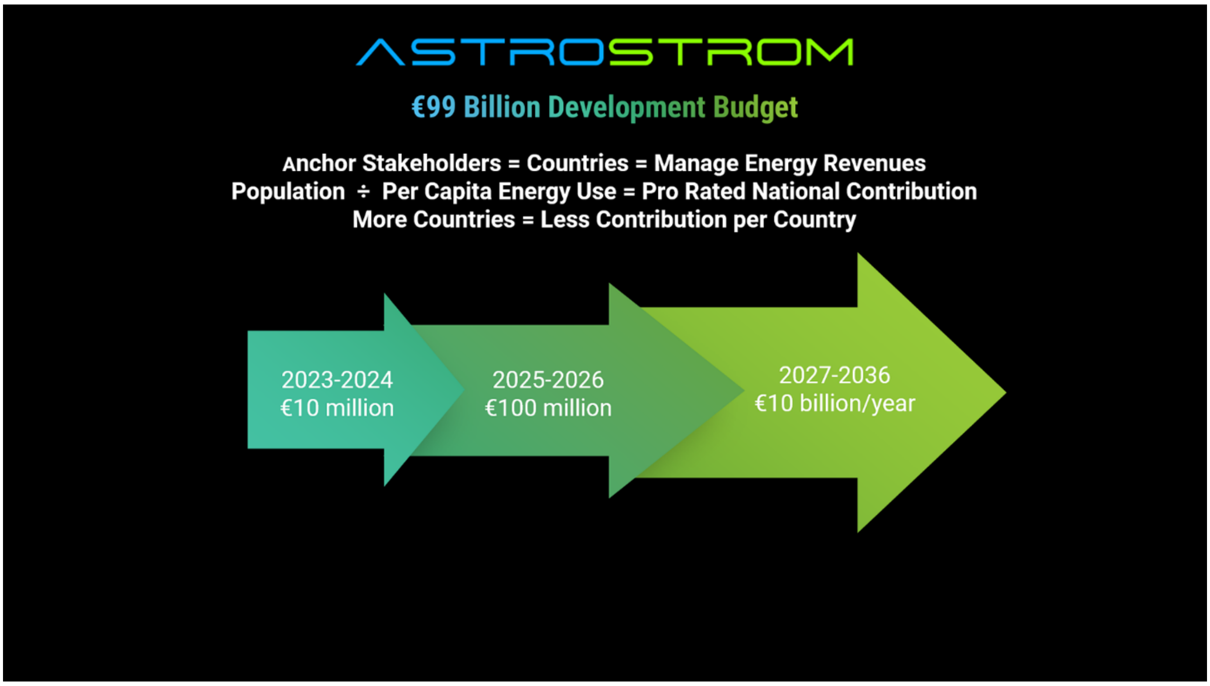


Figure 101: 3-Step approach for financing the GE⊕-LPS concept. (Credit: Astrostrom)

The study proposes a 3-step financial development path for GE⊕-LPS development shown in Figure 101. 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 GEEO 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.

19.2.1. Step One: €10 Million Commitment

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.

19.2.2. Step Two: €100 Million Commitment

The results of Step One would be dedicated to establishing a stakeholder consortium such as the proposed GEEO with a yearly annual budget of €100 million. 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.

19.2.3. Step Three: €10 Billion Yearly Commitment

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.

19.3. 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. Any attempts to control the source of energy powering the world economy will obviously become a reason for global conflict.

In the case of SBSP, power generation stations in orbit or on the Moon could become targets in case of war and this aspect would lead to further militarization of space activities. The fallout of any large-scale destruction of space assets could result in making the space environment unusable and in the worst case, trapping humanity on its home planet for the foreseeable future. Therefore, a large multi-national consortium of nations dedicated to jointly developing the *Space Energy Option* described in this report 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.

19.3.1. Consensus and Commitment

The global use of energy sharply accelerated at about the same time the first satellite was launched in 1957 which marks the beginning of the space age.

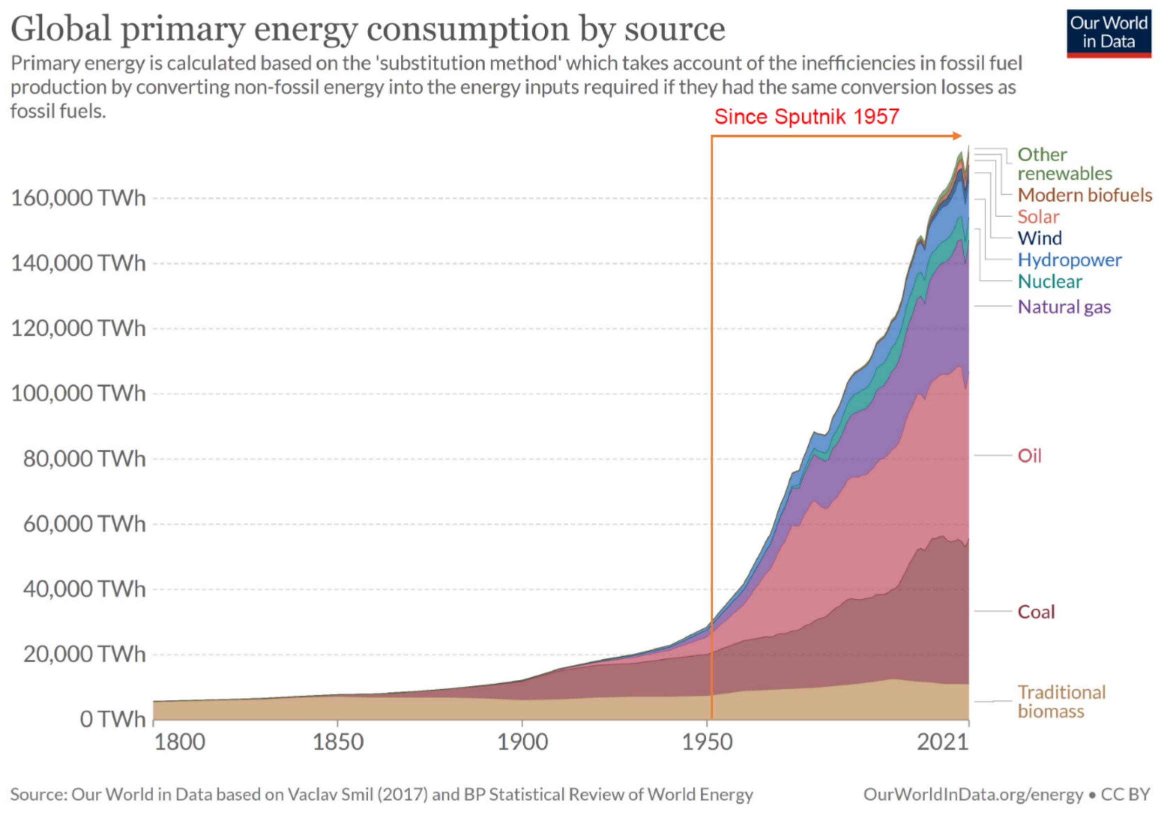


Figure 102: Global Energy Consumption since the launch of Sputnik, October 10, 1957. (Our World in Data, 2021)

Energy security emerged as a major concern in 2022. This was especially relevant for Europe as geopolitical developments drastically reduced the imports of fossil fuels from its largest supplier. Estimates of global energy supply versus consumption indicate the middle of the 21st century as the critical point when world energy supply will no longer keep pace with the demand.

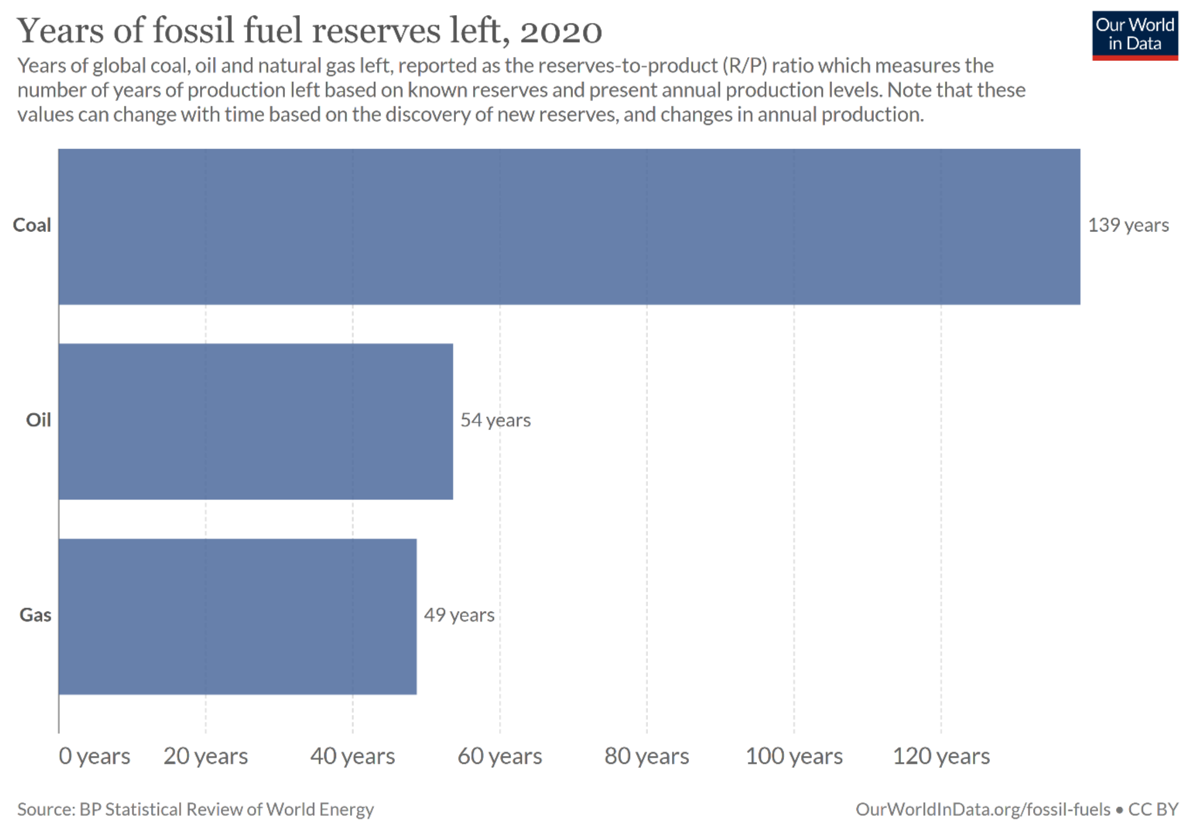


Figure 103: Years of fossil fuel reserves left, 2020 (Our World in Data, 2020)

The demand grows inexorably because of both the world population growth as well as the growth of average per capita energy consumption. Policies that force society to retreat from the use of fossil fuels and policies that promote inadequate energy solutions will result in an energy poor world – a situation that may lead to further global conflict and to the eventual collapse of civilization. Hence inadequacy of energy supplies would limit the progress of human civilization, stifling any hope for a sustainable and prosperous future.

Recognizing and accepting the reality of the *Energy Dilemma* currently confronting humanity should lead to a consensus and a committment to address this critical issue with the most promising energy solutions available – including clean energy from space.

19.3.2. Establishing the Greater Earth Energy Organization (GEEO)

Astrostrom proposes the creation of a Greater Earth Energy Organization (GEEO) with a 10-year budget of approximately €100 billion to implement the GE⊕-LPS concept and, by doing so, possibly initiating a new space energy industry. The GEEO would be set up as a democratic multi-national organization composed of national entities with a projected yearly budget of €100 million as an administrative platform for managing the organizational and financial aspects as well as research and development. Such a multi-national consortium of national entities working together with a shared goal would also facilitate the solution of regulatory issues such as spectrum allocation, orbital positioning, and energy distribution.

As the primary goal of the GEEO would be to provide Europe and the entire world with a substantial supply of clean energy in an equitable, economical, and socially just manner; the environmental advantages, the technical feasibility and the economic advantages must become compelling and overwhelming arguments in order to gain the support and commitment of the main stakeholders which will most likely be a consortium of nations, corporations, multi-national organisations, and other interested entities. Setting up such an organization with this proposed budget will surely be a challenge, but is seen as a logical and essential step in creating a new space energy industry.

19.3.3. The Outer Space Treaty (OST)

A growing number of nations are developing programmes to return to the Moon and begin ISRU activities there especially at the lunar poles where water ice is expected. These countries are approaching the legal parameters associated with these activities from different perspectives with different interpretations of the Outer Space Treaty provisions. Indeed, Europe has joined the U.S. and is a partner in the Artemis Accords. One of the key principles of the Artemis Accords is to affirm the importance of countries complying with 1967's Outer Space Treaty (The Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies). To adhere to the provisions of the OST, and to avoid any potential conflicts, it would advantageous and indeed practical if all, or at least most, of the current signatories would become members of the GEEO.

19.3.4. Economics Versus Geopolitics

In their recent book '*Scramble for the Skies: The Great Power Competition to Control the Resources of Outer Space'* Goswami and Garretson discuss the recent growth of interest in accessing and using space resources, notably including lunar and asteroid mining, among US space advocates, start-up companies and government agencies, including NASA. While these peoples' vision of future settlement in space may be correct overall, the crucial step to realising it is to develop a path towards it that will start to earn commercial revenues capable of growing to sufficiently large scale to repay much of the initial investment needed, as soon as possible (Goswami and Garretson, 2022).

The GE⊕-LPS concept, uniquely, proposes that the global energy market, and more specifically the multi-trillion Euro market for electric power, and its potential growth over the next few decades as developing countries aspire to a living standard comparable to G7 countries, is a promising target as a source of funding for development of a range of industrial capabilities in space. That is, the GE⊕-LPS project differs from other researchers' plans by clearly focusing on the goal of using physical resources on the lunar surface to make components for SPS units in Earth orbit supplying electric power to users on the Earth's surface.

If SPSs are successfully developed and put into service, and if lunar factories making major components such as solar panels and structural members are able to sell these to companies operating the SPSs at prices competitive with components launched from Earth, part of the multi-trillion Euro stream of electricity supply revenues will start to fund such space development activities.

This will represent a major success for space agencies' long-continued efforts to develop a commercially self-sustaining space industry. Although these two conditions clearly face major uncertainty today, there are several reasons for believing that, over the medium term, the value of this project could grow very high.

1. The demand for electric power on Earth is expected to grow by at least 100% from today's level.
2. The technologies needed to realise lunar manufacturing are progressing at unprecedented speed.
3. As lunar surface industrial and commercial capabilities grow, other major new markets will also arise for their output.

To ignore this potential, and thereby fail to participate in its growth, would risk facing the loss of the opportunity to take a significant share in a major, new, strategic industrial field.

20. Recommendations and the Path Forward

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. Only then will the hope of addressing the climate and energy crises in a time frame short enough to make a difference be realistic. Therefore, it is useful to articulate the path forward in a series of successive time-specific developmental milestones.

20.1. 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

20.2. 2025-2026

- €100 million funding milestone
- GEEO organizational development and staffing
- Recruit additional members 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

20.3. 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

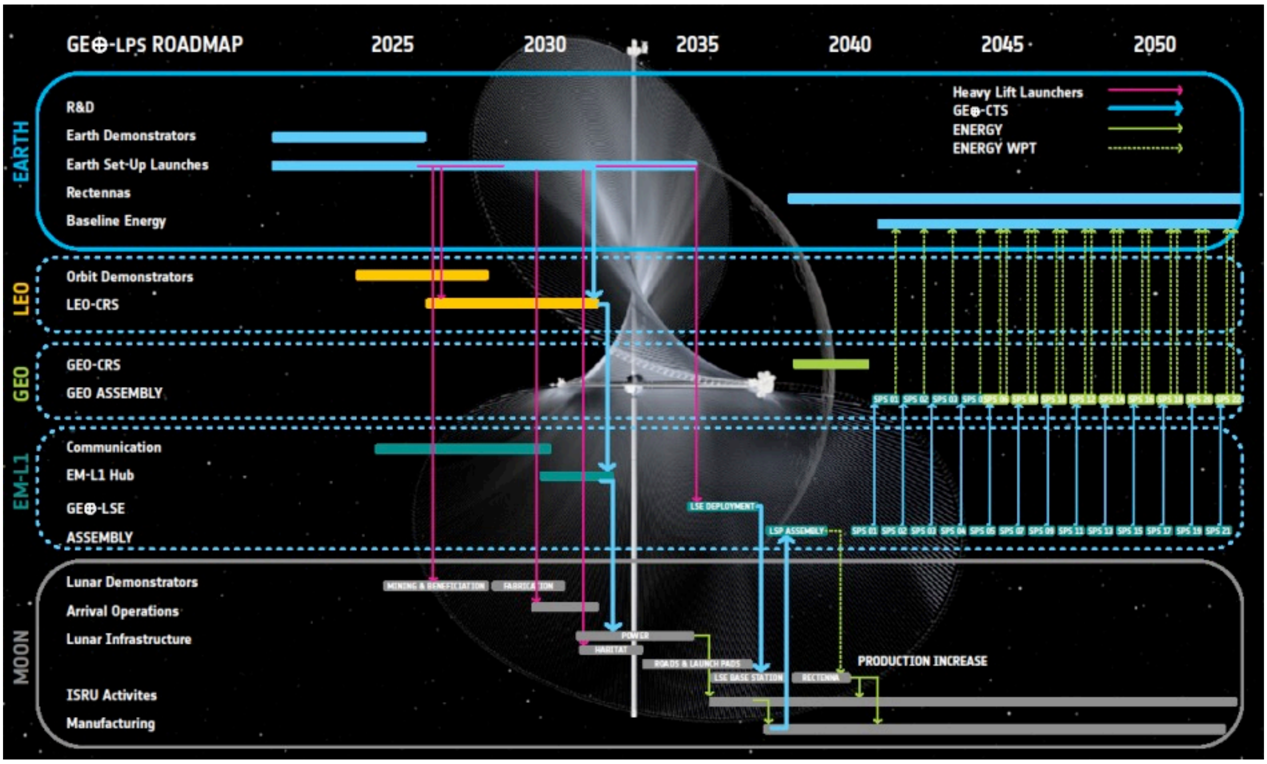
20.4. 2037-2050

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

20.5. 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.

20.6. Roadmap



21. Outreach

It is hoped that the results of this study will have a positive influence in the development of the Solaris initiative at ESA and in Europe. Wider understanding by the general public of the potentially huge scale of the supply of environmentally clean energy from space to Earth that is feasible with existing technology, and more broadly of the benefits of choosing and implementing the "Space Option" should be very helpful in expanding humanity's access to resources, and preserving and reviving civilisation worldwide.

21.1. Inreach

Now that programs like Solaris are bringing attention to SBSP and to the contribution this space technology could make to the global energy mix in addressing the climate and energy crises, all feasible approaches that can make the Space Energy Option viable need to be pursued, researched, discussed, and debated.

This study has put forth a lunar-based approach to producing SPS components that can be eventually used to produce solar power satellites serving terrestrial energy needs. It is an ambitious plan that goes beyond the traditional approach to realizing Solar Power Satellites which has been discussed and researched for more than fifty years. The recent achievement of lower launch costs and more efficient space technologies have contributed to a renewed interest in SBSP. Earth's gravity well and the rocket equation still dictate the eventual success of this technology.

A parallel approach - Earth produced SPS and Moon produced SPS - to providing clean energy to Earth would seem to be an optimal strategy, based on the understanding that the GE⊕-SPS system could double the capacity of existing concepts, in the nearer term, and grow essentially without limit thereafter.

Therefore, the SBSP community needs to be made aware of the technical feasibility and economical advantages of the GE⊕-LPS concept that, with appropriate investment, could evolve into a GE⊕-SPS system that could eventually contribute to mitigating the launch bottleneck and environmental impact problems facing SBSP. The results of this study, if found to be valid, need intensive additional discussion internally and externally. This is the first outreach - and inreach - priority. This should not only be the task of the authors of this study but of ESA's Solaris team as well.

21.2. Astrostrom Website

Astrostrom already manages several websites dedicated to the concepts outlined in the study. On its main website: astrostrom.ch resources related to the study are regularly posted:

- Database of news articles related to SBSP,
- Database of news articles specially mentioning Solaris,
- Database of news articles related to lunar development,
- Database of books about SBSP,
- Database of Videos about SBSP,

- Press releases and press articles about the study,
- Video productions developed during the study (see below).

21.3. Publications and Presentations

It is the intention of the Astrostrom team to make presentations about the results of the study in various professional venues.

21.4. Videos of the Study Findings

In today's digital society, video is an effective means of communication. During the study the various conceptual ideas have been translated into video productions. This process has served to concretize many of the technical concepts that have been expressed in written form. Most people will not have the time or intertest to read the report or the book. Thus, videos about the project's concepts will be a way to easily access the fundamental information. Indeed, some of the project's most interesting concepts will be best understood in the video format. Some of these video clips can found on the Astrostrom website. An end-to-end video production of the GE⊕-LPS will be one of the main outreach products of the study.

The videos shall also stimulate the imagination of today's generation of engineers, political and business leaders to contribute to the ambitious project of generating energy for Earth with Moon-built satellites. The visualization and animation shown in the videos about what could become reality in a few years should result in a technological pull-effect.

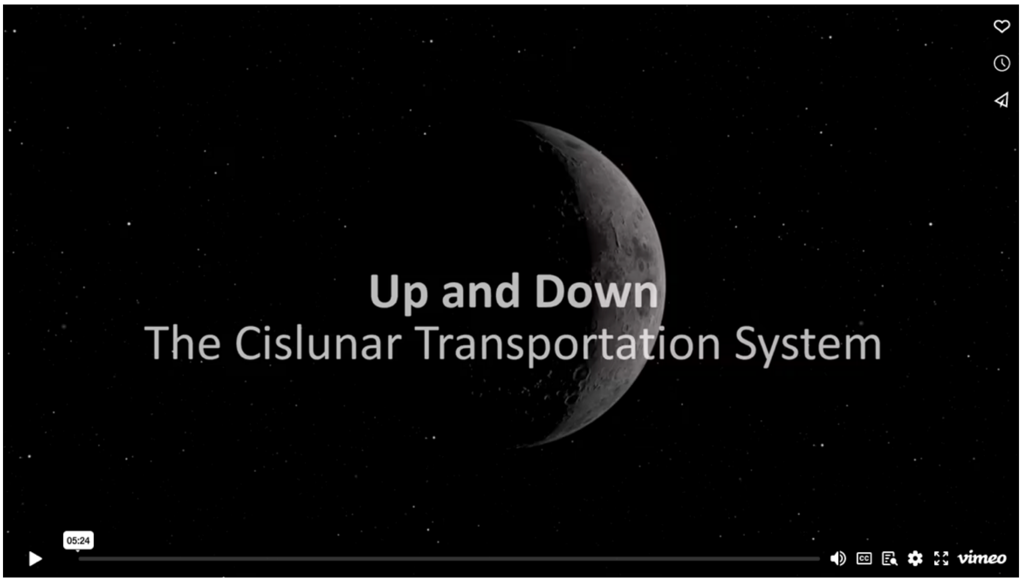
SOLARIS Animations
This video shows all the CGI animations made by Astrostrom for the ESA SOLARIS video and which will be adapted to the GE⊕-LPS concept.
https://vimeo.com/729101931

Greater Earth Energy Synergies
Video presented at the 2023 Luxembourg Space Resources Week, April 19, 2023
https://vimeo.com/816688969

Here to Stay
This video shows our vision of arriving on the Moon, deploying a mobile solar power system, commencing mining operations and protecting the habitat from radiation
https://vimeo.com/676839339

Mining the Moon for Energy
This video shows our vision of mining operations on the Moon with the finished components being transferred to the Lunar Space Elevator for assembly in lunar orbit.
https://vimeo.com/792594964

Greater Earth Lunar Space Elevator
This shows the Deployment of the Cislunar Transportation System
https://vimeo.com/702526849



Up and Down the Cislunar Transportation System
This video shows the lunar space elevator base station operations, the lunar landing gantry and the robotic assembly operations at EM-L1
https://vimeo.com/825370900

21.5. Art and Technology Exhibitions

Museums are very interested in presenting and addressing current topics which combine art and technology. As visualization and animation have been main activities throughout the study and the study offers an optimistic approach to addressing the climate and energy crises in a futuristic space approach, it can be assumed cultural institutions will be open to exhibition proposals.

22. Results of the Study

The study team concluded that the GE⨁-LPS is indeed technically and financially feasible without any major technological breakthroughs needed. 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 and delivered in modular form and managed telerobotically on the lunar surface. Although no technological breakthroughs may be necessary, due to the lack of experience operating in the lunar environment and direct in-situ access to lunar materials, substantial engineering would be required. Financially, the scaled version of the GE⨁-LPS - the GE⨁-SPS - was shown to be not only be more economically attractive than a comparable Earth-launched SPS, but also cost-competitive with any terrestrial energy alternative. If this proves to be the case, then the impact on the global energy economy and society in general would be as unprecedented as was the introduction of fossil fuels. Finally, in a time of 'Mega-Crises', humanity needs to believe in a future full of expectations, excitement, challenge, inspiration, and hope. Implementing the GE⨁-LPS concept and expanding civilization to the Moon with a dedicated purpose and using lunar resources to address one of the most pressing issues on Earth may be the only way to insure humanity's future.

The results have been itemized as follows and described in the Executive Summary.

- The GE⨁-LPS System Architecture
- The Reference Design of the GE⨁-LPS
- Solar Panels from Lunar Materials
- Structural Elements from Basalt Fibres
- Mining
- Beneficiation and Processing
- Fabrication
- Site Considerations
- Transfer of GE⨁-LPS Components to the Assembly Location at EM-L1
- Robotic Assembly Operations
- The Greater Earth Cislunar Transportation System
- Economic Considerations
- Initial Infrastructure Investment
- Lunar produced SPS compared with terrestrially produced SPS
- Profit/Loss estimate of a GE⨁-SPS
- Economic Synergies and Flywheel Effects
- Greater Earth Energy Organization (GEEO)
- Cultural Impact
- Enhancing the Overview Effect
- Choosing a Space Age or a Stone Age

23. 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, humans' 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 not less than starting a whole new two-planet economy without further exploitation of the home planet. And last but not least, giving 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 the threshold of 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".*

24. Frequently Asked Questions

Q 1. What is the Greater Earth Lunar Power System?

The GE⊕ Lunar Power System is a multi-purpose proposal for producing Solar Power Satellite components on the Moon and thus initiating a lunar economy, while providing a solution to the world's fossil fuel energy dilemma.

Q 2. What is the Greater Earth Lunar Power Station (GE⊕-LPS)?

The GE⊕ Lunar Power Station (GE⊕-LPS) will be the first of a generation of Solar Power Satellites (SPS) mostly built from lunar materials. It will collect solar energy at EM-L1 and deliver MW of microwave power to the lunar surface, where it will power the production infrastructure and thus accelerate the production of more SPSs, which will be transferred to GEO or another Earth orbit. It also contains a small habitat and can be extended with other space station functions.

Q 3. How would the GE⊕-LPS on the Moon contribute to energy production on Earth?

If shown to be technically feasible, the lunar manufacturing operations could be scaled to any dimension, and SPSs assembled in lunar orbit could provide much needed clean solar energy for terrestrial purposes, at much lower cost due largely to the Moon's low gravity reducing the cost of delivery to GEO.

Q 4. Why not just launch Solar Power Satellites (SPS) from the Earth?

The main obstacle to the longer term scaling up of the building and launching Solar Power Satellites from the surface of Earth is the launch bottleneck created by the large number of heavy-lift launches needed to transport material required for the massive, GW-scale SPS units from Earth to GEO.

Q 5. Why is Space-Based Solar Power (SBSP) considered as a 'baseload' power source?

Outside of the Earth's shadow, the Sun is always shining. A SPS can collect this energy, convert it into electricity and send it via microwaves down to Earth. This is also possible with cloudy skies and at night. Other than using nuclear power and/or fossil fuels for baseload power, a SPS works with sunlight and delivers pure energy without any radiation or other polluting side effects. Thus, in addition to hydroelectricity, SBSP can provide 'green baseload power' at a significant level.

Q 6. Are microwaves from space dangerous for people on Earth?

Due to the considerable distance from space to Earth, the microwave beam widens considerably. The peak energy density of the beam will be about 1/4 that of mid-day sunlight. The energy density outside the rectenna area is far less, in the region of per square meter is in the region of microwaves emitted from a home WiFi router, or the harmless leakage from microwave ovens.

Q 7. If SBSP is such a great idea, why it hasn't it been done before?

The idea was introduced in the 1960's and researched by NASA and others during the oil crisis of the 1970's. However, as fossil energy was so inexpensive and widely available without any serious environmental concerns, the concept was not developed beyond academic studies. In recent years, several developments have come together, which makes the idea relevant to today's energy discussion: (1) significantly decreasing launch costs, (2) high level of automation and robotics, (3) powerful semiconductor technologies and increasing PV efficiencies, (4) the climate crisis and net-zero targets, (5) growing world population, and (6) geopolitical energy insecurities.

Q 8. Why not build more rockets?

To launch just one SPS with a mass of ca. 2,500 metric tonnes (MT) into geostationary orbit would require between 86 and 119 launches of a rocket launcher equivalent to the SpaceX Starship heavy launch system currently under development delivering 29MT and 21 MT respectively to GEO. Hence launching 100 GW of capacity would require perhaps 10,000 launches, burning more than 1 million tons of propellants, of which the environmental impact would probably be prohibitive.

Q 9. Why not use available terrestrial energy sources?

None of the terrestrial energy options – nuclear – wind – ground solar (PV) – hydroelectricity - can be sufficiently scaled to achieve the goal of divesting from fossil fuels by the year 2050. Nuclear power has political, economical, waste disposal and location restraints. Wind and solar photovoltaic generators have significantly lower availability than nuclear power systems as well as inherent intermittency and storage limitations.

Q 10. Is it possible to build Solar Power Satellites on the Moon?

We assume that 80% of the SPS could be built from lunar materials produced in a highly automated mining and fabrication system. The photovoltaic solar cells that will be made on the Moon will use very different technology such as Monograin Layer (MGL) that are easier to manufacture that those now mass-produced on Earth. The structural elements will come from basalt fibre and metals mined and produced in factories on the Moon. 20% of the SPS components such as electronics and special materials will need to be imported from Earth.

Q 11. Will the Solar Power Satellites for Earth be launched with rockets from the Moon?

No. The lunar built SPS components will be transported from the lunar surface to the Earth-Moon Lagrange point 1 for assembly using a lunar space elevator (LSE). Once assembled, they will need to be sent to Earth using a rocket powered space tug or with integrated ion drives and/or with an extended LSE.

Q 12. Surely a Lunar Space Elevator will take decades to develop?

There are certainly many topics that need to be researched, evaluated and tested in order to be able to manufacture and operate a LSE. However, as of 2023 no fundamental problem has been identified. Importantly, a lunar space elevator is a far easier project than a terrestrial elevator, for which suitably strong materials do not even exist yet.

Q 13. How much will this cost?

The initial infrastructure investment is estimated to cost approximately €100 billion including the research and development cost for the SPS system, a European reusable heavy lift launch system and a cislunar transportation system. As a comparison, the US Artemis program is expected to cost about the same amount. The annual development budget of the GE⊕-LPS concept is only 1% of yearly subsidies of USD $1 trillion given to the fossil fuel industries around the world *(IEA, Subsidies, 2022).*

Q 14. Who will make this investment?

The clean energy transition in Europe is estimated to cost over €5 trillion by the year 2050. The initial investment to set-up GE⊕-LPS would cost just 2% of this amount. A consortium of collaborating countries and their industries could easily guarantee the initial investment and share the benefits.

Q 15. How will the initial investment be repaid?

Due to the low cost per SPS unit, each lunar built SPS could generate a €600 million profit per year. Therefore, it would only take 20 SPSs and 20.5 years to repay the initial investment. 78 SPSs, each with a capacity of 1.44 GW SPS, could supply 11% of Europe's projected electricity needs in 2050 with 101 GWe of baseload power providing 886 TWh of clean electricity. This would generate a potential profit of approximately €1.4 trillion over a 30-year period.

Q 16. How much electricity will Europe need in 2050?

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 seems likely to increase by at least 75%, but more realistically by 120% - 150% by the year 2050. Thus, Europe's annual electricity demand could increase from 4032.5 TWh currently to approximately 8,065 TWh in the year 2050. This would require the equivalent an overall continuous electrical power-generation capacity of approximately 920 GWe.

Q 17. What would be the contribution of Space-Based Solar Power (SBSP)?

A realistic goal of SBSP is to provide Europe with at least the same amount of baseload electrical power as nuclear power provided in 2021, i.e. 883 TWh. This would require 78 SPS systems with a capacity of 1.44 GW each operating with an availability of 90% (1.30 GW/SPS) to provide the 101 GWe of power.

Q 18. Surely the need for lunar manufacturing will delay SPS production for Earth?

The first SPS units will need to be developed and launched from Earth if they are to contribute to reaching Net-Zero by 2050. To supply 100 GWe of European electricity demand in 2050, it will likely be necessary to launch as many as 78 SPS units from Earth. However, the demand for clean energy on Earth will not peak then. In order for SBSP to expand further and to supply a useful proportion of worldwide electricity demand, such as 1,000 GWe or more, mass-production on the lunar surface will be essential thereby reducing the cost and environmental burden of launching ever more SPS units from Earth. Provided that long lead-time research topics start soon, there is no reason why lunar production should delay the supply of SBSP.

Q 19. What are the legal issues?

Today, the legal framework for the eventual use of extraterrestrial resources including energy from space rests with the Outer Space Treaty (OST) which forms the basis of international space law. Ideally, an international consortium of nations would be able to avoid conflict and to provide a transparent process for the development and eventual distribution of this new space energy resource.

Q 20. Why is space tourism important?

Tourism adds to the business case. Developing a lunar industrial complex will require the construction of extensive buildings including manufacturing facilities from lunar materials. These are core capabilities for future tourism facilities, and so once they are in place and functioning reliably and safely, there will be an immense motivation for companies in several countries to develop lunar tourism destinations. This will inform and inspire more people about the advantages of space development.

Q 21. As space tourism services are so expensive will only the rich benefit from their development?

In all industries the rich are the first to benefit from new products and services. But new industries work to increase their sales and profits by cutting costs and prices to grow their market. The history of air travel shows this clearly: services that were initially accessible only to the rich are now used by billions of people every year, creating employment for tens of millions of people. The speed of development of new technologies today suggests strongly that, once fully reusable passenger spaceplanes and rockets are developed, space travel services will become ever cheaper for decades to come, just like air travel services.

Q 22. Surely, talk of constructing lunar hotels is sheer fantasy?

Construction methods on the lunar surface will be very different from construction on Earth. For example, roads (which need only be strong enough to carry vehicles weighing one sixth of those on Earth) can be made by directly melting regolith with concentrated sunlight. Walls have already been made by melting simulated regolith. 1/6 of Earth's gravity greatly reduces the gravitational stresses on buildings. Consequently, based on the wealth of accumulated, worldwide engineering knowhow, constructing hotels and other buildings on the Moon is unlikely to pose any insurmountable difficulties.

Q 23. Would any spinoff benefits to other industries not arise for decades?

To continue economic growth, there is a profound need for new industries, as older industries continue to move out of Europe and USA to lower-cost countries. There is a very large, unsatisfied, pent-up demand for space tourism services. As these services grow progressively through sub-orbital, orbital and lunar phases, which are already starting, they could create employment for tens of millions of people, like air travel services have done.

Q 24. What is Astrostrom?

Astrostrom is the German word for *Astroelectricity* coined by Michael Snead in his book with the same title about providing electricity from space. The company, Astrostrom GmbH functions as a think-tank of industries, institutions, organizations, and individuals dedicated to developing and providing clean and inexhaustible energy from space to Europe and the world. The company conducts feasibility studies and visualization projects promoting the *Space Energy Option.*

25. Key Resources

25.1. Books

Over the past few decades, several dozen books have been published (in English) that discuss potential benefits of accessing the resources of the Moon and asteroids, and of using microwave beams to deliver solar-generated power from space to users on Earth. Collectively these books contain much useful knowledge, and many suggestions about different aspects of these projects, from chemical engineering and space science to geopolitics, tourism and finance.

What the present study adds to this wealth of material is to create a detailed, concrete, economical plan to realise these benefits by helping to solve one of the major problems facing the world today: to use lunar resources to build space-based systems to supply large quantities of environmentally benign energy to the Earth, and to use the projected revenues from this to finance the development of the technologies needed. This is particularly relevant today due to the severe energy shortages in Europe and elsewhere, and the recent rapid advances in many relevant fields of technology. The present study builds on these and other earlier studies and makes a coherent case that the time is now ripe for this epoch-making development, which will also create numerous new business opportunities, and entire new fields of employment.

1. **Electric Space: Space-based Solar Power Technologies & Applications**, by **Ali Baghchehsara** and **Danny Jones** Amazon; First edition, February 19, 2014
   https://amzn.to/3d4ZxGv

   The authors argue that innovation has delivered humanity from caves to the ability to access the edge of space and to send robotic explorers deep into the solar system. It is the driving force in mankind's expansion, growth and both technological and non-technical development. And now, the innovation of beamed energy technology could potentially lower the cost of access to space and transportation though space, thereby lowering the cost of transporting goods and people to many destinations in the solar system and beyond.

2. **Building Habitats on the Moon: Engineering Approaches to Lunar Settlements** Springer Praxis Books) 1st ed. 2018 by **Haym Benaroya**, professor at Rutgers University.
   https://amzn.to/3bcWEVo

   This book provides an overview of various concepts for lunar habitats and structural designs and characterizes the lunar environment - the technical and the nontechnical. The designs take into consideration psychological comfort, structural strength against seismic and thermal activity, as well as internal pressurization and 1/6 g. Also discussed are micrometeoroid modelling, risk and redundancy as well as probability and reliability, with an introduction to analytical tools that can be useful in modelling uncertainties.

3. **Moon Rush: The New Space Race**
   by **Leonard David**, National Geographic, May 7, 2019
   https://amzn.to/3djUzFT

   Veteran science journalist Leonard David explores the Moon in all its facets, from ancient myth to future "Moon Village" plans. The 21st-century "Space Race" back to the Moon has become more urgent, and timelier, than ever. This book sheds new light on our "constant lunar companion" and gives reasons to gaze up and see it in a different way than ever before.

4. **Mining the Moon: Bootstrapping Space Industry**
   by **David Dietzler**, Amazon Kindle, October 12, 2020
   https://amzn.to/3etrKe8

   This book discusses the industrialization and settlement of the Moon, our stepping stone to free space, Mars, the solar system and ultimately the stars. It looks at the technical challenges of mining the Moon for all sorts of materials to build solar power satellites, spaceships and space settlements in orbit.

5. **Krafft Ehricke's Extraterrestrial Imperative** by Marsha Freeman, Apogee Books February 1, 2009
   https://amzn.to/3cr5WLN

   A summation of Krafft Ehricke's work on encouraging the exploration of space, this account offers biographic information on the man himself; encompasses details of his new, innovative ideas; and portrays his thoughts on the importance and value of space travel for society. Providing an understanding of the early history of the space pioneers, what they helped accomplish, and how Ehricke's vision came to fruition, this reference details the continuing need for a creation of a long-term vision for the exploration of space. Historic and yet topical, this resource also includes many of Ehricke's original works, many of which were previously out of print.

6. **Solar Power Satellites** by **Don M. Flournoy**, Springer, December 2, 2011
   https://amzn.to/3eTKWyE

   'Solar Power Satellites' shows why and how the space satellite industry will soon begin expanding its market from relaying signals to Earth to generating energy in space and delivering it to the ground as electricity. In all industrialized nations, energy demand is growing exponentially. In the developing world, the need for energy is as basic as food and water, and is due to grow by many hundreds of percent.

7. **Solar Power Satellites: A Space Energy System for Earth** by **Peter E. Glaser**, **Frank P. Davidson** and, **Katinka I. Csigi** Wiley, 2nd edition December 11, 1997
   https://amzn.to/3dLgpTG

   This book creates awareness of the potential global benefits of power from space. It discusses space power options based on wireless power transmission (WPT) to meet global energy demands and to reduce reliance on fossil and nuclear fuels. It also discusses the current and emerging international regulatory and legal regimes to enable the realization of the solar power satellite concept Earth orbits, and on the Moon.

8. **Colonies in Space**, by **T. A. Heppenheimer**, Published 1977 (Out of Print) Available online by the National Space Society (2007) https://space.nss.org/colonies-in-space-by-t-a-heppenheimer/

   Considered to be one of the best early books on space settlement, Heppenheimer describes, in comprehensible terms, the construction of the initial facility to house those working on the first settlement, the lunar mine to gather materials, the mass driver catapult to send lunar materials into orbit, the catcher to gather the materials and control them, the major settlement designs of the times, and the solar power satellites to pay for it all. The author extends Gerard O'Neill's book *The High Frontier* with an extensive discussion of high-intensity agriculture and discovers a better location for the first settlements, a high Earth orbit rather than L5. There are also unique details such as the low-g swimming pool.

9. **Mining The Sky: Untold Riches From The Asteroids, Comets, And Planets** by **John S. Lewis**, Helix Books Basic, 1997 https://amzn.to/3gv0RFc

   In this book, noted planetary scientist John S. Lewis explains how we can mine precious metals from the asteroids, comets, and planets in our own solar system for use in space construction projects. And this is just one of the possibilities. John S. Lewis also contemplates harvesting the moons of Mars for water and hollowing out asteroids for space-bound homesteaders—all while demonstrating the economic and technical feasibility of plans that were once considered pure fiction. As we worry over the depletion of the earth's natural resources, the pollution of our planet, and the challenges presented by the Earth's growing population, billions of dollars worth of metals, fuels, and life-sustaining substances await us in nearby space.

10. **Asteroid Mining 101: Wealth for the New Space Economy** by **John S. Lewis**, Deep Space Industries, December 12, 2014 https://amzn.to/3h83AVp

    The emerging asteroid mining industry has extremely ambitious intentions. Lewis argues that it is within the realm of possibility that their work may usher in a change in global economics as profound as the Industrial Revolution. Press reports dealing with asteroid mining have ranged in scope from short and breezy to broad and serious, and in quality from accurate to impressionistic to simply uninformed. There is good reason to be investigate further what may become a major gamechanger in humanity's economic history.

11. **The Case for Space Solar Power** by **John Mankins,** Virginia Edition Publishing, January 5, 2014 https://amzn.to/2MkZdrZ

This book makes the Case for Space Solar Power by recounting the history of this fascinating concept and summarizing the many different ways in which it might be accomplished. It describes in detail a highly promising concept – SPS-ALPHA (Solar Power Satellite by means of Arbitrarily Large Phased Array) – and presents a business case comprising applications in space and markets on Earth. The book explains how it is possible to begin now with technologies that are already at hand, while developing the more advanced technologies that will be needed to deliver power economically to markets on Earth. The Case for Space Solar Power concludes by laying out a path forward that is both doable and affordable: within a dozen years or less, the first multi-megawatt pilot plant could be in operation. Getting started could cost less than $10 million over the first 2 years, and less than $100 million over the next half dozen years.

12. **Energy Crisis: Solution from Space** by **Ralph Nansen,** *Apogee Books Space Series, – October 1, 2009*
https://amzn.to/2BrRu9n

This book by aerospace visionary Ralph Nansen presents a bold solution for global climate change and dependence on oil and the threat of war over its diminishing supply. This visionary reference explores how developing solar energy could bring about unprecedented economic prosperity and opportunity on a global scale. By using existing technology in revolutionary ways, this new energy plan would have the potential to create jobs and revitalize the economy while offering a clean, affordable, and long-term solution. Asserting that the current generation can develop this innovative energy source to change the world economically, environmentally, and politically for the better, this stunning guide offers an unexpected new hope for the future.

13. **Sun Power: The Global Solution for the Coming Energy Crisis** by **Ralph Nansen**
Published by Nansen Partners, January 8, 2012
https://amzn.to/3ePecqC

Nansen describes how the world is fast approaching a crisis of global proportions when our comfortable lives will be plunged into darkness as the last drop of oil is sucked from the ground. Our planet is choking on the deadly by-products of our energy hunger—foul air, radiation poisoning, oil-slicked waters, and acid rain. Sun Power offers a plan to begin the long journey to energy independence and global healing within ten years by capturing the vast power of the Sun. Ralph Nansen reveals an elegant solution to the problems plaguing our energy-hungry world—a plan for capturing the vast power of our sun in space.

14. **The High Frontier** by **Gerard K. O'Neill** Published by Space Studies Institute, Inc, January 5, 2014 Original Publication Date: 1976
https://amzn.to/3dsS8l9

In 1974, Dr. O'Neill put his three-pronged plan of Space Colonization, Space Solar Power and Large Scale Space Construction into easily accessible form with the release of the book The High Frontier. Fourteen years later, The Space Studies Institute, founded by O'Neill, re-released the original text, unchanged except for the addition of the Appendix "A View from 1988." This book is one of the milestone and timeless classics of Space Habitation, Alternative Power and Human Potential, all made possible with technology we already have.

15. **Return to the Moon: Exploration, Enterprise, and Energy in the Human Settlement of Space**
    by **Harrison H. Schmitt,** Copernicus Books, Praxis Publishing 2006
    https://amzn.to/30a6yCK

    Former NASA Astronaut Harrison Schmitt advocates a private, investor-based approach to returning humans to the Moon—to extract Helium 3 for energy production, to use the Moon as a platform for science and manufacturing, and to establish permanent human colonies there in a kind of stepping stone community on the way to deeper space. With governments playing a supporting role—just as they have in the development of modern commercial aeronautics and agricultural production—Schmitt believes that a fundamentally private enterprise is the only type of organization capable of sustaining such an effort and, eventually, even making it pay off.

16. **Space Systems Architecture for Resource Utilization: A Workbook for Practitioners**
    by **Peter J. Schubert**, Cambridge Scholars Publishing, 26th April 2021
    https://bit.ly/3nx3VFd

    According to Peter Schubert, space resources will transform human enterprise. This practical workbook is a comprehensive guide for start-ups, students, and space enthusiasts, who will find insights to strengthen and deepen their own capabilities. Systems are complex and architectures tie them together, requiring technical understanding, and so much more. This book will show the reader how to start a space business, appeal to legislators, interact with regulators, engage the public, and to coordinate diverse, international teams. It will allow them to gain the confidence to build, live, work, and move about in space.

17. **The Moon: Resources, Future Development and Settlement (Springer Praxis Books) 2nd Edition** by **David Schrunk** (Author), **Burton Sharpe** (Author), **Bonnie L. Cooper** (Author), **Madhu Thangavelu** (Author) Springer Praxis; 2nd edition, 2007
    https://amzn.to/3ePe0aQ

    In *The Moon: Resources, Future Development, and Settlement* David Schrunk describes how the Moon could be used as a springboard for Solar System exploration. He and his contributors present a realistic plan for placing and servicing telescopes on the Moon and highlights the use of the Moon as a base for an early warning system from which to combat threats of near-Earth objects. The author presents a realistic vision of human development and settlement of the Moon over the next one hundred years and explains how global living standards on Earth can be enhanced through the use of lunar-based solar power generation and transmission to

Earth. From that beginning, the people of the Earth could evolve into a spacefaring civilization.

18. **Astroelectricity** by **James Michael Snead,** PE Published by Spacefaring Institute LLC, January 4, 2019
https://bityl.co/Aiyd

The author argues that during this century, the United States faces two serious and related threats. The first is the abnormally high atmospheric carbon dioxide concentration due to anthropogenic causes. The second is an inadequate domestic fossil fuel supply that will lead to shortages, and likely warfare, later this century. This book begins by defining these two threats to establish why America now needs to transition, this century, from non-sustainable fossil fuels to sustainable energy. The book continues by evaluating the domestic options for sustainable energy. Each of the three primary terrestrial options—nuclear, wind, and solar—are quantitatively assessed and found to be impractical solutions at the scale needed to replace fossil fuels. The book then examines what will be required to use geostationary Earth orbit (GEO) space solar power—astroelectricity—to replace fossil fuels and the cultural and military implications of transitioning to sustainable energy. The book concludes with a call for American engineers to advocate establishing a national astroelectricity program and explains why American engineers have a clear ethical obligation to undertake this advocacy.

19. **The Value of the Moon: How to Explore, Live, and Prosper in Space Using the Moon's Resources**
by **Paul D. Spudis**, Smithsonian Books, April 26, 2016
https://amzn.to/2U6sknc

Paul Spudis explores three reasons for returning to the Moon: it is close, it is interesting, and it is useful. The proximity of the Moon not only allows for frequent launches, but also control of any machinery we place there. It is interesting because recorded deep on its surface and in its craters is the preserved history of the Moon, the Sun, and indeed the entire galaxy. And finally, the Moon is useful because it is rich with materials and energy. Spudis argues that the Moon is a logical base for further space exploration and even a possible future home for many of us. Throughout his work, Spudis incorporates details about man's fascination with the Moon and its place in our shared history. He also explores its religious, cultural, and scientific resonance and assesses its role in the future of spaceflight and our national security and prosperity.

20. **Return to the Moon**, Edited by **Rick N. Tumlinson with Erin R. Medlicott**, Apogee Books, November 1, 2005
https://amzn.to/3cx9EU2

In this volume of essays, the top experts and major players debate over lunar exploration. This book takes the controversy out of the realm of pure science and into the mainstream of national debate. Lunar experts Alan Binder, Andy Chaikin, Patrick

Collins, Yoji Kondo, Courtney Stadd, Frank White, and many others weigh in on the case for a return, point out the best way to do it, and speculate on what could be done with this newly obtained real estate. The essays are accompanied by illustrations of what life on the moon might look like. Contributions come from different perspectives and styles, offering a broad take on the very real possibility that humans will again walk—and work, live, and play—on the lunar landscape. From telescopes and tourism, to training for Mars, to building a new branch of humanity and saving the Earth, this compendium makes the case for sending people back to the moon.

21. **Moonrush: Improving Life on Earth with the Moon's Resources**
    by **Dennis Wingo**, Apogee Books, 2004
    https://amzn.to/2AzQJKQ

    The advent of cheap energy in the form of oil has been the key factor that has enabled us to develop a planetary civilization of unprecedented size, complexity, and comfort. However, that same energy is accused of altering our climate and at best will be depleted within a hundred years. Additionally, tremendous amounts of water and air pollution are generated by the extraction of the remaining reserves of nickel, copper, aluminium, and other primary metals from the Earth. In other areas, resources are strained; from the fisheries of the North Atlantic to clean water in India and China. Indeed, many in the environmental movement believe that we have gone beyond the limits to growth and that it is only a matter of time before the whole system collapses. This book concentrates on the economic development of the world that is closest to us in space: our Moon. We need to go to the Moon and on to Mars and do it now: to make life better for all of us on the Earth, not just for today, and not just for a hundred years. This can be the best legacy that our generation leaves the world: a way beyond the limits to growth, and toward a peaceful and prosperous future.

22. **The Case for Space: How the Revolution in Spaceflight Opens Up a Future of Limitless Possibility** by **Robert Zubrin** (2019)
    https://amzn.to/2ZMYpGP

    Astronautical engineer Robert Zubrin explains the current revolution in spaceflight, where it leads, and why we need it. In "The Case for Space" the Zubrin explains the potential of these new developments in an engrossing narrative that is visionary yet grounded by a deep understanding of the practical challenges.

25.2. Publications

There have been numerous publications made over the years about the potential and the approach to access lunar materials for industrial purposes. This section lists the key publications that support the different aspects of the study.

25.2.1. Lunar Economics

- Corey Bergsrud, Jeremy Straub, James Casler and Sima Noghanian. (2013)
  Space Solar Power Satellite Systems as a Service Provider of Electrical Power to Lunar Industries
  American Institute of Aeronautics and Astronautics, AIAA 2013-5395 Session: Commercial Space Science

- David Criswell, Robert Waldron. (1990)
  Lunar System to Supply Solar Electric Power to Earth
  Proceedings of the 25th Intersociety Energy Conversion Engineering Conference

- David Criswell and Robert Waldron. (1993)
  International lunar base and lunar-based power system to supply earth with electric power

- David R. Criswell. (2010)
  Enabling Sustainable & Rapidly Growing Global Wealth by Implementing the Lunar Solar Power (LSP) System
  Published by the American Institute of Aeronautics and Astronautics

- Krafft E. Ehricke. (1985)
  A Vision of Lunar Settlement - Lunar Industrialization and Settlement - Birth of Polygonal Civilization
  Lunar and Planetary Institute

- Krafft A. Ehricke. (1978)
  The Extraterrestrial Imperative
  Air University Review

25.2.2. Lunar Photovoltaics

- David R. Criswell. (2002) **Solar Power via the Moon**, The Industrial Physicist (Research Gate)

- Drew Gillespie, Andrew Ross Wilson, Donald Martin, Gareth Mitchell, Gianluca Filippi, Massimiliano Vasile. (2020)
  Comparative analysis of solar power satellite systems to support a moon base
  University of Strathclyde Glasgow

- Katriin Kristmann, Mare Altosaar, Jaan Raudoja, Maarj Grossberg, Jüri Krustok, Taavi Raadik.(2020) **Monograin layer solar cell for future lunar outpost**
  71st International Astronautical Congress (IAC) IAC-20-C3.4.10 (x56905)

- Taavi Raadik, Katriin Kristmann, Mare Altosaar, Maarja Grossberg, Jüri Krustoka, Maris Pilvet, Valdek Mikli, Marit Kauk-Kuusik.(2021)
  Pyrite as prospective monograin layer solar cell absorber material for in-situ

solar cell fabrication on the Moon
IAC-21, C3, 4, 7, x64087

- Dr. Taavi Raadik.(2022)
  Monograin layer technology Monograin layer solar cell (MGL) Presentation Slides
  TALLINN UNIVERSITY OF TECHNOLOGY

25.2.3. Mass Driver

- Thomas A. Heppenheimer. (1986)
  Resources and Recollections of Space Colonization
  AIP Conference Proceedings 148

- Erik Inger.(November, 2019)
  Mass Driver Design Traveling Earth to the Moon
  IEEE Access (erk.inger@atilim.edu.tr)

  William R. Snow, R. Scott Dunbar, Joel A. Kubby, Gerard K. O'Neill.(1982)
  Mass Driver Two: A Status Report (1982)
  Research Gate, Joel Kubby

- Woodcock, Babb, Davis, Phillips, Stump, Keaton, Heppenheimer, Anderson, Dougherty, Pankod, Rosenberg.(1985)
  Lunar Bases and Space Activities of the 21st Century Chapter 3: Transportation Issues W. W. Mendell, Editor ©1985, Lunar and Planetary Institute

- Michael R. Wright, Dr. Steven B. Kuznetsov and Kurt J. Kloesel.(January 2010)
  A Lunar Electromagnetic Launch System for In-Situ Resource Utilization
  NASA

25.2.4. Lunar ISRU

- 30 Authors including: Jared Atkinson, Gary Barnhard, Barry W. Finger, Jonathan Goff .(2019)
  Commercial Lunar Propellant Architecture: A Collaborative Study of Lunar Propellant Production
  Research Gate (190 pages)

- U. Hegde, R. Balasubramaniam, S. Gokoglu.(2012)
  Analysis of Water Extraction From Lunar Regolith
  NASA/TM-2012-217441 / 50th Aerospace Science Conference sponsored by the American Institute of Aeronautics and Astronautics

- Bethany A. Lomax, Melchiorre Conti, Nader Khan, Nick S. Bennett, Alexey Y. Ganin, Mark D. Symes.(2020)
  Proving the viability of an electrochemical process for the simultaneous extraction of oxygen and production of metal alloys from lunar regolith

Planetary and Space Science, Volume 180, January 2020, 104748, Elsevier

- Josh Schertz.(2019)
  ESA Study of Water Extraction from Lunar Regolith
  The Space Resource

- Peter J Schubert.(2019)
  Plasma Extraction of Metals in Space
  Insights in Mining Science & Technology /Juniper Publishers

- Carsten Schwandt, JamesA.Hamilton, DerekJ.Fray, Ian A.Crawford.(2012)
  The production of oxygen and metal from lunar regolith
  Planetary and Space Science - Volume 74, Issue 1, December 2012, Pages 49-56

- Paul D. Spudis, Anthony R. Lavoie.(2011)
  Using the resources of the Moon to create a permanent, cislunar space faring system
  American Institute of Aeronautics and Astronautics / spudislunarresources.com

- Robert Waldron.(1985)
  Lunar Materials Refinement
  Space Studies Institute / SSI Newsletters: 1985, March-April

25.2.5. Lunar Manufacturing

- Marlies Arnhof, Shima Pilehvar, Anna-Lena Kjøniksen and Ina Cheibas.(2019)
  Basalt fibre reinforced geopolymer made from lunar regolith simulant
  8TH EUROPEAN CONFERENCE FOR AERONAUTICS AND SPACE SCIENCES (EUCASS)

- Ina Cheibas, Mathilde Lao,Vera Popovich, Sarah Rodriguez Castillo.(2020)
  Additive Manufacturing of Functionally Graded Materials With In-Situ Resources
  Conference: Aerospace Europe Conference (AEC 2020), 3AFAt: Bordeaux, France

- Bonnie L. Cooper.(2007)
  Sintering of Lunar and Simulant Glass
  NASA, Robotics and Automation Group, Oceaneering Space Systems, Houston TX 77058

- David R. Criswell.(1979)
  The Initial Lunar Supply Base
  USRA Houston Repository

- Miranda Fateri, Andreas Gebhart, et al.(2015)
  Additive Manufacturing of Lunar Regolith for Extra-terrestrial Industry Plant
  Academia.edu

- Barbara Imhof, Diego Urbina, Peter Weiss, Matthias Sperl, a.o..(2017)
  Advancing Solar Sintering for Building A Base On The Moon
  IAC-17, C2.9.13, x37414

- Barbara Imhof, Matthias Sperl, Diego A. Urbina, Peter Weiss, Clemens Preisingere, Rene Waclavicek,Waltraut Hoheneder, Alexandre Meurisse, Miranda Fateri, Thibaud Gobert, Makthoum Peer,Shashank Govindaraj, Hemanth Madakashira, Joseph Salini .(2018) **Using Solar Sintering to Build Infrastructure on the Moon – latest advancements in the RegoLight project.**
  IAC-18.E5.1. x47746

- Dr. P. Markandeya Raju and S. Pranathi. (2012)
  Lunarcrete – A Review
  Proceedings of AARCV 2012 - International Conference on Advances in Architecture and Civil Engineer

- A. Meurissea, A. Makayab, C. Willschc, M. Sperla. (2018)
  Solar 3D printing of lunar regolith
  Acta Astronautica

- Panajotović Stefan, Tobias Meinert, Thilo Becker, Juan Carlos Arañó Romero, Alexander Lüking.(2019)
  MoonFibre – Fibres from Lunar Regolith
  ResearchGate / PrePrint

- Lixiong Cai, Lieyun Ding, Hanbin Luo, Xingcun Yi.(2019)
  Preparation of autoclave concrete from basaltic lunar regolith simulant: Effect of mixture and manufacture process
  Construction and Building Materials 207 (2019) 373–386 - Elsevier

- Tai Sik Lee, Jaeho Lee, Ki Yong Ann. (2015)
  Manufacture of polymeric concrete on the Moon
  Acta Astronautica 114 (2015) 60-64

- Justin Lewis-Weber .(2016)
  Lunar-Based Self-Replicating Solar Factory
  New Space 4(1):53-62

25.2.6. Lunar Space Elevator

- T.M. Eubanks, C.F. Radley. (2016)
  Scientific Return of a Lunar Elevator
  Space Policy

- T.M. Eubanks, . Laine. (2011)
  LADDER: The Development of a Prototype Lunar Space Elevator

Liftport Luna, P.O. Box 141, Clifton, Virginia 20124,USA

- Jerome Pearson, Eugene Levin, John Oldson and Harry Wykes. (2005)
Lunar Space Elevators for CisLunar Transportation
Research Gate

- Charles F. Radley. (2017)
The Lunar Space Elevator, a Near Term Means to Reduce Cost of Lunar Access
Leeward Space Foundation, Inc., Palm Bay, Florida, 32907 American Institute of Aeronautics and Astronautics

- Zephyr Penoyre, Emily Sandford. (2019)
The Spaceline: A Practical Space Elevator Alternative Achievable with Current Technology Acta Astronautica.

25.2.7. Space Solar Power

- Henry W. Brandhorst, Jr.. (2008)
Energizing the Future of Space Exploration: Applications of Space Solar Power
Space Research Institute, Auburn University, AL 36849-5320, U.S.A

- Henry W. Brandhorst,Julie A. Rodiek, Michael S. Crumpler, Mark J. O'Neill. (2009)
A solar electric propulsion mission for lunar power beaming
Acta Astronautica, 65 (2009) 177–183

- Ian Cash. (2019)
CASSIOPEIA – Beamed Power Through the Lunar Night
International Electric Company Limited, United Kingdom

- Ian Cash. (2020)
CASSIOPeiA – A new paradigm for space solar power
Acta Astronautica

- David R. Criswell. (2002)
Solar Power via the Moon
The Industrial Physicist (Research Gate)

- Lewis M. Fraas, Geoffrey A. Landis, Arthur Palisoc, Paul Jaffe.(2016)
Space Solar Power, Mirror Development, & The International Space Station
67th International Astronautical Congress (IAC)2016

- Drew Gillespie, Andrew Ross Wilson, Donald Martin, Gareth Mitchell, Gianluca Filippi, Massimiliano Vasile. (2020)
Comparative analysis of solar power satellite systems to support a moon base
University of Strathclyde Glasgow

- Les Johnson. (2017)
  Orbital Space Solar Power Option for a Lunar Village
  NASA, IAC

- Jean N. Koster. (2012)
  Solar Power Satellite Demonstration System for Lunar and Planetary Exploration
  AIAA

- Geoffrey A. Landis* and Ronald C. Cull. (1990)
  Applications of Thin Film Technology Toward a Low-Mass Solar Power Satellite
  NTRS - NASA Technical Reports Server

- Geoffrey A. Landis. (2005)
  Materials Refining for Solar Array Production on the Moon
  NASA/TM—2005-214014

- Erik J. L. Larson, Robert W. Portmann, Karen H. Rosenlof, David W. Fahey, John S. Daniel, Martin N. Ross. (2016). **Global atmospheric response to emissions from a proposed reusable space launch system,** AGU, Advancing Earth and Space Science.

- John C. Mankins. (2017)
  New Developments in Space Solar Power
  NSS Space Settlement Journal, December 2017

25.2.8. Wireless Power Transmission

- J. Benfors, R. Dickinson. (1995) **Space propulsion and power beaming using millimeter systems**, Proceedings of SPIE, September 1995

- C. Bergsrud S, Noghaanian, J. Straub, D. Whalen, R. Fevig, (2013), **Orbit-to-Ground Wireless Power Transfer Test Mission,** 2013 IEEE Aerospace Conference

- P. Collins, (2008), **Crew-Tended Deployment of MW-scale SPS Operational Demonstrator in Low Equatorial Orbit, using Soyuz Launched from Kourou: Case for a Feasibility Study,** Space Solar Power Networkshop, European Space Technology Centre (ESTEC), February.

  P. Collins & H. Matsuoka, (2008), **Comparative Benefits of a Low Equatorial Orbit Microwave Solar Power Satellite (SPS) Operational Demonstrator,** Proceedings of RFM2008, Subang.

  P. Collins, S. Sasaki, K. Tanaka & Mazlina Esa, (2009), **Ground-Based Experiments Using Microwave-Power Beam-Forming "Small Satellite,** Proceedings of IEEE/INAS2009, Johor Baru.

- C. Rodenbeck, P. Jaffe, B. Strassner, P. Hausgen, J. McSpadden, H. Kazemi, N. Shinohara, B. Tierney, C. DEpuma, A. Self, (2021) **Microwave and Millimeter Wave Power Beaming**, IEEE Journal of Microwaves, January 7, 2021

25.2.9. Lunar Tourism

- Patrick Collins, (2003), **"The Future of Lunar Tourism",** Invited Speech, International Lunar Conference, Waikoloa, Hawaii, 21 November, 2003 http://spacefuture.com/archive/the_future_of_lunar_tourism.shtml

- Patrick Collins, (2005), **"The Future of Lunar Tourism",** In **Return to the Moon**, Edited by Rick N. Tumlinson with Erin R. Medlicott, Apogee Books, Pages 151-161 https://amzn.to/3cx9EU2

- Patrick Collins, (2006), **"Space tourism: from Earth orbit to the Moon",** Advances in Space Research, Vol 37, Issue 1, Pages 116-122, https://www.sciencedirect.com/science/article/abs/pii/S0273117705007258

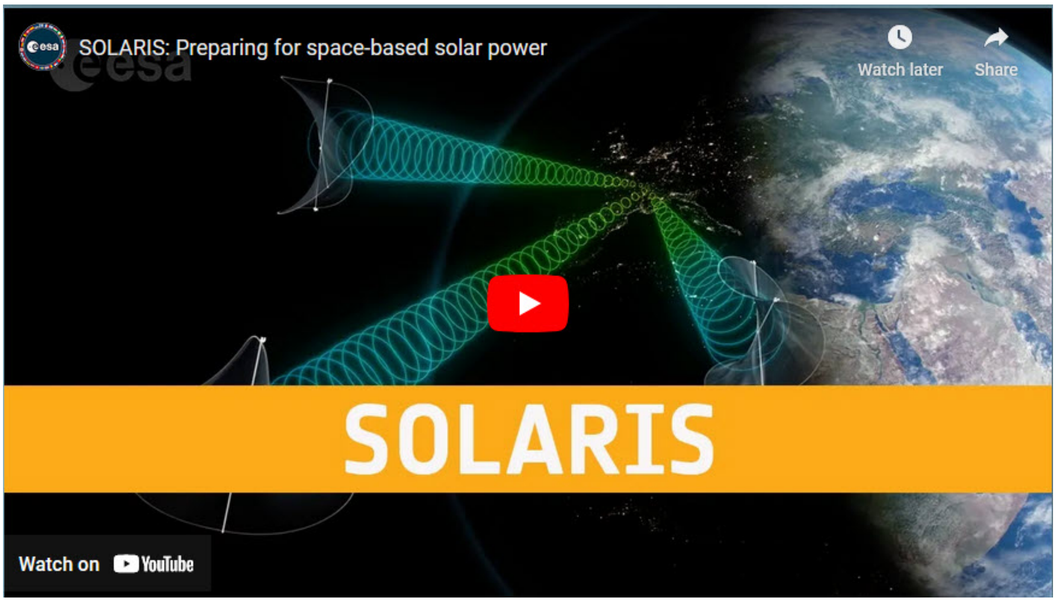
- Monica Grady, Professor of Planetary and Space Sciences, The Open University. (2019) (Article accessed: February 23, 2023)
  Moon 2069: lunar tourism and deep space launches a century on from Apollo?
  The Conversation: https://theconversation.com/moon-2069-lunar-tourism-and-deep-space-launches-a-century-on-from-apollo-121218

- M. Lali and M. Thangavelu. (2016)
  MOBIUS: An Evolutionary Strategy for Lunar Tourism
  AIAA

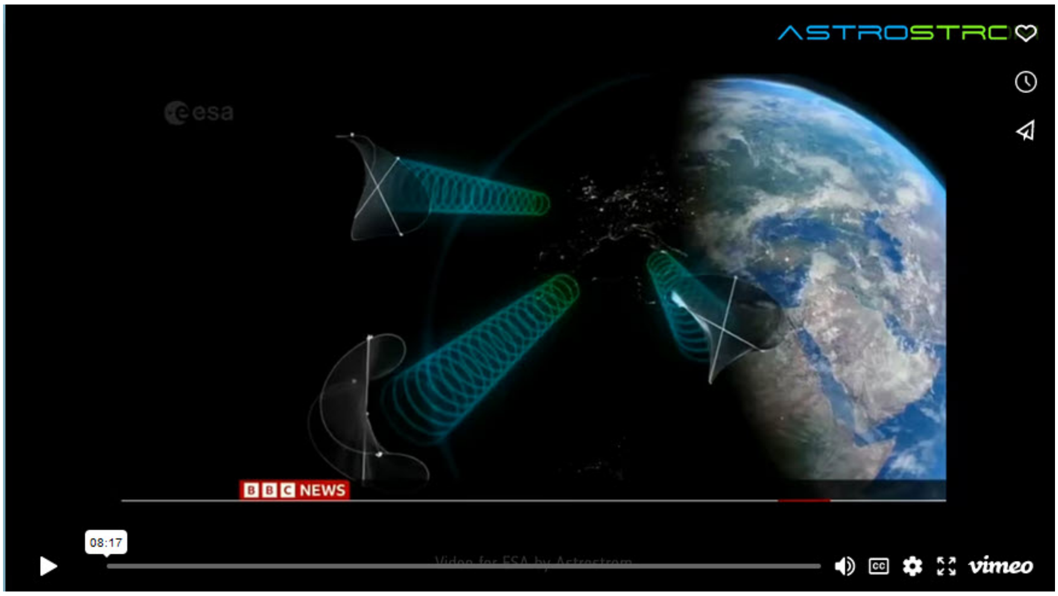
- M.Thangavelu. (2019)
  Lunar Tourism: Catalyst for Jumpstarting a Cislunar Economy
  70th International Astronautical Congress (IAC), Washington D.C., United States, 21-25 October 2019.

25.3. Reference Videos

The following videos are useful references:

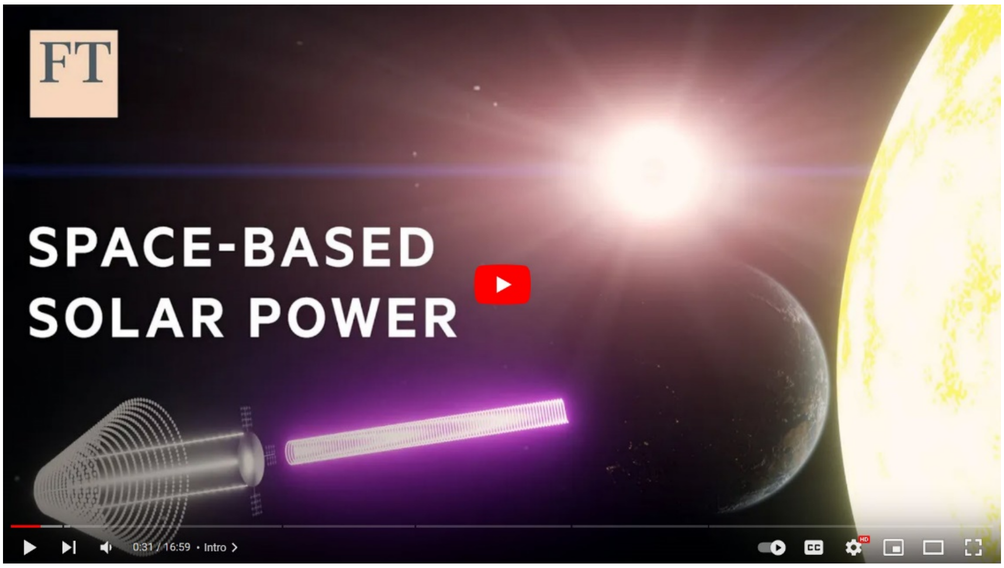


ESA: SOLARIS (Video by Astrostrom)
https://www.youtube.com/watch?v=8ScTbb-43A4



ESA's Solaris Initiative on BBC News
https://vimeo.com/774975806

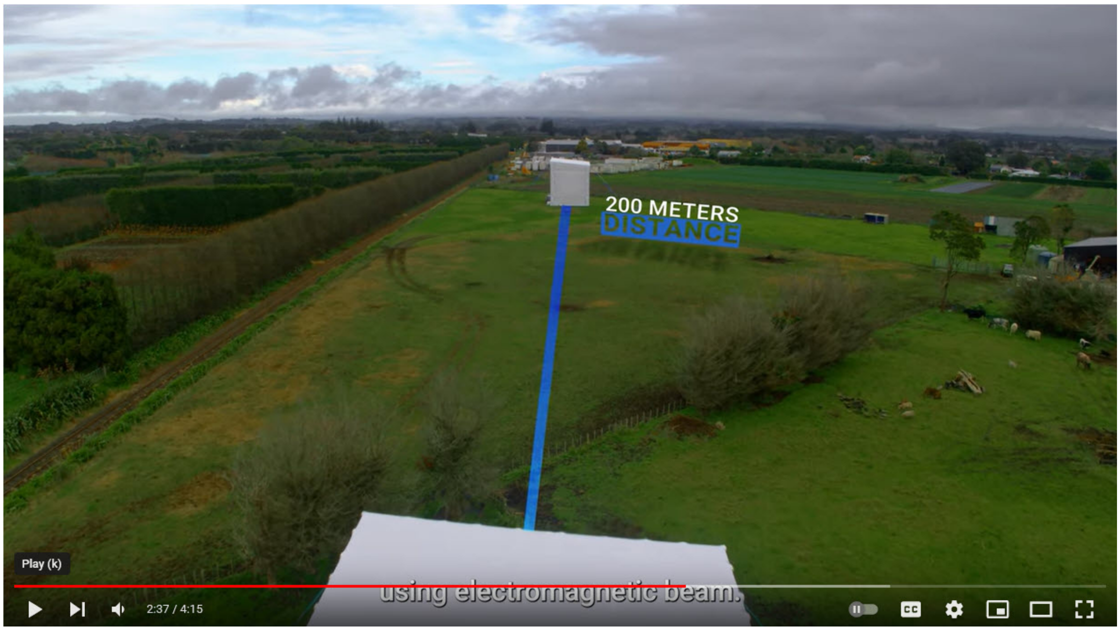
Space Solar Power: The UK Government's independent study
https://vimeo.com/560486162/54794caa3a



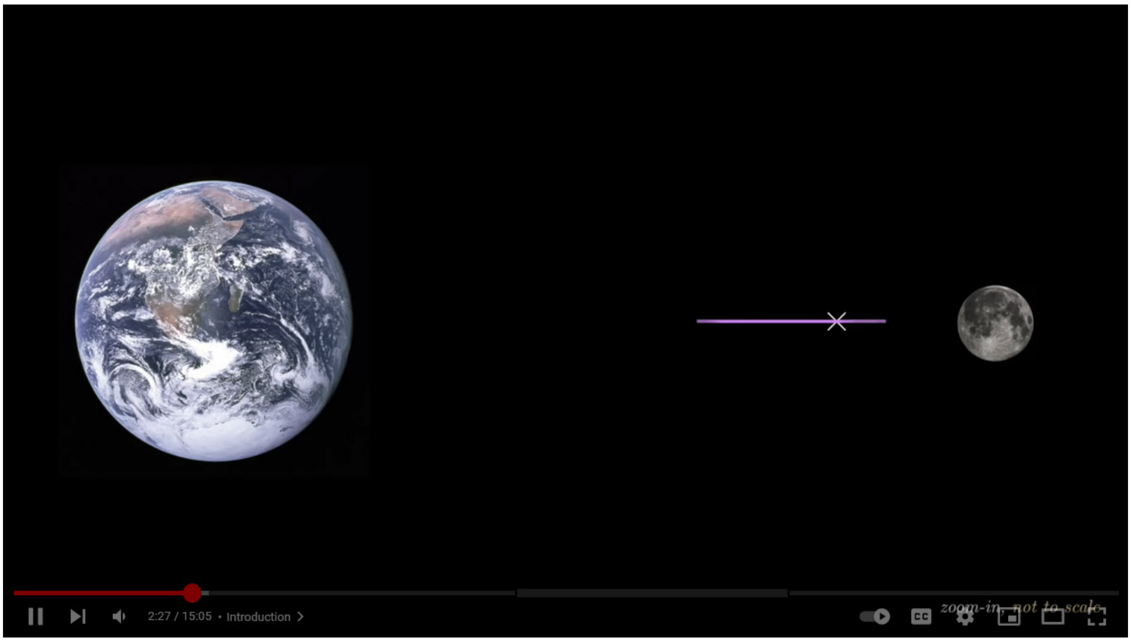
Financial Times: Space-Based Solar Power
https://www.youtube.com/watch?v=oBlOb2z26Do&t=31s

CASSIOPeiA Space Solar Power (Ian Cash, ISDC, 2018)
https://www.youtube.com/watch?v=0XHuHsY5WrY&t=4s

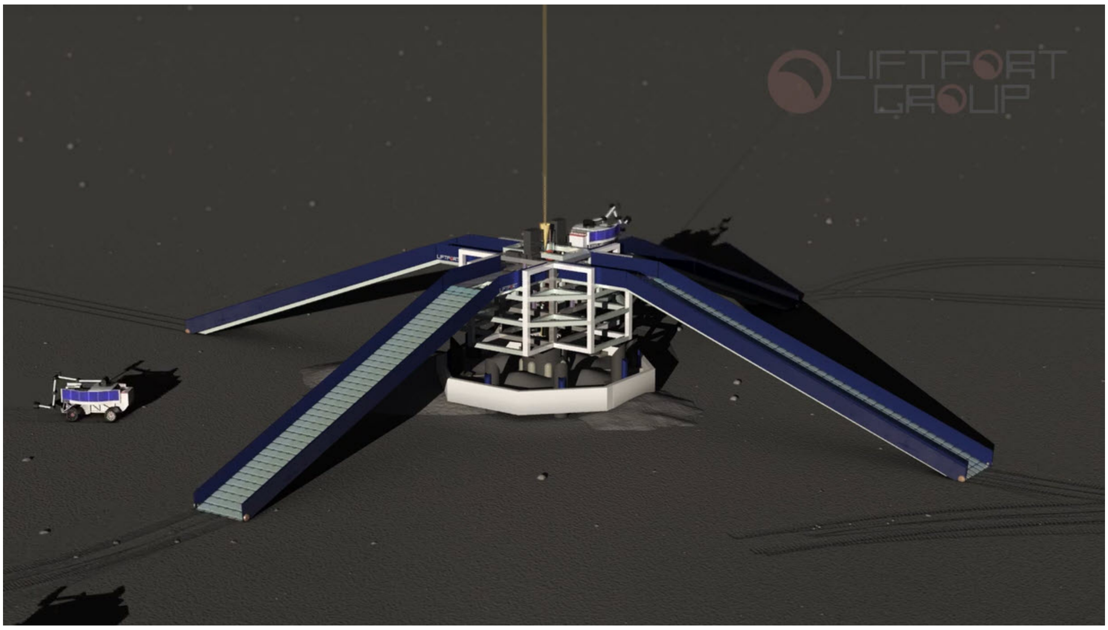
The Coming Age of Astroelectricity (Michael Snead, 2021)
https://www.youtube.com/watch?v=5E-0NYnAaUA



Emrod's Power Beaming Technology (WPT) | The Future of Energy
https://www.youtube.com/watch?v=WaAR6-Bex6Y&t=157s

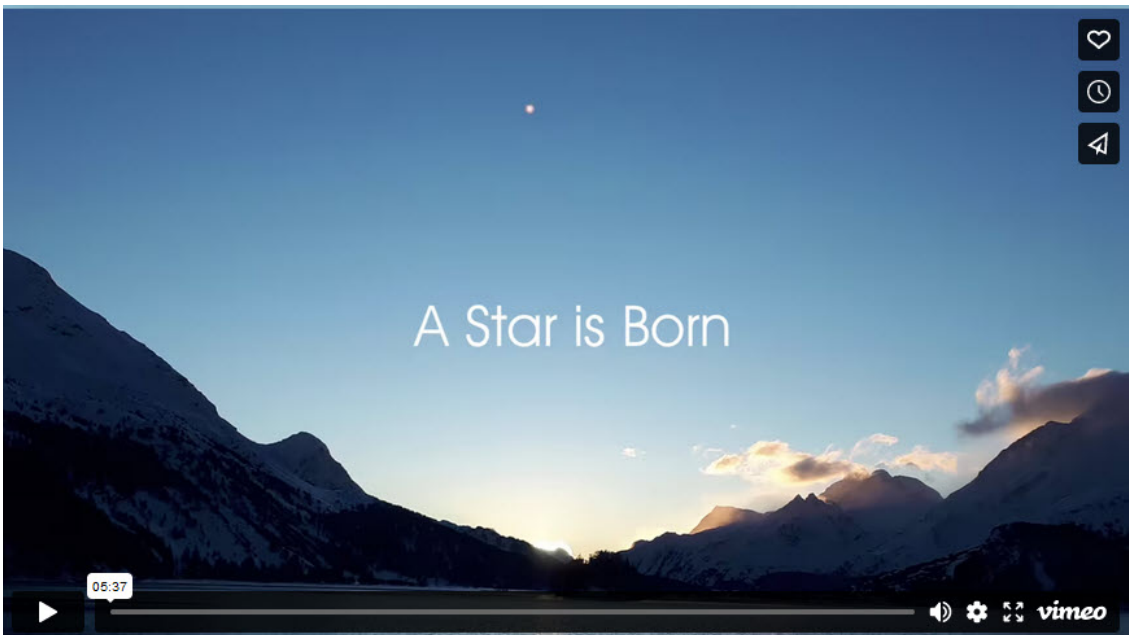


The Lunar Space Elevator (Dr. Emily Sandford)
https://www.youtube.com/watch?v=L1ytpj3y21E&t=12s



Lunar Space Elevator (Liftport Group)
https://www.youtube.com/watch?v=v7NvmD1JLSo&t=10s

MoonFibre – Fibres from Lunar Regolith
https://www.youtube.com/watch?v=49lA8A-vIHQ



A Star is Born – Video of the S.O.S. Space Option Star
Idea Submitted to OSIP "What's Next? New Mission Ideas and Concepts" ideas.esa.int
https://vimeo.com/511524939

The Greater Earth System
https://vimeo.com/413996733

26. References

AFRL, (2021) A Primer on Cislunar Space, (M. J. Holzinger, C. C. Chow, P. Garretson) https://permanent.fdlp.gov/gpo156896/A%20Primer%20on%20Cislunar%20Space_Dist%20A_PA2021-1271.pdf

Ashford, D.M. (1994) A Preliminary Feasibility Study of the Spacecab Low-Cost Spaceplane and of the Spacecab Demonstrator", Bristol Spaceplanes Limited Report Number TR6. Prepared for the European Space Agency under Contract No 10411/93/F/TB. (Volume 1 subsequently published as " The Potential of Spaceplanes" in the Journal of Practical Applications in Space, Spring 1995.)

Ashford, David. (2009). An Aviation Approach to Space Transportation", The Aeronautical Journal, Volume 113, No. 1146, pp 499 – 515 https://www.nasa.gov/pdf/383340main_58%20-%2020090814.3.Aviation%20Approch.pdf

Artemis Accords, (2023). NASA. https://www.nasa.gov/specials/artemis-accords/img/Artemis-Accords-signed-13Oct2020.pdf

Astrostrom: Solaris, (2023) SOLARIS News Items https://astrostrom.ch/en/solaris_space_news.php

Asimov, Isaac, (1941). Reason. Astounding Science-Fiction [04], 33-45; also in: Isaac Asimov (1950). I, Robot. Gnome Press.

Bergsrud, C., Straub, J., Casler, J., Noghanian, S. (2013). Space Solar Power Satellite Systems as a Service Provider of Electrical Power to Lunar Industries. American Institute of Aeronautics and Astronautics, AIAA 2013-5395 Session: Commercial Space Science

Bernasconi, Marco C. and Woods, Arthur R., (1993) *Implementing the Space Option: Elaboration & Dissemination of a New Rationale for Space: Part I: The Rationale, Part 2: The Spaced Option.* Paper IAA.8.1-93-764 a & b presented at the 44th International Astronautical Congress https://thespaceoption.com/implementing-the-space-optionpart-1-the-rationale/ https://thespaceoption.com/implementing-the-space-option-part-2/

Bigelow Aerospace, (2022) Bigelow Aerospace website. https://bigelowaerospace.com

Bigelow, (2022) Bigelow Aerospace Meet "First Base" A lunar landers best friend. https://bigelowaerospace.com/pages/firstbase/

BloombergNEF: Europe's Path to Clean Energy, (2022) A $5.3 Trillion Investment Opportunity. (Published: April 13, 2022) https://about.bnef.com/blog/europes-path-to-clean-energy-a-5-3-trillion-investment-opportunity/

BloombergNEF: Energy Transition Investment Trends, (2022). (Published: January 27, 2022) Global Investment in Low-Carbon Energy Transition Hit $755 Billion in 2021 https://about.bnef.com/blog/global-investment-in-low-carbon-energy-transition-hit-755-billion-in-2021/

Blue Origin, (2023) *Blue Alchemist Technology Powers our Lunar Future*, (February 10, 2023) *https://www.blueorigin.com/news/blue-alchemist-powers-our-lunar-future/*

Bonnassieux, Y., Brabec, C. J., Cao, Y., Carmichael, T. B., Chabinyc, M. L., Cheng, K.-T., Cho, G., Chung, A., Cobb, C. L., Distler, A., Egelhaaf, H.-J., Grau, G., Guo, X., Haghiashtiani, G., Huang, T.-C., Hussain, M. M., Iniguez, B., Lee, T.-M., Li, L., … Wu, Y. (2021). The 2021 flexible and printed electronics roadmap. Flexible and Printed Electronics, 6(2), 023001. https://doi.org/10.1088/2058-8585/abf986

BP, (2020). BP Statistical Review of World Energy 2020, 69th edition https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2020-full-report.pdf

BP, (2021). BP Statistical Review of World Energy 2021, 70th edition https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2021-full-report.pdf

BP, (2022). BP Statistical Review of World Energy 2022, 71st edition https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2022-full-report.pdf

Cash, Ian, (2017). CASSIOPeiA: Constant Aperture, Solid State, Integrated, Orbital Phased Array, Presentation at WiSEE 2017, Montreal, (YouTube) https://www.youtube.com/watch?v=OvueIEvsPZo

Cash, Ian, (2019) CASSIOPeiA – Beamed Power Through the Lunar Night, Presented at International Astronautical Congress, Paper: IAC-19-C3 https://bis-space.com/shop/product/cassiopeia-beamed-power-through-the-long-lunar-night/

Cash, Ian, (2020). CASSIOPeiA – A New Paradigm for Space Solar Power, 71st International Astronautical Congress (IAC), Acta Astronautica https://www.spaceenergyinitiative.org.uk/wp-content/uploads/2021/09/CASSIOPeiA-A-New-Paradigm-for-SSP.pdf

Chen, Stephen, (2018). China has strongest fibre that can haul 160 elephants – and a space elevator? South China Morning Post, October 26, 2018 (Accessed: March 7, 2023) https://www.scmp.com/news/china/society/article/2170193/china-has-strongest-fibre-can-haul-160-elephants-and-space

Corey Bergsrud, Jeremy Straub, James Casler and Sima Noghanian (2013). Space Solar Power Satellite Systems as a Service Provider of Electrical Power to Lunar Industries. American Institute of Aeronautics and Astronautics, AIAA 2013-5395 Session: Commercial Space Science

Clarke, Arthur C. (1968) The Promise of Space, Harper and Row; Book Club (BCE/BOMC) edition (January 1, 1968)

Curreri, Peter, (2023) NASA, "Lunar South Pole Oxygen Pipeline" Lunar Resources, Inc. https://www.nasa.gov/directorates/spacetech/niac/2023/Lunar_South_Pole_Oxygen_Pipeline/

ClimateEmergency.com, (2023) Why climate change is now a climate emergency (Accessed: February 18, 2023) https://climateemergency.com/the-emergency

Collins, Patrick and Bernasconi, Marco C., (2019). Risk Analysis of Climate Change, and Potential SPS Contribution to Global Warming or Global Cooling Mitigation (Accessed: February 18, 2023) https://thespaceoption.com/risk-analysis-of-climate-change-and-potential-sps-contribution-to-global-warming-or-global-cooling-mitigation/

Collins, Patrick, (2003). "The Future of Lunar Tourism", Invited Speech, International Lunar Conference, Waikoloa, Hawaii, 21 November, 2003 http://spacefuture.com/archive/the_future_of_lunar_tourism.shtml

Collins, Patrick, (2005). "The Future of Lunar Tourism", In Return to the Moon, Edited by Rick N. Tumlinson with Erin R. Medlicott, Apogee Books, Pages 151-161 https://amzn.to/3cx9EU2

Collins, Patrick, (2006). "Space tourism: from Earth orbit to the Moon", Advances in Space Research, Vol 37, Issue 1, Pages 116-122, https://www.sciencedirect.com/science/article/abs/pii/S0273117705007258

CNN Travel. (March 2021). Where the Possibilities are Endless World's first space hotel scheduled to open in 2027. https://edition.cnn.com/travel/article/voyager-station-space-hotel-scn/index.html

Criswell, David, (2002). Solar Power via the Moon, The Industrial Physicist, April/May 2002, American Institute of Physics

Criswell, David, (2010). Solar Power Via The Moon, Lunar Solar Power Blogspot, https://lunarsolarpowersystem.blogspot.com/2010/03/solar-power-via-moon.htm

Crotts, Arlin, (2011). Water on The Moon, I. Historical Overview, Columbia University https://arxiv.org/ftp/arxiv/papers/1205/1205.5597.pdf

Delta-*v* budget, (2023) *Wikipedia*. (Accessed: February 27, 2023) https://en.wikipedia.org/w/index.php?title=Delta-v_budget&oldid=1130875715

Deloitte Insights, Thomas Schlaak, Johannes Trüby, (2021). 50 million Future of Power : Scenarios to evolve the European electricity sector (19 July, 2021) https://www2.deloitte.com/us/en/insights/industry/power-and-utilities/renewable-power-generation-in-europe.html

DoE, (1978). Satellite Power System Concept Development and Evaluation Program Department of Energy (DoE) and NASA 1977-1981 https://space.nss.org/satellite-power-system-concept-development-and-evaluation-program/

Ehricke, Krafft A. (1970). *In-Depth Exploration of the Solar System and Its Utilization for the Benefit of Earth.* Annals New York Academy of Sciences 187, 427-456.

Ehricke, Krafft A. (1978) The Extraterrestrial Imperative, Air University Review, January-February 1978

Ehricke, Krafft A. (1984) *Lunar Industrialization and Settlement: Birth of a Polyglobal Civilization*, Lunar Bases and Space Activities of the 21st Century (Houston, TX: Lunar and Planetary Institute Press, 1985), 827–855; (Accessed: February 20, 2023) http://adsabs.harvard.edu/full/1985lbsa.conf..827E

EIA, (2019) U.S. Energy Information Administration, (24 September 2019) EIA projects nearly 50% increase in world energy usage by 2050, led by growth in Asia (Accessed: February 18, 2023) https://www.eia.gov/todayinenergy/detail.php?id=41433

EIA, (2021) International Energy Outlook 2021, October 6, 2021 https://www.eia.gov/outlooks/ieo/narrative/electricity/sub-topic-01.php

Elser, S., Moore, B., Stadela, J., Morishima, R., (2011). *How common are Earth-Moon planetary systems?*, University of Zurich, 2011 (Accessed: February 20, 2023) https://www.sciencedirect.com/science/article/abs/pii/S0019103511001989

EMBER, (2023) EmberClimate.org, European power price tracker, Wholesale Price of Electricity. (Accessed: March 9, 2023) https://ember-climate.org/data/data-tools/europe-power-prices/

Energy.Gov, (2022). *How Much Power is 1 Gigawatt?* Mikayla Rumph (Accessed February 20, 2023) https://www.energy.gov/eere/articles/how-much-power-1-gigawatt

ESA: Advanced Concepts Team, (2018). Basalt fibre reinforced geopolymer, 28 June 2018. https://www.esa.int/gsp/ACT/projects/geopolymers/

ESA: Business, (2023). Industrial policy and geographical distribution
https://www.esa.int/About_Us/Business_with_ESA/How_to_do/Industrial_policy_and_geographical_distribution

ESA: LBST, (2005). Earth & Space-Based Power Generation Systems: A Comparison Study
https://www.esa.int/gsp/ACT/doc/POW/ACT-RPT-NRG-0501-SPS_LBST_ExecutiveSummary.pdf

ESA: Solaris, (2022). Solaris, Enabling and Support
https://www.esa.int/Enabling_Support/Space_Engineering_Technology/SOLARIS

ESA: Solaris, RFI, (2022). Request for Information – Breakthrough technologies for Space-Based Solar Power
https://www.esa.int/Enabling_Support/Space_Engineering_Technology/SOLARIS/Request_for_Information_Breakthrough_technologies_for_Space-Based_Solar_Power

ESA: SBSP Cost vs. benefit studies, (2022)
https://www.esa.int/Enabling_Support/Space_Engineering_Technology/SOLARIS/Cost_vs._benefits_studies

ESA: SBSP, FAQ, (2022). FAQ: Frequently Asked Questions on Space-Based Solar Power
https://www.esa.int/Enabling_Support/Space_Engineering_Technology/SOLARIS/FAQ_Frequently_Asked_Questions_on_Space-Based_Solar_Power

ESA: Solaris, YouTube, (2022) SOLARIS: Preparing for space-based solar power
https://www.youtube.com/watch?v=8ScTbb-43A4

ESA: Solaris, (2022). Solaris, Enabling and Support
https://www.esa.int/Enabling_Support/Space_Engineering_Technology/SOLARIS

ESA: Solaris, RFI, (2022). Request for Information – Breakthrough technologies for Space-Based Solar Power

ESA: Swarm probes weakening of Earth's magnetic field, (2020)
https://www.esa.int/Applications/Observing_the_Earth/FutureEO/Swarm/Swarm_probes_weakening_of_Earth_s_magnetic_field

Etherington, Darrell, (2022). Max
https://techcrunch.com/2022/01/24/max-q-sports-in-space/

ETH Zurich, (1998) 2000-watt society (Wikipedia)
https://en.wikipedia.org/wiki/2000-watt_society

EU Reference Scenario, (2020) Energy, transport and GHG emissions : trends to 2050
https://op.europa.eu/en/publication-detail/-/publication/96c2ca82-e85e-11eb-93a8-01aa75ed71a1/language-en/format-PDF/source-219903975

Flamanville, (2019) *EDF warns of added costs of Flamanville EPR weld repairs*. World Nuclear News, Accessed March 5, 2023) http://world-nuclear-news.org/Articles/EDF-warns-of-added-costs-of-Flamanville-EPR-weld-r

FNC/LE, (2022). Frazer Nash Consultancy and London Economics, Space-Based Solar Power: A Future Source of Energy For Europe?
Brochure (EN) - Space-Based Solar Power - A Future Source of Energy for Europe.pdf

FNC, (2022). Frazer Nash Consultancy, Study on Cost-Benefit Analysis of Space-Based Solar Power (SBSP) Generation for Terrestrial Energy Needs
FNC_014843_53886R_SBSP CBA Final Report_ISSUE_1.0.pdf

FNC, (2022). Frazer Nash Consultancy, Study on Cost-Benefit Analysis of Space-Based Solar Power (SBSP) Generation for Terrestrial Energy Needs, TN3-System Breakdown, Costs and Technical Feasibility
FNC_014843_53334R_TN3_System Breakdown and Technical Feasibility_ISSUE_1.3.pdf

Glaser, Peter, (1968) Power from the Sun: Its Future. Science, 22 November 1968

GWPF, Henrik Svensmark, (2019) Force Majeure: The Sun's Role in Climate Change, (Accessed: February 18, 2023)
https://www.thegwpf.org/content/uploads/2019/03/SvensmarkSolar2019-1.pdf

Goswami, Namrata, and Garretson, Peter, (2022). *Scramble for the Skies: The Great Power Competition to Control the Resources of Outer Space',* Lexington Books (May 9, 2022)

Gutowski, Timothy, Dahmus, Jeffrey, Thiriez, Alex (2006). Electrical Energy Requirements for Manufacturing Processes. Proceedings of 13th CIRP International Conference on Life Cycle Engineering

Hempsell, Mark, (1989). Space Industrialization – A New Perspective. Spaceflight 31[07], 224-227.

Hinkley Point, (2019). *Hinkley Point nuclear plant building costs rise by up to £2.9bn* (Accessed March 5, 2023)
https://www.theguardian.com/uk-news/2019/sep/25/hinkley-point-nuclear-plant-to-run-29m-over-budget

Hou, Xinbin, (2018). Space Solar Power development in China and MR-SPS, Qian Xuesen Laboratory of Space Technology, Chinese Academy of Space Technology (CAST), 4th SPS Symposium 2018, Japan

Hu, D., Li, M. and Li, Q. (2021) 'A solar thermal storage power generation system based on lunar in-situ resources utilization: modeling and analysis', *Energy*, 223, p. 120083. https://doi.org/10.1016/j.energy.2021.120083.

Kristmann, K., Altosar, M, Mikli, V., Raadik, T., Makaya, A., Kauk-Kuusik, M., Krustok, J., Pilvet, M., Grossberg, M. (2022) Pyrite FeS2 Solar Cells Fabrication for Lunar Base Energy Production, Paper: 71543, presented at the 73rd International Astronautical Congress, Paris

IAA, (2011) International Academy of Astronautics, Space Solar Power, The First International Assessment of Space Solar Power: Opportunities, Issues and Potential Pathways Forward https://iaaweb.org/iaa/Studies/sg311_finalreport_solarpower

IEA, (2021). Net Zero by 2050 A Roadmap for the Global Energy Sector https://iea.blob.core.windows.net/assets/deebef5d-0c34-4539-9d0c-10b13d840027/NetZeroby2050-ARoadmapfortheGlobalEnergySector_CORR.pdf

IEA, (2021). Summary for Policy Makers: Net Zero by 2050 A Roadmap for the Global Energy Sector: https://iea.blob.core.windows.net/assets/7ebafc81-74ed-412b-9c60-5cc32c8396e4/NetZeroby2050-ARoadmapfortheGlobalEnergySector-SummaryforPolicyMakers_CORR.pdf

IEA, (2022) WEO: World Energy Outlook 2022 https://iea.blob.core.windows.net/assets/830fe099-5530-48f2-a7c1-11f35d510983/WorldEnergyOutlook2022.pdf

IEA, (2022). Energy Statistics Data Browser. https://www.iea.org/data-and-statistics/data-tools/energy-statistics-data-browser?country=WEOEUR&energy=Balances&year=2019

IEA, (2022). Renewables Data Explorer https://www.iea.org/data-and-statistics/data-tools/renewables-data-explorer

IEA, (2023). Electricity Market Report 2023, Executive Summary https://www.iea.org/reports/electricity-market-report-2023

IEA, (2023) The world is entering a new age of clean technology manufacturing, and countries' industrial strategies will be key to success, 12 January 2023 https://www.iea.org/news/the-world-is-entering-a-new-age-of-clean-technology-manufacturing-and-countries-industrial-strategies-will-be-key-to-success

IEA, (2023) Fossil Fuels Consumption Subsidies 2022, Policy Report February 2023 https://www.iea.org/reports/fossil-fuels-consumption-subsidies-2022

ISPACE. (2022) Website, https://ispace-inc.com/

Jones, A. (2022, August 31). *NASA and China are eyeing the same landing sites near the lunar south pole, Space News. https://spacenews.com/nasa-and-china-are-eyeing-the-same-landing-sites-near-the-lunar-south-pole/*

Kadam, T. (2022, June 1). *Lunar Research Station: Russia, China Almost Ready To Ink Pact On 'Moon Base' That Will Rival Artemis Accords - Rogozin*. Latest Asian, Middle-East, EurAsian, Indian News. https://eurasiantimes.com/russia-china-almost-ready-to-ink-pact-on-moon-base/

Knoema, (2018) BP: World Reserves of Fossil Fuels, (Published: Monday, July 30, 2018) https://knoema.com/infographics/smsfgud/bp-world-reserves-of-fossil-fuels

Landis, Geoffery, (2005). Materials Refining for Solar Array Production on the Moon. NASA/TM—2005-214014

Larsen, Erik J.L., Portman, Robert, Rosenlof, David, Daniel, john, Ross, Martin, (2016). Global atmospheric response to emissions from a proposed reusable space launch system, AGU, Advancing Earth and Space Science. https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2016EF000399

Lea, Robert, (2023). Space.com: What are the Artemis Accords? https://www.space.com/artemis-accords-explained

Lele, Ajey. (2021, June 1). *The Space Review: Should India join China and Russia's Lunar Research Station?* https://www.thespacereview.com/article/4185/1

LE-SBSP-TN4, (2022). London Economics: Cost-Benefit Analysis of Space-based solar power (SBSP) for terrestrial energy needs Assessment of strategic, economic, environmental, and societal benefits, costs, and risks (TN4)

Li, D., Wang, Y., Zhang, H., Zhuang, J., Wang, X., Wang, Y., et al. (2019). In situ measurements of lunar dust at the Chang'E-3 landing site in the northern Mare Imbrium. Journal of Geophysical Research: Planets, 124, 2168– 2177. https://doi.org/10.1029/2019JE006054

Mankins, John, (2014) The Case for Space Solar Power, Virginia Edition Publishing; First Edition, January, 2014

Mankins, John, (2022) Space Solar Power: An Overview (ISDC, May 28, 2022) http://www.spacedevelopmentfoundation.org/wordpress/wp-content/uploads/2022/06/Mankins-John-ISDC-2022-SPS-Overview-Briefing-at-ISDC-2022-v1RR-26May22.pdf

McKinsey & Company, (2019). The decoupling of GDP and energy growth: A CEO guide (April 24, 2019) https://www.mckinsey.com/industries/electric-power-and-natural-gas/our-insights/the-decoupling-of-gdp-and-energy-growth-a-ceo-guide

Monat, S., Abdin, A., et all, (2023) From Spacecraft to Space Habitat: A conceptual study of using the Starship HLS as a Permanent Habitable Lunar Base, Preprint https://www.researchgate.net/publication/370106476_From_Spacecraft_to_Space_Habitat_A_conceptual_study_of_using_the_Starship_HLS_as_a_Permanent_Habitable_Lunar_Base

Murphy, Ken. (2011) EM-L1: the next logical destination. The Space Review, January 24, 2011. https://www.thespacereview.com/article/1764/1

Musk, Elon, (2021) (Tweet) – via Twitter. August 11, 2021) https://twitter.com/elonmusk/status/1425473261551423489

Nakamura, T., Smith, B.K. and Irvin, B.R. (2015) 'Optical Waveguide Solar Power System for Material Processing in Space', Journal of Aerospace Engineering, 28(1), p. 04014051. Available at: https://doi.org/10.1061/(ASCE)AS.1943-5525.0000294

Nanalyze.com, (2020) Space-Based Solar Power for Energy Transmission (Published April 13,2020) https://www.nanalyze.com/2020/04/space-based-solar-power-energy-transmission/

Nansen, Ralph, (1995/2012) Sun Power: The Global Solution for the Coming Energy Crisis, Amazon Kindle location 391, Ocean Press 1995, Nansen Partners 2012 (e-book)

Nolan, Kay, (2023) Thousands of satellites are launched into low orbit. It could harm the ozone layer. The Washington Post Article: March 5, 2023 (Accessed March 7, 2023) https://www.washingtonpost.com/weather/2023/03/05/low-orbit-satellites-ozone-layer/

NREL, (2023) National Renewable Energy Laboratory: Levelized Cost of Energy Calculator https://www.nrel.gov/analysis/tech-lcoe.html

NREL, PVWatts, (2023) National Renewable Energy Laboratory: PVWatts® Calculator https://pvwatts.nrel.gov/

RB-OHB, (2022). System breakdown, costs and technical feasibility of a SPS, (SBSP-OHB-TN-003)

NASA: Artemis, (2022). https://www.nasa.gov/specials/artemis/

NASA: Artemis. (n.d.). NASA. Retrieved 10 August 2022, from https://www.nasa.gov/specials/artemis/index.html

NASA-OIG. (2021). *Artemis Status Update*. Office of Inspector General. https://oig.nasa.gov/docs/IG-21-018.pdf

NEI, (2015). Nuclear Energy Institute: Land Needs for Wind, Solar Dwarf Nuclear Plant's Footprint, (Accessed: February 18, 2023) https://www.nei.org/news/2015/land-needs-for-wind-solar-dwarf-nuclear-plants

Off Grid Energy Independence, (2021) Production of Electricity on the Moon, Accessed 04.04.2022 https://www.offgridenergyindependence.com/articles/25524/production-of-electricity-on-the-moon

OST, (2023). Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/introouterspacetreaty.html

Our World in Data, (2020) Years of fossil fuels left, 2020 (Accessed: February 18, 2023) https://ourworldindata.org/grapher/years-of-fossil-fuel-reserves-left

Our World in Data, (2021). Energy Production and Consumption (Accessed: February 21, 2023) https://ourworldindata.org/energy-production-consumption

Our World in Data, Ritchie, H., (2021). Primary energy production is not final energy use: what are the different ways of measuring energy? (Accessed: April 18, 2023) https://ourworldindata.org/energy-substitution-method

Palos, M.F. *et al.* (2020) 'Lunar ISRU energy storage and electricity generation', *Acta Astronautica*, 170, pp. 412–420. https://doi.org/10.1016/j.actaastro.2020.02.005.

Pearson, J., Levin, E. Oldson, J., Wykes, H.. (2005) Lunar Space Elevators for CisLunar Transportation, Phase I Final Technical Report, Research Subaward No.: 07605-003-034, Star Technology and Research, Inc. NASA: Grant #07605-003-034

Raadik, T., Kristmann, K., Altosaar, M., Grossberg, M., Krustoka,J. Pilvet, M., Mikli,V., Kauk-Kuusik , M. (2021). Pyrite as prospective monograin layer solar cell absorber material for in-situ solar cell fabrication on the Moon. IAC-21, C3, 4, 7, x64087

Radley, Charles F. (2017) The Lunar Space Elevator, a Near Term Means to Reduce Cost of Lunar Access **,** Leeward Space Foundation, Inc., Palm Bay, Florida, 32907 American Institute of Aeronautics and Astronautics

RB-OHB, (2022). System breakdown, costs and technical feasibility of a SPS, (SBSP-OHB-TN-003)

Sandford, Emily, Zephyr Penoyre. (2019) The Spaceline: A Practical Space Elevator Alternative Achievable with Current Technology , Acta Astronautica.

SEI, (2022) Space Energy Initiative, UK, https://www.spaceenergyinitiative.org.uk

Shimizu Corporation, (2009). Luna Ring, Solar Power Generation on the Moon, (Accessed: February 18, 2023) https://www.shimz.co.jp/en/topics/dream/content02/

Sierra Space, (2022). Deploying in 2023, Dream Chaser Opens New Horizons for Commercial Space Travel https://www.sierraspace.com/newsroom/blog/deploying-in-2023-dream-chaser-opens-new-horizons-for-commercial-space-travel/

Smil, Vaclav, (2022). How the World Really Works: A Scientist's Guide to Our Past, Present and Future

Solar Power Europe, (2022) New report reveals EU solar power soars by almost 50% in 2022 December 19, 2022 https://www.solarpowereurope.org/press-releases/new-report-reveals-eu-solar-power-soars-by-almost-50-in-2022

South China Morning Post, (2021). *China to harvest sun's energy in space and beam it to Earth for power by 2030*. (August 17 2021). https://www.scmp.com/news/china/science/article/3145237/china-aims-use-space-based-solar-energy-station-harvest-suns

Space Daily, (2021). *China Pursues Helium-3 on the Moon*. (2021, December 17). https://www.spacedaily.com/reports/China_Pursues_Helium_3_on_the_Moon_999.html

SpaceWeather.com, (2019) Experts Predict a Long, Deep Solar Minimum. (Accessed: February 18, 2023) https://spaceweatherarchive.com/2019/04/10/experts-predict-the-solar-cycle/

Spudis, Paul D. and Lavoie, Anthony R., (2011). Using the resources of the Moon to create a permanent, cislunar space faring system American Institute of Aeronautics and Astronautics / spudislunarresources.com

Spudis, Paul D. and Lavoie, Anthony R., (2016). The Purpose of Human Spaceflight and a Lunar Architecture to Explore the Potential of Resource Utilization AIAA Space 2016 https://arc.aiaa.org/doi/10.2514/6.2016-5526

Tracking SDG 7, (2022). The Energy Progress Report, Chapter 1: Access to Electricity https://trackingsdg7.esmap.org/data/files/download-documents/sdg7-report2022-ch1-access_to_electricity.pdf

Tsiolkovsky, Konstantin, (1929) The Plant of the Future. (Accessed: February 18, 2023) https://www.tsiolkovsky.org/en/the-cosmic-philosophy/the-plant-of-the-future-konstantin-tsiolkovsky-1929-2021/

UK FIRES, (2019) "Absolute Zero: Delivering the UK's climate change commitment with incremental changes to today's technologies" https://www.ukfires.org/wp-content/uploads/2019/11/Absolute-Zero-online.pdf

UK FIRES, (2023) "Is Absolute Zero pessimistic about UK energy supplies?" https://ukfires.org/is-absolute-zero-pessimistic-about-uk-energy-supplies/

UN: Agenda 2030, (2015). Transforming our world: the 2030 Agenda for Sustainable Development (Accessed: February 18, 2023) https://sdgs.un.org/2030agenda

UN: News, (2019). Climate emergency: City mayors are 'world's first responders', says UN chief (Accessed February 18, 2023) https://news.un.org/en/story/2019/10/1049091

UN: SDG 7, (2020) Goals: 7: Ensure access to affordable, reliable, sustainable and modern energy for all (Accessed: February 18, 2023) https://sdgs.un.org/goals/goal7

Vandette, Kay, (2019) Increased cloud cover buffers against warming temperatures, Earth.com March 20, 2019 https://www.earth.com/news/cloud-cover-buffers-warming-temperatures/

Virtus Solis, (2022). Persistent, Global, Economical Energy from Space (Website) (Accessed: February 21, 2023) https://www.virtussolis.space/

WEF, (2020). The Net-Zero Challenge: Fast-Forward to Decisive Climate Action, World Economic Forum, Insight Report (January 2020). https://www3.weforum.org/docs/WEF_The_Net_Zero_Challenge.pdf

White, Frank, (1987). *The Overview Effect: Space Exploration and Human Evolution*, pp.126, Houghton Mifflin Company, Boston

Wilkinson, Angela (2022). Remaking energy for peace and progress. World Energy Council https://www.worldenergy.org/news-views/entry/remaking-energy-for-peace-and-progress

Wikipedia: Artemis-Program, (2022). https://en.wikipedia.org/wiki/Artemis_program

Wikipedia: Artemis Accords, (2022). https://en.wikipedia.org/wiki/Artemis_Accords

Wikipedia: ISS – International Space Station https://en.wikipedia.org/wiki/International_Space_Station

Wikipedia: World Energy Supply and consumption, (2023) https://en.wikipedia.org/wiki/World_energy_supply_and_consumption#Total_energy_supply

Wind Europe, (2022). Wind energy in Europe: 2021 Statistics and the outlook for 2022-2026, February 24, 2022 https://windeurope.org/intelligence-platform/product/wind-energy-in-europe-2021-statistics-and-the-outlook-for-2022-2026/

Yokota, S. *et al.* (2020) 'KAGUYA observation of global emissions of indigenous carbon ions from the Moon', *Science Advances*, 6(19), peaba1050. https://doi.org/10.1126/sciadv.aba1050.

YSG Solar, (2021) 15 Largest Solar Farms in the World in 2021 (Accessed 24 April 2023) https://www.ysgsolar.com/blog/15-largest-solar-farms-world-2021-ysg-solar