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The Lunar Space Elevator: A Key Technology for Realising the Greater Earth Lunar Power Station (GE⊕-LPS)

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The Greater Earth Lunar Power Station (GE⊕-LPS) is a multi-purpose concept that aims to solve several critical issues related to lunar development and terrestrial energy production. As the GE⊕-LPS concept and its energy production functions may be scaled to any dimension, larger versions could be positioned in Earth orbit to provide clean solar energy for terrestrial purposes and thereby reduce the mass needed to be launched from Earth to build SPS units by 80% or more. The construction of the GE⊕-LPS from mostly lunar materials requires the establishment of industrial-scale automated mining and manufacturing processes on the Moon. A key technology is a Lunar Space Elevator (LSE) deployed as a transportation system to move SPS components from an anchor point on the surface of the Moon to a docking and assembly station at Earth-Moon Lagrange point 1 (EM-L1). Significantly, a LSE could be built today with existing tether materials such as Dyneema or Zylon which are already commercially available. Additionally, lunar sourced basalt fibre may be sufficient for reinforcing and extending the LSE once it becomes operational. An Earth-pointing LSE could become a valuable cislunar infrastructure asset - "the Suez Canal of cislunar space" - linking the Earth and Moon economies.

Note: The '⊕' symbol is an ancient European symbol for planet Earth: it is used here to mean "Greater Earth", a region defined by the Earth's gravitational field, which includes the Moon.

Keywords: Solar Power Satellite, Lunar ISRU, Lunar Space Elevator, Energy, Europe

1 INTRODUCTION

Europe today finds itself in a very difficult situation trying to secure its future energy needs, unpredicted even just a few years ago. Over the coming decades Europe needs to invest some € 5 trillion in its energy transition from fossil fuels to more sustainable energy supplies but it remains unclear which energy systems could guarantee energy security. This has led to growing interest in the feasibility of Space-Based Solar Power (SBSP) as a possible large-scale supplier of environmentally benign electricity. The UK and ESA are already funding research - as are the USA, China and Japan. Among the key issues being studied is the launch bottleneck (i.e. uncertainty about the availability and high cadence of reusable heavy lift launch systems) which threatens to sharply limit how rapidly SBSP units could be deployed, even once commercially viable systems have been developed.

Now an unexpected approach to solving this problem has recently been proposed by Astrostrom GmbH which has been investigating the feasibility of a "Greater Earth Lunar Power Station" (GE⊕-LPS) manufactured on the Moon and assembled at the Earth-Moon Lagrange Point 1 (EM-L1) to provide wireless power from lunar orbit to operations on the surface of the Moon. Once the initial station is in operation, the production facilities on the lunar surface could then be used to produce additional Solar Power Satellites (SPS) to be shipped into Earth orbits to deliver clean baseload solar-generated electricity to Earth. This approach could reduce the mass-to-orbit needed for an SPS by 80% or more.

As such, the GE⊕-LPS addresses the launch bottleneck, the environmental impact, and the cost of launching many SPSs from the surface of Earth – major challenges to realizing SBSP on the scale necessary to make a significant difference by 2050. This "Space Energy Option" would contribute to a massive reduction of the use of fossil fuels for energy production on the way towards meeting international climate and energy targets.

Astrostrom GmbH has recently delivered a 269-page report to the European Space Agency (ESA) tying these ideas together into an eye-opening scenario [1]. Astrostrom's report shows, for the first time, how just 2% of Europe's energy transition budget could pay to develop the ability to produce SBSP components on the Moon and deliver them to Earth orbit to supply electric power to Europe at a competitive price. The report also shows how the enormous and growing demand for electric power in Europe will easily repay this investment at a profit for the manufacturers and operators of the system.

Solar technology, launch systems, crewed space systems, robotics, AI, advanced materials and many others are all fields in which Europe has enormous expertise. By urgently start-

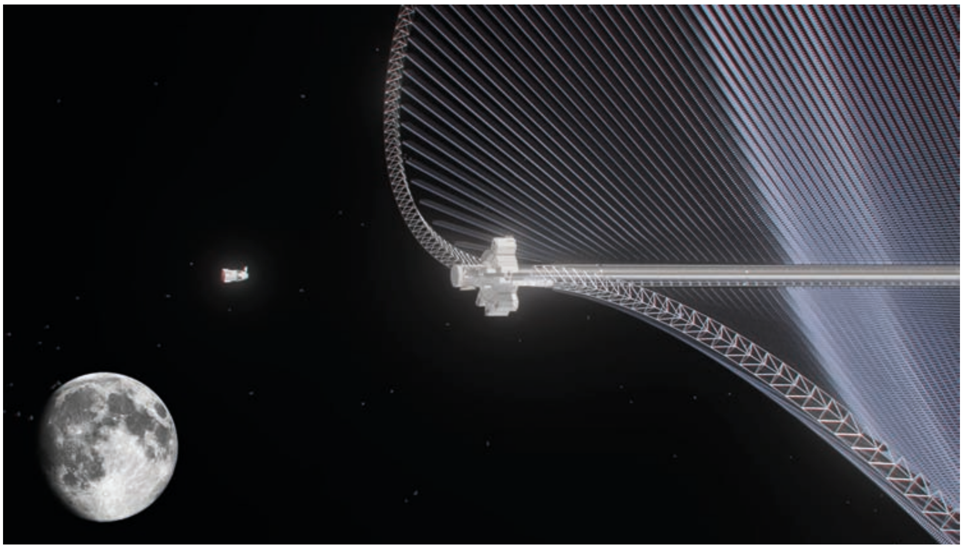

Fig.1 ESA Lunar Solar Power Satellite (Credit: ESA)

ing to fund the development of long lead-time components of the SBSP system, European countries will open the door, not only to unlimited clean electric power for Earth, but will also thereby create the industrial capabilities on the lunar surface which will enable human civilisation to spread to the Moon, bringing innumerable new opportunities for growth.

This research has been conducted in the context of ESA's open call "Clean Energy from Space" which sought novel ideas related to Space-Based Solar Power (SBSP) systems [2]. During the study, ESA announced the SOLARIS programme [3] to explore the feasibility and potential of SBSP to provide clean energy to Earth, for which funding was approved by the ESA Council at the Ministerial Level in November 2022. Astrostrom was asked by ESA to produce a promotional video introducing the SOLARIS initiative that was shown during this meeting, and is available on the ESA website [4].

The GE⊕-LPS is a crewed facility in lunar orbit (Fig 1). The construction of GE⊕-LPS with lunar materials requires developing facilities on the Moon for automated mining and manufacturing processes. The materials required for GE⊕-LPS include cast basalt and basalt fibre for the structural elements. Basalt fibre production would create a base construction material on the Moon. Cast basalt and basalt 3-D printing are mature terrestrial technologies that can be used for lunar construction.

Silicon, ilmenite and especially pyrite are considered for semiconductors and photovoltaics, whereas metals such as iron and aluminium will serve for the electrical connections. Specifically, Monograin layer (MGL) solar cells are a single-crystalline type of solar cell that do not require wafer technology. Under development at the Tallinn Technical University in Estonia [5] and at Crystalsol GmbH in Vienna, Austria [6], these photovoltaics could be manufactured from lunar pyrite in a much simpler process than silicon cells.

The establishment of industrial-scale, robotic beneficiation and processing plants will provide access to several other materials, which may become valuable to other users in the cislunar region (Fig 2). A vast amount of oxygen will be produced as a by-product which can be used in life support systems and as rocket propellant, thereby creating additional business cases for new cislunar enterprises.

Once shown to be both feasible and scalable, manufacturing

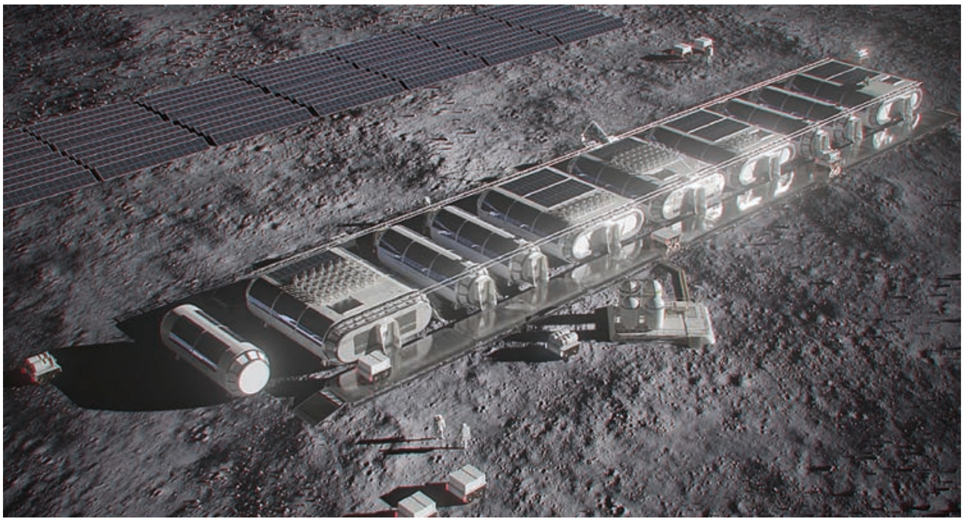

Fig.2 Lunar Fabrication Facilities for the GE⊕-LPS (Credit: Astrostrom).

future SPS components from lunar materials and transporting these to geostationary orbit (GEO) would be a means to avoid the need to launch hundreds or thousands of massive SPSs from the surface of the Earth in order to supply environmentally benign, baseload electricity to Earth. As such, the GE⊕-LPS is a concept that advances lunar development with the additional aim to address the terrestrial energy and climate crises.

Dr. Sanjay Vijendran, overseeing ESA's SOLARIS program explains [7]:

"Launching large numbers of gigawatt-scale solar power satellites into orbit from the surface of the Earth would run into the problem of a lack of launch capacity as well as potentially significant atmospheric pollution. But once a concept like GE⊕-LPS has proven the component manufacturing processes and assembly concept of a solar power satellite in lunar orbit, it can then be scaled up to produce further solar power satellites from lunar resources to serve Earth. This would also create many other benefits in addition to providing sufficient clean energy for Earth, including the development of a cislunar transportation system, mining, processing, and manufacturing facilities on the Moon and in orbit resulting in a two-planet economy and the birth of a spacefaring civilisation."

2 A LUNAR SPACE ELEVATOR AS AN ENABLER OF A CISLUNAR ECONOMY

In previous NASA colonialization and industrialization studies of the Moon, the mass-driver has been proposed as a possible technology to transport significant amounts of material from the lunar surface to EM-L2 [8, 9]. EM-L1 was excluded in these studies, since if the cargo could not be reliably captured by a mass-catcher there, it would become a potentially dangerous projectile directed towards Earth. If cargo at EM-L1 would be needed, it would have to be transferred from EM-L2 to EM-L1 by rockets. This scenario for lunar industrialization with a mass-driver sending lunar material to EM-L2 has been repeated and has rarely been questioned over the past decades. However, the belief that large space settlements and communities will one day be built in orbit as envisioned by Gerard O'Neill [10] and others, has been fading. Settlement of the Moon has mainly been reduced to human science and exploration activities, and building and maintaining the supporting infrastructure. If any industrial business case was ever mentioned, it was for Helium-3 to be mined and brought back to Earth.

However, in recent years several parameters have significantly changed. Automation and robotics have become established industrial technologies. Materials technology has made giant steps forward since the beginning of the millennium. New digital manufacturing processes like additive manufacturing have been developed and deployed on an industrial level. SpaceX has reduced rocket launch costs through reusability and is planning to refuel its Starship rocket in LEO, thus suddenly creating a market for propellants in LEO. All these and many more recent developments cast a new light on lunar industrialization and the need for a cislunar transportation system. The Astrostrom study investigated these aspects and proposes a modular transportation system with the deployment of a Lunar Space Elevator (LSE) as a core element to complement the necessary rocket vehicles. The LSE was found to be a superior, more flexible and less complicated technology than a mass-driver.

Generally, there are three ways to deliver the SPS components manufactured from lunar materials from the surface of the Moon to an assembly point at EM-L1:

- chemically propelled rocket launchers (existing technology)
- via a Lunar Mass-Driver (LMD) (technology proposed in the 1970's)
- via a tether called a Lunar Space Elevator (proposed by Pearson, Liftport and Astrostrom)

The following overview highlights the advantages and disadvantages of the three transportation technologies suitable for the GE⊕-LPS system.

2.1 Rockets

Rocket technologies are well proven and continuously developing in a more and more competitive market. Rockets are capable tools to lift payload to orbit, including human cargo, but they are inefficient tools for massive quantities and economic scale needed for setting up the long-term infrastructure for the GE⊕-LPS system. However, they will be important in the initial setup phase, as a redundant emergency system, and for passenger transportation. Although the infrastructure already exists on Earth for propellant production and launch, even with decreasing launch costs there is a big price to pay in delivering propellants to the Moon. Conversely, although it takes less energy to launch commodities produced on the Moon, this will still require use of traditional liquid propellants. And the production of propellant on the Moon requires a certain infrastructure. However, once mining the Moon starts, this infrastructure for In-Situ Propellant Production, or ISPP may develop quickly.

2.1.1 Oxygen

Oxygen makes up nearly half the mass of the lunar crust and is expected to be a major by-product of industrial operations on the Moon. As oxygen comprises much of the mass of currently used propellant systems (as much as 80%), its production alone would cut down the amount of propellant that would have to be imported by a large factor. Manufacture of the remaining fraction from lunar resources is hampered by the fact that most of the substances used in the manufacture of terrestrial propellants are rare or non-existent in the lunar environment.

2.1.2 Hydrogen

Hydrogen-Oxygen rockets have two main advantages in a lunar environment. First, the specific impulse (essentially the amount of thrust gained per unit of fuel burned) is listed as 450 seconds, the highest of any chemical rocket ever flown, meaning less fuel mass is needed compared to other fuel types. Second, hydrogen-oxygen rockets have been used since the early days of spaceflight, and as such the technology is well developed. The biggest disadvantage of this approach is the scarcity of hydrogen from lunar sources: hydrogen is present at the poles in the form of water ice, as well as being available in the regolith in low concentrations.

The mining of water ice in the polar regions is complicated by very cold (100 K and below) temperatures. There is also concern about the depletion of these resources, as the exact amount available is not yet known. Also, considering human spaceflight, water may be too precious a resource to use as rocket propellant. Another scenario is that if volatiles from regolith are extracted then hydrogen will become available everywhere on the Moon, since it is the most common component of regolith volatiles. However, extraction from the lunar regolith is an extremely energy intensive process, requiring the processing of massive quantities of lunar material at high temperatures. Further, hydrogen is difficult to store, so might be best processed as follows: a) react hydrogen with CO from regolith, which creates methanol, or b) react hydrogen with CO_2 from the regolith which creates methane (CH_4) and water.

2.1.3 Methanol

Methanol does not exist naturally on the Moon. Yet it would be expedient to synthesize it as follows: once volatiles are extracted from lunar regolith, some quantities of carbon monoxide (CO) will be released, together with hydrogen.

2.1.4 Methane

Methane (CH_4) has also been proposed as a fuel for lunar use. Carbon is present in the lunar regolith in concentrations several times that of hydrogen and heating the regolith to extract volatiles would result in some methane being produced, along with carbon monoxide and dioxide (which could be converted to methane by reacting with hydrogen). Methane, as an all-liquid chemical propellant, is used in relatively low complexity systems. The SpaceX-developed Raptor methalox bipropellant rocket engine has been tested successfully.

To support exploration beyond cislunar space, such as a mission to Mars and Jupiter, concepts for fuelling interplanetary vehicles in low-earth orbit (LEO) or the Earth-Moon L1 and/or L2 Lagrangian points have been proposed. An interplanetary fuel station for rockets at the GE⊕-LPS is likely to be an integral part of that future business model. Methane seems to be the propellant of choice. However, to transport large quantities of cargo as needed to build a SPS at EM-L1, the construction of a space elevator on the Moon will be a more robust and sustainable transportation system, saving valuable resources of lunar produced rocket fuel for beyond-Moon missions and contributing to the economic model of the GE⊕-LPS.

2.2 Lunar Mass-Driver – LMD

The idea for a Lunar Mass-Driver (LMD) was established as a serious alternative to rockets by Gerard O’Neill’s space colonialization studies in the 1970s [11]. These early concepts of large-scale Moon-based production systems 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, the strong weight and volume restriction of such payloads alone makes a mass-driver a very inflexible device, in addition to many other unsolved problems such as the energy use of a mass-catcher at EM-L2. In addition, the presence of lunar gravity simplifies many production techniques compared to conducting these operations from raw materials in the microgravity of lunar orbit e.g., the handling of molten materials. Thus, the mass-driver was found to be less suitable for use in the GE⊕-LPS system.

2.3 The Lunar Space Elevator (LSE)

A Lunar Space Elevator is anchored on the lunar surface and connects to the Earth-Moon L1 or L2 Points. Unlike Earth-anchored space elevators, the materials for a LSE will not require extreme strength, which enables a lunar elevator to be made with materials available today. An LSE could significantly reduce the costs and improve reliability of both delivering materials to orbit from the lunar surface, and soft-landing equipment on the Moon. For example, it would permit the use of mass-efficient (high specific impulse), low thrust drives such as ion drives which otherwise cannot land on the Moon. A GE⊕-LPS installed as a LSE hub could potentially provide the necessary electrical power for LSE operations.

3 THE LSE HISTORY

The idea of a lunar space elevator has been around since 1960 when Yuri Artsutanov wrote a Sunday supplement to *Pravda* on how to build such a structure and the utility of geosynchronous orbit [12]. In 1966, John Isaacs, a leader of a group of American Oceanographers at Scripps Institute, published an article in *Science* about the concept of using thin wires hanging from a geostationary satellite called the ‘Sky Hook’ [13]. In 1972, James Cline submitted a paper to NASA describing a "mooncable" concept similar to a lunar elevator [14].

In 1975, Jerome Pearson independently came up with the space elevator concept and published it in *Acta Astronautica* [15]. That made the aerospace community at large aware of the space elevator for the first time. His article inspired Sir Arthur Clarke to write the novel *The Fountains of Paradise* (published in 1979 [16], almost simultaneously with Charles Sheffield's novel on the same topic, *The Web Between the Worlds* [17]. In 1979 Pearson extended his theory to the Moon and changed to using the Lagrangian points instead of having it in geostationary orbit [18].

In 1977, some papers of Soviet space pioneer Fridrikh Tsander (Friedrich Zander) were posthumously published, revealing that he conceived of a lunar space tower in 1910 [19]. In 2005 Jerome Pearson completed a study for NASA Institute of Advanced Concepts which showed the concept is technically feasible within the prevailing state of the art using existing commercially available materials [20].

In October 2011 on the Liftport website Michael Laine announced that Liftport was pursuing a Lunar Space Elevator as an interim goal before attempting a terrestrial elevator. At the 2011 Annual Meeting of the Lunar Exploration Analysis Group (LEAG), Liftport CTO Marshall Eubanks presented a paper on the prototype Lunar Elevator co-authored by Laine [21]. In August 2012, Liftport announced that the project may actually start near 2020. However, in April 2019, Liftport CEO Michael Laine reported no progress beyond the lunar elevator company's conceptualized design [22]. In 2019, Emily Sandford and Zephyr Penoyre published their version of the LSE called “The Spaceline” in *Acta Astronautica* [23].

4 THE LSE CONCEPT

A Lunar Space Elevator is a transportation system that uses a cable or tether to move materials from an anchor point on the surface of the Moon to a docking station at EM-L1 or EM-L2 (Fig. 3). Unlike terrestrial space elevators, which are feasible in principle anywhere around Earth’s equator, there are only two stable sites for a lunar space elevator, due to the Earth’s gravitational influence, namely pointing directly towards the Earth and directly away from the Earth. The centrifugal forces essential for a terrestrial space elevator are minimal compared to the gravity well of Earth and Moon acting on such a lunar space elevator. The Moon does not rotate fast enough for an elevator to be supported by centrifugal force (the proximity of the

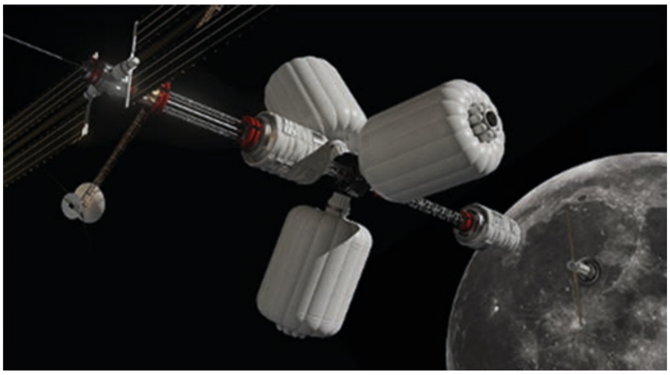

Fig.3 **Lunar Space Elevator Deployment (Credit: Astrostrom).**

Earth means there is no effective lunar-stationary orbit), but differential gravity forces permit an elevator to be constructed traversing the Earth-Moon Lagrangian points 1 and 2.

The means of transportation will consist of the use of "climbers" that would crawl between these two locations powered by electrical energy using wheeled "trucks". Its main function is to allow for a reusable, controlled means of transporting payloads of cargo, or possibly people, between a base station at the bottom of a gravity well on the Moon and the docking port at EM-1. For the GE⊕-LPS system, the LSE potentially offers an economic and reliable means to deliver the lunar manufactured elements to a relatively stable orbital assembly point.

The Earth-Moon Lagrange points 1 and 2 are two points in space where the LSE docking port could maintain a stable, lunar synchronous position. The 0.055 eccentricity of the lunar orbit means that these points are not fixed relative to the lunar surface: the L1 is 56,315 km +/- 3,183 km away from the Earth-facing side of the Moon (at the lunar equator) and L2 is 62,851 km +/- 3,539 km from the centre 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 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 remains stationary relative to the lunar surface [24].

For a space elevator to remain 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 centre of mass, which keeps the tether in tension [25]. 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. To suspend a 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. This feature could be optimized when considering it as an Earth-Moon transportation system. The average Earth-Moon distance is 384,400 km. Sandford proposes that a longer tether in the direction of Earth would be sufficient as a counterweight, with the additional advantage that it could be extended almost to Earth's GEO. The advantages of such an Earth-Moon transportation system are obvious [26].

The lunar surface anchor point of a LSE is normally considered to be at the equator. However, there are several possible cases to be made for locating a lunar base at one of the Moon's poles; a base on a peak of eternal light could take advantage of near-continuous solar power, for example, or of water and other volatiles that may be trapped in permanently shaded crater bottoms. An LSE could be anchored near a lunar pole, though not directly at it [27]. Due to the uniqueness of LSE, several different lower segments, starting from different points, could be used in a mature system. Lunar space elevators could revolutionize operations in cislunar space and could be a key component in the development of the Moon and the use of its resources for advanced space development.

According to Pearson [28], in addition to enhancing the viability of the GE⊕-LPS system, LSE will contribute to lunar development by:

- Providing lunar materials in Earth orbit at less cost than launching from the Earth.
- Providing an unlimited supply of construction material in Earth orbit.
- Providing for continuous supplies to lunar installations.
- Providing the basis of a new paradigm for robotic lunar construction and development.
- Supporting astronomical observatories on the lunar far side.

Essential to the GE⊕-LPS system, the LSE could provide unlimited amounts of lunar material for the construction of the power generation segment and the shielding for the space habitat.

4.1 LSE Materials

In contrast to an Earth-to-Orbit Space Elevator and, as a compelling reason for its consideration in the GE⊕-LPS system, the Lunar Space Elevator can be built today from existing commercial polymers which can be manufactured, launched, and deployed from Earth. The first technical challenge of the LSE was finding a material which is both light enough and strong enough to support its own weight over the entire distance in the cislunar gravity field, and still be strong enough to carry a payload. Until the late 20th century, such materials did not exist, but since the 1990s, revolutionary new polymer materials have become commercially available.

The first material which was theoretically capable of supporting a lunar elevator was Kevlar™, but it was only barely strong enough. Fortunately, newer even stronger (by weight) materials have subsequently come on to the market; four in particular are T1000G™, Dyneema™ 7, Magellan-M5™ 8, and Zylon™ 9 [29]. Of these, Magellan-M5 is superior to everything else currently available; however, supplies are very limited on the commercial market. The reasons for this are that M5 is difficult to manufacture, partly because its extraordinary strength tends to destroy the tooling. Secondly, it is in high demand by the U.S. Government, especially for bullet-proof vests and helmets, and the U.S. Government has bought up nearly all of the available production to date.

The three other materials, T1000G, Dyneema and Zylon, are available in large quantities, and are currently the best candidates for LSE construction, at least until M5 eventually becomes available in greater quantity, or until an even better material become widely available. Carbon nanotubes, which are made of graphene manipulated into tube-like structures provide a very promising glimpse into the future of strong, lightweight materials, and, indeed, single-layer graphene is a serious candidate material for an eventual Earth-to-space elevator and is under development in the UK [30].

The choice of material is important because the effective length of a LSE is a function of the relative strength of the material. A few simple parameters, intrinsic to the material of which the cable is made, define the physical capabilities of a cable in tension. Ignoring defects and wear, a material will break when the stress (force per unit cross-sectional area, a) exceeds some critical value, the breaking stress B. Thus, a heavier load and larger force can be accommodated by a cable made of stronger material (higher B) or a cable with larger cross-sectional area (higher a). The density of the material, ρ, which can reasonably be assumed to be constant and intrinsic to the material, will also be important. Most of the load a cable must bear is its own weight: it is possible to construct a cable that would break solely from the tension due to the gravitational forces acting upon it, before introducing any payload (in fact, this is the major stumbling point of current space elevator designs) [31].

4.2 LSE Deployment

LiftPort Group and Marshall Eubanks have calculated the parameters for a 48-ton LSE design which is light enough to be launched on a single SLS launch vehicle using direct injection, or a single Falcon-Heavy class vehicle using electric propulsion to transfer from LEO to EM-L1 or EM-L2 [32]. This design is probably the smallest that can reasonably be built. Radley estimates that this LSE could be built today from existing commercial polymers, and could be manufactured, launched, and deployed for less than $2 billion [33].

The essential components comprise: the tether, the EML station, the Counterweight (CW), the Surface Attach Fixture (SAF), and the Climbers. Upon arrival at the EM-L1 (or EM-L2) location, the deployment sequence will begin. The CW and the SAF simultaneously detach from the EM-L1 station, and the respective attached tethers begin to unspool. The two tethers are concurrently unreeled at rates which maintain the centre of gravity of the system at the EM-L location. Once the tether is fully deployed, the SAF will drill into the lunar surface by a meter or two, sufficient to counteract the small residual tension force and small lateral disturbance forces.

Once the system is stabilized, and residual deployment transients have damped, the first attempt will be made to lower a climber towards the lunar surface. In order to descend to the lunar surface, no injection of energy is required; instead the climber will accelerate by falling under gravity until it reaches a cruising speed, and thereafter will apply braking to limit the descent speed, and to decelerate for a final soft landing. Hence the descent can be performed during daylight or during darkness.

Ascent from the lunar surface must be done during lunar daytime since the climbers are solar-powered and will need input of solar power to drive the motors to ascend the tether. An initial run will be made using a single climber to descend and then ascend along the tether. Once the basic function of the system is thus validated, then multiple climbers can be put into action. According to Radley, if speeds as high as 700 m/s can be achieved then it would be possible to have six evenly spaced climbers with attached solar arrays for power, which can travel on the tether simultaneously, achieving 80 ascents and descents per two-week period, resulting in payload throughput of 8 tons per month to and from the Moon in each direction. Furthermore, a prototype LSE could be executed in a single NASA Discovery class mission, starting with the delivery of 58,500 kg of Zylon HM fibre plus associated equipment to the EM-L1 site. The planned base station location is Sinus Medii, near 0° Latitude and Longitude on the lunar near side [34].

The LSE will be able to return 100 kg payloads via climbers powered by solar cells. These payloads could be deposited at EM-L1 for use there or sent to the Earth end of the LSE tether 220,670 km above the lunar surface. Any payload separated from the tether at this distance will re-enter the Earth's atmosphere in approximately 1.4 days at a speed of about 10.9 km/s.

4.3 LSE Advantages

Building a facility at EM-L1 is one of the most immediately useful and exciting utilities of the LSE. A habitat there could house many scientists and engineers, much like the Antarctic base camp. This would allow experimentation and construction in a near-pristine, gravity-free environment.

There are additional advantages of fabricating and assembling structures at the Lagrange point rather than at any other stable orbit [35]:

Cost of transport – from Earth, it costs slightly less, in fuel, to reach the LSE than geostationary orbit. Transport along it with solar-powered climbing vehicles needs no propellant. This would reduce the cost of moving to anywhere along its length substantially – for example, it would reduce the fuel needed to reach the surface of the Moon to a third of the current value.

Haulage to and from the surface of the Moon – similar to the Suez and Panama canals on Earth, a permanent cislunar transportation system would revolutionise the economics of scientific and industrial possibilities throughout cislunar space.

Docking – objects in space float freely in a truly 3-dimensional space, but when tethered to a line movement between the objects becomes a one-dimensional journey. Motion along a tether is simpler and safer than navigating through empty space, and docking and safely soft-landing cargo by rockets.

Deep Space Harbour – as an exchange point for resources from the Earth and Moon the LSE Hub at EM-L1 will naturally become a busy location. The hub can be extended to accommodate scientific and private sector facilities. Eventually it will be a starting point for missions beyond cislunar space.

Permanence and Resilience – like a bridge or a new railway line, the LSE will provide a reliable long-term access to cislunar space and to the Moon and will mark not the pioneering but the economic beginning of the Space Age. As such, it will facilitate and accelerate economic development as bridges and canals have done on Earth in the last centuries.

Precursor for an Earth Space Elevator – As the materials needed to build an Earth Space Elevator (ESE) are not yet available in industrial quantities, the LSE would be a test-bed for engineering and technology development that later could be applied to an Earth elevator. Thus, it would radically accelerate the eventual implementation of an ESE.

4.4 LSE Technical Challenges

Payload Throughput: In terms of delivering substantial quantities of mass from the surface of the Moon to EM-L1 for assembly, the size of the payloads and the frequency rate of delivery are prime considerations. This means one could load over 2,000 kg at the Earth end of the cable, or over 6,000 kg at the most fuel-efficient point to intersect with the LSE. At the Moon, this would only allow transport to EM-L1 of masses up to 100 kg. However, these numbers rise quickly for stronger materials and thicker cables scaling approximately linearly with both [36]. A climber speed of 0.7 km/s is needed to achieve a throughput of 8 tons per month to and from the Moon in each direction [37]. This amount could be doubled if the power to the climbers is sent by lasers to solar arrays attached to the climbers while travelling through the shadow cone of the Moon.

Damping: Earth's gravity anchors the end of the LSE, always pulling it back towards straight. However, the system is in a rotating frame, and substantial movement of mass along the cable will generate motion via the Coriolis force. There is no inherent damping in the system, and due to the varying tension along the length of the cable the propagation of waves along its length is not trivial to calculate. More in-depth analysis will be needed to assess whether such payload movements could cause instability, and how best this can be addressed. Depending on the magnitude of energy inputs, countermeasures could be taken to damp the motion, ranging from increasing the natural damping of the cable, to the use of solar sails or corrective thrusters.

Impacts: close to gravitating bodies, micro-meteoroids will accumulate. Though they may be almost imperceptibly small, they could still damage or even break the cable upon impact. The simple solution to this is to distribute the tension in the cable across multiple strands, such that one or more can break without greatly reducing the strength of the cable. These broken strands could theoretically then be repaired systematically, much like small damage to a railway line. The problem can be further contained by breaking the cable up into individual spans – many strands all connected to a terminating plate at each end – such that a breakage of one strand only affects the strength of that span, not the cable as a whole. To fully understand the measures that must be taken to reduce this risk, the rate at which such impacts might occur must be calculated.

Climber speed: Another key issue is the speed with which the climber travels up and down the tether. For the GE⊕-LPS system we wish to maximize the payload throughput of the system. This means maximizing the velocity of climbing up and down. The Technion University team in 2008 suggested that 700 m/s (0.7 km/s) is a reasonable velocity, since it is below the speed of sound in the tether material, which would otherwise result in a destructive shock wave developing [38]. In 2005, Pearson *et al.* suggested that 15 m/s would be a more conservative velocity. This questions whether 700 m/s is realistic and this aspect would have to be researched further. Challenges in achieving such high speeds include high gear ratios, friction, lubrication, wear of all the respective moving parts, and abrasion of the tether material.

Maintaining centre of mass: Another overall challenge of the LSE is to always maintain the centre of mass of the system at or close to the EML location. The EML is an equilibrium point between the Earth and the Moon, but it is not stable. Objects which are offset from the EML will tend to move away from the EML. Hence, some method of active station-keeping will be required. Geosynchronous satellites around Earth suffer from a similar challenge, and they typically use chemical rockets or Hall thrusters to maintain station. In similar fashion, electric propulsion or Hall thrusters could be used to maintain the EM-L1 station in place. There are several disturbance forces which will need to be dealt with, for example, the lunar orbit around Earth is not circular, it is elliptical and as a result the location of the EM-L1 point itself is not stationary and will tend to move in a cyclical manner. It has been proposed that a Lissajous orbit [39] be used around the EML, which has a greater time constant than the EM-L1 itself. Furthermore, although the Moon is tidally locked to the Earth, it experiences periodic rocking motions back and forth, about two axes, known as "libration". In order to compensate for these various orbital and libration disturbance forces, it has been proposed that an active control system could actively vary the length of the tether to the lunar surface and/or to the CW, and achieve some degree of station-keeping control.

The Coriolis Effect: A climber which travels up and down the tether will experience Coriolis force due to the difference in lateral velocity between the EML location versus the lunar surface. It would be feasible to use electric propulsion to compensate for the Coriolis force, with a modest loss of payload capacity, taken up by the weight of the thruster and a small amount of power used to maintain cruise speed of the climber up the tether. It would be feasible to have two lunar elevators, one for downwards descending payloads, and another for ascending payloads. Coriolis force on each tether would act in opposite directions. The easterly tether would be used for downwards traffic, and the westerly tether for upwards traffic. The respective Coriolis forces would act in opposite directions and cause the two tethers to be pulled apart so they would not interfere with each other. In such a dual tether system, the downwards tether could be in continuous operation, both day and night. The upwards tether would only be able to operate during the lunar daytime unless power beaming becomes available.

Capacity: The payload capacity of the LSE is relatively low on the Moon side and dependent on the tether material strength, climber speed and the counterweight on the other end. Further studies are needed to explore how capacity can be extended, e.g., the influence of sectioning the tether and its scalability.

Lunar Night: For climbers driven by lightweight solar panels, lunar night cuts the transportation capacity into half. This could be solved by power beaming with a rotating laser beam feeding the solar panels through the shadow of the Moon.

4.5 LSE Summary

The Lunar Space Elevator is considered to be a suitable and technically feasible method to deliver GE⊕-LPS elements manufactured on the lunar surface to the EM-L1 assembly location and, as such, is a key technological component of the GE⊕-LPS concept. The possibility that a LSE could be built today from existing commercial polymers, manufactured, launched via Falcon Heavy and deployed for less than $2 billion makes this a very tangible option. Using the newer SpaceX Starship or a launcher with similar capabilities such as ESA's planned PROTEIN launcher with its additional payload capacity would make LSE even more attractive from a cost and feasibility perspective.

With a larger tether and the use of a more robust tether material, the size of the payloads can be proportionally increased. Multiple tethers could enhance the throughput operations. An operational power producing GE⊕-LPS installed as a LSE hub could potentially provide the necessary electrical power for LSE operations. Whether this can also satisfy the requirements of the GE⊕-LPS system needs to be further researched. A LSE in the configuration needed for full GE⊕-LPS operations would most likely be the result of a major international effort, and could lead to an attractive, low-cost transportation system between the Earth and the Moon.

5 THE ECONOMIC OPPORTUNITY AND BUSINESS CASE

Most space programs are considered in terms of cost. However, by enabling cost-effective Space-Based Solar Power, the impact of the GE⊕-LPS concept needs to be considered in terms of economic opportunity. SPS can deliver clean baseload solar-generated electricity to Earth on a 24/7 basis and thus is an important addition to the future energy mix. Compared with fusion energy, SPS is an engineering challenge, rather than a scientific challenge. The technologies are available and are understood, but they need to be scaled.

According to Bloomberg NEF's "Energy Transition Investment Trends 2022", global investment in the energy transition was a total of $755 billion in 2021 due to rising climate ambitions and policy action from countries around the world [40]. This is about 10 times the total funding of all space agencies. Bloomberg NEF'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 [41].

By mitigating the procurement and launch costs associated with Earth-launched Solar Power Satellites, a viable business case can be made for the lunar approach to SPS procurement. Not only is it more economically attractive than an Earth launched SPS, it is also very competitive with any terrestrial energy system. 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 in three different units:

- mass that needs to be launched from Earth and so causes atmospheric pollution,
- terrestrial energy resources used and thereby causing pollution within the biosphere,
- monetary cost.

As in a typical break-even analysis, the cost (as well as energy used and mass launched) to make things on the lunar surface will initially 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 orbit from the lunar surface than from the Earth – about 95% less. The advantage of the much lower energy needed for transportation from the lunar surface 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. A "mature" system should be able to manufacture products as well as those on Earth. As data become available, cost modelling should enable estimates of how much investment and how many years it would take for lunar sourced SPS components to reach break-even and become cheaper than terrestrial components in GEO. This will depend on the rate at which lunar launch costs fall with the development of the non-rocket launch systems of a lunar space elevator.

For the foreseeable future, launches from Earth will use chemical-propellant rockets, which use terrestrial energy resources and cause atmospheric pollution. The development and implementation of various lunar-surface facilities, particularly those including a range of materials processing and manufacturing systems, will use terrestrial energy, launch systems, and other terrestrial resources in the initial phases. However, as their operation on the lunar surface leads to increasing lunar surface capabilities, there will be less and less need for resources delivered from Earth, leading to advantages of lunar over terrestrial manufacturing by reducing both the energy that is used within the biosphere and the atmospheric pollution caused.

5.1. 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.

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 will become lower than Earth-produced sub-systems. Part of the revenue stream paid by electricity companies for microwave power supplies delivered from SBSP 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. 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.

6 CONCLUSIONS

> *"If God wanted man to become a spacefaring species, he would have given man a Moon."*
>
> **Krafft A. Ehricke** [42]

For the security of humanity's future well-being on Earth, the time has come to extend its civilization beyond the home planet and establish it on its closest celestial neighbour. The climate and energy crises on Earth have created an unprecedented economic opportunity for the realisation of Space-Based Solar Power. The GE⊕-LPS concept is a visionary opportunity to refocus humanity's perception of its place and purpose in the cosmos and, if successful, eventually providing clean and plentiful energy from space will lead to solving both the climate and the energy crises confronting Europe and the world. A key technology to make GE⊕-LPS happen is the Lunar Space Elevator, which would be essential and practical for transporting the lunar fabricated SPS components from the lunar surface to the assembly location at EM-L1 and later to GEO. By setting up a permanent transportation infrastructure to and from the Moon, the LSE will also mark an irreversible step beyond the home planet and become a catalyst for a cislunar economy.

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