The Greater Earth Lunar Power Station (GE⊕-LPS)

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2.5 Space-Based Solar Power, Powering Civilian Space Development
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ABSTRACT

The Greater Earth Lunar Power Station (GE⊕-LPS) is a habitable space station in lunar orbit that is designed to provide solar energy for lunar operations. Space-Based Solar Power (SBSP) and space tourism could become synergistic economic drivers for future space development. The main obstacle to implementing SBSP is launching a solar power satellite (SPS) from the surface of Earth. John Mankins' SPS-ALPHA Mark-II concept proposes that the photovoltaic (PV) power generation system would consist of an extremely large number of mass-produced modular PV elements that would "self-assemble" into the SPS structure. David Criswell introduced a significant variation of the SPS concept called the Lunar Power System (LPS) system which proposed the in-situ use of lunar materials for the construction of the SPS elements. The GE⊕-LPS is a SBSP concept that incorporates both technological approaches with a possible lunar tourist destination. The elements of the GE⊕-LPS would be constructed primarily from lunar resources using a lunar based automatized manufacturing process connected to a mass driver system for transport into a lunar orbit. Earth Moon L1 would be an appropriate assembly point. The toroidal design allows for the addition of a habitat and control center that would use water and lunarcrete 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 maneuverability and attitude control. As the lunar manufacturing operations could be scaled to any dimension, SPSs assembled in lunar orbit could provide much needed clean solar energy for terrestrial purposes.

The GE⊕-LPS has two practical objectives:

1. It is an optimized technical approach to economically realizing SBSP as a means to address the energy dilemma and climate emergency issues on Earth, and,

2. it provides an inspiring and purposeful facility for developing humanity's lunar aspirations.

PAPER

1 Introduction

The 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 GE⊕ Lunar Power Station is a habitable space station in lunar orbit that is also a solar power satellite. GE⊕-LPS will be constructed primarily from lunar resources and materials using lunar based automatized manufacturing processes. As such, 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. Last, but not least, as the GE⊕-LPS concept and its energy production functions can 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 unities the aims of lunar development with widely shared aspirations of spaceflight while addressing the critical energy and environmental needs of human civilization on Earth.

2 Greater Earth and the GE⊕ Symbol

⊕ is the Greek astronomical symbol for planet Earth and is the symbolic form of the GE⊕ Lunar Power Station – a circle divided by a central cross. *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. Earth's gravitational influence extends 1.5 million kilometers in all directions from its center where it meets the gravitational influence of the Sun. This sphere, with a diameter of 3 million kilometers, has 13 million times the volume of the physical Earth and through it, passes some 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 other resources, including the Moon and occasional passing asteroids. Greater Earth is also understood to be an interdependent dynamic system involving the cosmic interactions of the Sun, the Moon and the Earth that has enabled life on Earth to emerge, to survive and to thrive. Awareness of Greater Earth and extending civilization throughout its regions may help catalyze an optimistic path to a sustainable and prosperous future for all humanity on Earth and beyond.

(Website: https://greater.earth)

3 The Energy Dilemma

Among all of nature's diverse systems, energy is the principal driver of the increasing complexity of galaxies, stars, planets and life-forms in the expanding universe. Energy flows engendered largely by the expanding cosmos seem to be as universal as anything yet found in nature. Indeed, unlocking Earth's vast energy reserves enabled our species to embark on an industrial revolution leading to a technological civilization that is on the threshold of expanding permanently into the near cosmos beginning with a permanent presence on Earth's closest celestial neighbor – the Moon.

Earth's terrestrial energy reserves are finite and inadequate for this next stage of a cultural and societal evolution which would enable humanity to become a spacefaring species. Humanity is facing an imminent *Energy Dilemma* in that the limited proven reserves of fossil fuels could reach exhaustion levels at mid-century and none of the current terrestrial energy options – nuclear – wind - ground solar (PV) – can be sufficiently scaled to achieve the goal of divesting from fossil fuels by the year 2050 as is being called for by the United Nations, the European Union, and numerous organizations to address the *Climate Emergency.* However, the largest market on Earth is for energy and, as such, supplying inexhaustible and clean energy from space would be not only affordable but also immensely profitable.

Figure2. shows the BP Statistical Review of World Energy 2020, a commonly used as a source for global energy data which lists World Primary Energy Consumption by fuel, i.e. oil, natural gas, coal, nuclear energy, hydroelectricity, and renewables by region and by country.[1] The review shows that total world energy consumption in 2019 was 583.90 EJ including: renewables: 28.98 EJ, hydroelectricity: 37.66 EJ, nuclear energy: 24.92 EJ, coal: 157.86 EJ, natural gas: 141.45 EJ and oil: 193.03 EJ.

The BP report listed these in totals in exajoules (EJ) which, when converted to terawatt hours (TWh) results in the following figures: total world energy consumption was 162,194 terawatt hours (TWh), combined fossil fuels from coal, natural gas and oil = 492.34 EJ = 136,761 TWh (84.2%), nuclear energy 10,461 TWh (6.5%), hydroelectricity, 6,922 TWh (4.3%) and 8,050 TWh (5%) from renewables and other energy sources.

Primary energy: Consumption by fuel*

Exajoules	2018 Oil	2018 Natural gas	2018 Coal	2018 Nuclear energy	2018 Hydro-electricity	2018 Renew-ables	2018 Total	2019 Oil	2019 Natural gas	2019 Coal	2019 Nuclear energy	2019 Hydro-electricity	2019 Renew-ables	2019 Total
Total World	191.45	138.66	158.79	24.16	37.34	25.83	576.23	193.03	141.45	157.86	24.92	37.66	28.98	583.90
of which: OECD	90.32	63.24	36.19	17.62	12.75	15.27	235.39	89.63	64.84	32.10	17.77	12.32	16.77	**233.43**
Non-OECD	101.13	75.42	122.61	6.54	24.59	10.55	340.84	103.40	76.61	125.75	7.16	25.34	12.21	**350.47**
European Union	26.49	16.46	9.37	7.40	3.12	6.97	69.81	26.39	16.90	7.69	7.33	2.94	7.54	**68.81**

*In this review, primary energy comprises commercially traded fuels, including modern renewables used to generate electricity.
Energy from all sources of non-fossil power generation is accounted for on an input-equivalent basis. See the appendix or *bp.com/statisticalreview* for more details on this methodology.
†Less than 0.005.

Figure 2. Excerpt from the BP Statistical Review of World Energy 2020

As seen in Figure 3, for Europe the figures were: total energy consumption 83.82 EJ = 23,283 TWh, combined fossil fuels 61.7 EJ = 17,139 TWh (73.6%) , nuclear energy 8.28 EJ = 2,300 TWh (9.88%), hydroelectricity 5.66 EJ = 1,572 TWh (6.75%) and 8.18 = 2,272 TWh (9.76%) from renewables and other sources.

Primary energy: Consumption by fuel*

Exajoules	2018 Oil	2018 Natural gas	2018 Coal	2018 Nuclear energy	2018 Hydro-electricity	2018 Renew-ables	2018 Total	2019 Oil	2019 Natural gas	2019 Coal	2019 Nuclear energy	2019 Hydro-electricity	2019 Renew-ables	2019 Total
Austria	0.54	0.31	0.12	–	0.34	0.13	1.44	0.55	0.32	0.13	–	0.36	0.14	**1.50**
Belgium	1.42	0.61	0.13	0.26	†	0.17	2.59	1.38	0.63	0.13	0.39	†	0.19	**2.71**
Czech Republic	0.43	0.29	0.65	0.27	0.01	0.08	1.73	0.43	0.30	0.60	0.27	0.02	0.08	**1.71**
Finland	0.41	0.08	0.18	0.20	0.12	0.18	1.15	0.39	0.07	0.15	0.20	0.11	0.18	**1.10**
France	3.17	1.54	0.35	3.70	0.57	0.54	9.87	3.15	1.56	0.27	3.56	0.52	0.61	**9.68**
Germany	4.63	3.09	2.90	0.68	0.16	1.97	13.44	4.68	3.19	2.30	0.67	0.18	2.12	**13.14**
Greece	0.65	0.17	0.19	–	0.05	0.10	1.16	0.68	0.19	0.14	–	0.04	0.11	**1.15**
Hungary	0.37	0.35	0.09	0.14	†	0.04	0.98	0.37	0.35	0.08	0.15	†	0.05	**0.99**
Italy	2.60	2.49	0.37	–	0.42	0.64	6.53	2.49	2.55	0.30	–	0.40	0.64	**6.37**
Netherlands	1.68	1.27	0.34	0.03	†	0.19	3.53	1.65	1.33	0.27	0.03	†	0.23	**3.51**
Norway	0.41	0.16	0.03	–	1.24	0.05	1.90	0.39	0.16	0.03	–	1.12	0.07	**1.77**
Poland	1.33	0.72	2.08	–	0.04	0.21	4.38	1.34	0.73	1.91	–	0.04	0.25	**4.28**
Portugal	0.48	0.21	0.11	–	0.11	0.16	1.08	0.51	0.22	0.06	–	0.08	0.18	**1.04**
Romania	0.43	0.42	0.21	0.10	0.16	0.09	1.41	0.45	0.39	0.19	0.10	0.14	0.10	**1.37**
Spain	2.72	1.13	0.46	0.50	0.31	0.70	5.82	2.72	1.30	0.21	0.52	0.22	0.75	**5.72**
Sweden	0.56	0.04	0.08	0.61	0.56	0.32	2.17	0.57	0.04	0.08	0.60	0.59	0.36	**2.24**
Switzerland	0.43	0.12	†	0.22	0.31	0.04	1.13	0.44	0.12	†	0.21	0.31	0.04	**1.13**
Turkey	2.00	1.70	1.71	–	0.54	0.34	6.29	2.03	1.56	1.70	–	0.79	0.41	**6.49**
Ukraine	0.41	1.10	1.15	0.76	0.09	0.02	3.54	0.44	1.02	1.10	0.74	0.06	0.05	**3.41**
United Kingdom	3.17	2.85	0.32	0.58	0.05	0.99	7.96	3.11	2.84	0.26	0.50	0.05	1.08	**7.84**
Other Europe	2.61	1.09	1.41	0.33	0.70	0.51	6.66	2.63	1.08	1.43	0.34	0.62	0.56	**6.67**
Total Europe	30.46	19.73	12.92	8.37	5.79	7.50	84.76	30.40	19.95	11.35	8.28	5.66	8.18	**83.82**

Figure 3. Excerpt from the BP Statistical Review of World Energy 2020 - Europe

Using nuclear power as an example, to replace current worldwide fossil fuel usage of 136,761 TWh with nuclear power (assuming a 90% availability) would require the deployment of up to 17,347 new 1-GW nuclear reactors. This means, for the next 30 years, 578 nuclear power plants would have to go online each year. For Europe, this would mean 2,173 new 1-GW nuclear reactors would be required to replace fossil fuels.

Using renewables to meet this goal, the installed power generating capacity for wind power needs to be some 3.5 times higher and for solar PV, 6-7 times higher than nuclear power. Installing this much capacity seems unlikely and, more importantly, both of these energy sources are intermittent and cannot be stored efficiently and are particularly sensitive to winter weather. Therefore, these two alternative energy sources are not adequate for meeting humanity's energy needs and climate goals. In his book on space solar power with the title *Astroelectricity* (2019) and on his Spacefaring Institute YouTube channel , Michael Snead's assessment of the U.S. energy needs in the year 2100 reached a similar conclusion concerning the lack of scalability of terrestrial energy alternatives. [2]

As to economic considerations, using the 2019 total world energy consumption of 162,194 TWh mentioned in the BP report, it is possible to estimate the world energy market by using an average price per kWh US $0.13 as calculated by GlobalPetrtolRices.com, the value of the world energy market is approximately $21 trillion US dollars ($ 21,085,220,000.000). [3] The energy markets around the world are in a state of flux due to the pursuit of decarbonization and the search for viable terrestrial alternatives. However, as this market is the largest in the world, finding the most viable sustainable alternative is the ultimate economic opportunity and it will influence all areas of human activity.

4 The Climate Emergency

Due to the many assessments and reports issued since 1990 by the United Nation's IPCC – Intergovernmental Panel on Climate Change – and the subsequent international commitment to address the climate issue achieved in the 2015 Paris Agreement on climate change which, as of February 2020 has now been signed by 189 countries. Thus, the world population has become increasingly alarmed that a period of global warming may have commenced which could lead to environmental catastrophe by the end of this century. Numerous scientific studies have shown 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 [4] including the Paris Agreement and the 17 Sustainable Development Goals as well as through a number of international conferences [4], sub-organizations and public-private partnerships. Similar measures are being promoted, developed, and adopted by environmental and scientific organizations worldwide. [5] [6] Many prominent people such as former US vice-president Al Gore, British natural historian and broadcaster David Attenborough and the young Swedish activist Greta Thunberg have brought the Climate Emergency to the world's attention. [7]

As it is the Sun which 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 has much do with 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. [8] 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. [9] 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. [10]

5 The Space Energy Option

The idea of harnessing energy in space originated with the Russian and Soviet rocket scientist and astronautical pioneer Konstantin Eduardovich Tsiolkovsky in 1926. In 1941, science fiction writer Isaac Asimov published the short story "Reason", in which a space station transmits energy collected from the sun to various planets using microwave beams. The technical concept of delivering clean solar energy from space in the form of a Solar Power Satellite (SPS) was introduced by Peter Glaser in 1968 which he patented in 1973. Since then, Space-Based Solar Power (SBSP) has been researched in various governmental and institutional studies which have validated the technical feasibility. Although the engineering challenges are significant, all the core technologies already exist and have been tested. As such, the *Space Energy Option* is the only near term technically feasible and scalable energy alternative currently available to humanity to divest from fossil fuels while meeting its future energy needs, climate obligations and for restoring the environment. [11]

6 The Main Obstacle to Space-Based Solar Power

The standard objection to SBSP has been the initial cost to implement such a space power system. This cost is often unfairly compared to costs of terrestrial energy solutions which are highly subsidized by governments. A fair comparison considered in the context of the increasing demand for CO_2-neutral energy and the value of the global energy market by the year 2050, this objection should have lesser relevance as terrestrial energy alternatives prove to be insufficient, impractical, expensive, or undesirable and the magnitude of *Energy Dilemma* becomes apparent.

The main obstacle to implementing the Space Energy Option is not the cost of the system but rather the enormous manufacturing and logistical effort needed to launch solar power satellites from the surface of Earth into orbit.

Figure 4. Falcon Heavy launch. Photo NASA

Former NASA physicist John Mankins and current CEO of Artemis Innovation Management Solutions has looked deeply into "The Case for Space Solar Power" in his book. [12] He led a study on space solar power at the International Academy of Astronautics (IAA) [13] and has worked with NASA to develop the SPS-ALPHA (Arbitrarily Large Phased Array) concept which has now evolved into the SPS-ALPHA Mark-II version. The core element of his concept proposes that the photovoltaic (PV) power generation system would consist of an extremely large number of mass-produced modular PV elements that would robotically "self-assemble" into the SPS structure. His LCoE estimates shows that the Energy Payback Time would be brief and that SBSP would quickly become profitable. [14]

Using the SPS-Alpha MK-II concept as a reference, a 1-GW solar power satellite would have a launch mass of approximately 5,000 MT (5,000,000 kg). SpaceX's Falcon Heavy Partially Reusable version, the largest launch vehicle commercially available today, could theoretically place 57 tonnes (57,000 kg) into low Earth orbit (LEO) at a list price of CHF 85 million ($95 million) per launch or for CHF 1,491/kg ($1,667/kg). [15] Thus, to launch a 1-GW SPS into LEO based on the ALPHA-SPS MK-II design would require 88 Falcon Heavy launch vehicles costing approximately $7.5 billion. With an anticipated discount due to placing such a large order with SpaceX or another launch provider with equivalent capabilities, this amount could conceivably be reduced considerably. Estimating the manufacturing costs of the SPS to be in the order of CHF 1.3 billion, and rectenna on Earth to cost CHF 150 million, this puts the realization costs of launching a 1-GW SPS at about CHF 9 billion. Note this cost does not include the transfer from LEO to Geostationary Orbit (GSO) which would require an Orbital Transfer Vehicle (OTV) using either nuclear power or Solar Electrical Propulsion (SEP).

Another recent SPS concept is CASSIOPeiA (Constant Aperture, Solid-State, Integrated, Orbital Phased Array) introduced by Ian Cash of the International Electric Company Ltd. and under development in the U.K. with the participation of the British government. In this concept a 1-GW SPS would have a target mass of 1,348 MT. This obviously reduces the launch requirement to LEO by approximately 73%. Thus, using a Falcon Heavy expendable launcher which could potentially launch a payload of 26,700 kg into a Geosynchronous Transfer Orbit (GTO), launching a 1-GW CASSIOPeiA would require approximately 51 launches. This makes launching directly into GSO potentially feasible and this would avoid a major issue of assembling an SPS in LEO, namely the problem of damage by space debris before or during the transfer of the SPS from LEO into a higher orbit. However, due to the characteristics of the Falcon Heavy payload fairing, this capacity is reduced to just 8,000 kg or 8 MT delivered to 27^0 GTO. Therefore, launching a 1-GW CASSIOPeiA SPS directly into GSO would require approximately 169 Falcon Heavy launches which at today's price would cost CHF 134 million ($150 million) each. This comes to CHF 22.3 billion ($ 25 billion) for the launch alone. [16]

It has been shown that both CASSIOPeiA and SPS-ALPHA-Mk-II concepts could be deployed as multi-satellite systems in lower orbits which is an alternative to the classical concept of placing a SPS in a Geosynchronous or Geostationary orbit (GEO). [17]

The realization costs of these two SPS concepts can be compared with construction costs of a new nuclear power plant in Western Europe. There are two nuclear power plants currently under construction using a third generation EPR design (Evolutionary Power Reactor) which can be used as an actual reference.

> Hinkley Point C nuclear power station – a 3.2 GW facility in Great Britain that is expected to eventually cost £22.5 billion ($29 billion). [18]
>
> Flamanville in Manche, France begun in 2007 – 1.6 GW facility is now expected to eventually cost €12.4 billion ($14 billion). [19]

Hinkley Point C costs = $ 9.01 billion for 1-GW ($29 billion/3.2 = $9.0625 billion)
Flamanville costs = $8.75 billion for 1-GW ($14 billion/1.6 = $8.750 billion)

Using these examples, the average cost per GW to construct a nuclear power plant in Europe is approximately $9 billion. This amount is based on what is referred to as the Engineering, Procurement and Construction costs or EPC. This does not include the cost of fuel, waste disposal, maintenance, nor decommissioning.

John Mankins' SPS-ALPHA Mk-II concept considers the SPS components will be assembled in LEO and then these will be transferred to GEO using either a reusable Orbital Transport Vehicle (OTV) or an integrated ion Solar Electric Propulsion (SEP) system powered by electricity generated by the SPS itself.[20] Based on the latest SPS-ALPHA Mark-II design, Mankins estimates that his 2.1-GW SPS would have an overall mass of 9,192 MT, generating ca. 547,322 GWh over a period of 30 years. With an installed cost of $11.5 billion. In his example the LCoE would be about $0.03 per kWh. [21] This indicates a launch cost of approximately CHF 7.8 billion or CHF 856/kg ($8.8 billion $960/kg) and the cost of the LEO-to-GEO transfer is not indicated.

SpaceX's Falcon Heavy is the largest rocket launcher that is currently operational. SpaceX advertises that its Falcon Heavy Expendable Version has the capacity to place 63.8 tonnes of payload into LEO for CHF 80.25 million ($90 million) which is about CHF 1,257/kg ($1,410/kg). According to a Tweet by Elon Musk (12 February 2018) , the capacity of the Partially Reusable version with two recoverable side boosters and an expendable core would launch 10% less payload or 57 tonnes and would cost CHF 85 million ($95 million). [22] However, due to the characteristics of the Falcon payload fairing, the actual capacity is reduced substantially – probably 20 tonnes or less into LEO. As such, it would take approximately 460 Falcon Heavy launches to place a SPS-ALPHA MK-II into LEO. After assembly it would need to be moved into GEO by some means. According to Ian Cash of CASSIOPeiA, the Falcon payload configuration only allows for 8 tonnes for payloads to be placed directly into GSO and a 2-GW CASSIOPeiA with a mass of 2,045 tonnes would require approximately 256 Falcon Heavy launches. SpaceX's new Starship will be a fully reusable *super heavy launcher* that could place 100 - 156 MT into LEO.

Starship also allows for a launch into LEO and a 'refilling' or a refueling of the rocket with a second launch that would then then take the payload into GEO. This double launch concept - hardware + refilling - is the most interesting launch option available which is expected to be operational by 2023. However, while Starship might make a better economic case, humanity's enormous need for clean energy will require thousands of space power satellites and many thousands of heavy launch vehicles. While this would positively impact the launcher market and would attract other players resulting in lower launch prices, it is questionable that the industrial capacity can be scaled within the next twenty years to satisfy this demand.

Recall, to replace current fossil fuel consumption with nuclear power would require 17,347 new 1-GW nuclear reactors and a similar amount of electricity generating capacity would be required of SBSP. As with the waste disposal problems associated with nuclear power, wind and terrestrial photovoltaics, this many launches would likely create undesirable environmental issues which would surely be used as arguments against such a massive SBSP program leading to public and political resistance. Therefore, alternative approaches to the realization of the Space Energy Option are needed.

7 In Situ Resource Utilization is the Solution

In the mid-1980s, David Criswell introduced a significant variation of the SPS concept called the Lunar Solar Power (LSP) System. Instead of building the photovoltaic system in Earth orbit using materials transported from Earth, he proposed a potentially more efficient approach by using an existing orbiting platform – the Moon – for the location of the solar collectors and the use of lunar materials for their construction. The Moon receives sunlight continuously except during a full lunar eclipse, which occurs approximately once a year and lasts for less than three hours.

The lunar surface receives 13,000 TW of solar power. The LSP System uses 10 to 20 pairs of lunar bases - one of each pair on the eastern edge and the other on the western edge of the Moon, as seen from Earth - to collect approximately 1% of the solar power reaching the lunar surface. In Criswell's plan, each lunar power base consists of tens of thousands of power plots distributed in an elliptical area to form a fully segmented, phased-array radar that is solar-powered and these would be augmented by fields of solar converters located on the back side of the Moon, some 500 to 1,000 km beyond each visible edge and connected to the Earthward power bases by electric transmission lines. Each lunar power base would transfer the solar energy as electric power to microwave generators which would then convert the solar electricity into microwaves of the correct phase and amplitude and then send the microwaves to mirrored reflector satellites in lunar orbit that would reflect microwave beams toward Earth. Relay satellites in high-inclination eccentric Earth orbits would intercept this transmission and retransmit to rectennas located on Earth. [23]

The primary materials necessary for the manufacture of photovoltaic (PV) collectors are silicon, aluminum, and iron which can be chemically extracted from lunar soil. Extra trace elements needed for their manufacture can be brought from Earth or obtained from asteroids. The vacuum environment of the Moon is ideal for applying the completed PV elements to the silicon substrate. The solar energy converters would be thin-filmed photovoltaics made from lunar glass which would be created by using solar concentrators to heat lunar regolith to 2000 C. Robots will mine the lunar soil for silicon and other necessary materials and the photovoltaics would be manufactured in an automated factory constructed for this purpose. In addition to the production of solar cells, additive manufacturing technologies could be used to construct most of the machinery needed to manufacture the solar cells which would significantly reduce the cost of transporting these machines from Earth to the Moon.

In 2005, Criswell estimated that a fully developed LPS system with a capacity of 18 TWe would cost approximately $400-500 billion and this would basically supply the total energy needs of humanity. [24] [25] This would mean that $30 billion per year would be invested and spent over a period of 15 years. This is not an unrealistic sum when considered in the context of the current energy market which is estimated at $21 trillion per year. 18 TW of power capacity would provide 157,680 TWh of energy. Recall that in 2019 total worldwide energy consumption was 162,194 TWh. Given the expected 20% increase in human population between now and the year 2050, up to 30 TW of electrical power may be needed.

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 propellent (Fig.5.). Their plan relies on sending robotic assets to the Moon which are teleoperated from Earth to prospect, demonstrate and produce water from local lunar resources. These robots would be launched separately over several years, allowing the program to be implemented under varied funding conditions. As proposed, this lunar base could be established for an aggregate cost of approximately $88 billion. This total cost included development of a heavy lift (70 MT) launch vehicle ($17 billion), two versions (LEO and translunar) of a Crew Exploration Vehicle (CEV), a reusable lander, cislunar propellant depots and all robotic surface assets, as well as all the operational costs of mission support for this architecture.[26] [27]

Mission	Description	Launch Vehicle	Lander #	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15	Year 16	Total
1	Lunar Communications Satellites	Atlas 401		25	100	175	100													400
2	Characterize Water Deposits	Atlas 551	RML 01, 02	150	350	550	350	200												1600
3	Water Extraction Demo	Atlas 401	RML 03		50	350	250	100												750
4	LEO Fuel Station Phase 1	Atlas 551		100	600	700	550	400	250											2600
5	Water Processor #1	Atlas 551	RHL 001	200	450	600	650	500	420	300										3120
6	Water Tanker	Atlas 401	RML 04				50	150	230	135										565
7	Ore Excavator/Hauler #1	Atlas 551	RHL 002			100	150	350	550	440	200									1790
8	Water Electrolysis #1	Atlas 551	RHL 003				100	250	450	350	150									1300
9	Rover Fueling Tanker	Atlas 401	RML 05					50	150	220	145									565
10	LLO Way Station	Atlas 551					50	100	250	400	205	145								1150
11	LEO Fuel Station Phase 2	Atlas 551							150	430	500	300	170							1550
12	Reusable Water Tank Lander	Heavy Lift	RWTL #1					50	300	475	600	510	350	315						2600
13	Human Power and Logistics Cluste	Heavy Lift	CL 01						100	400	600	700	650	550	450					3450
14	Water Electrolysis #2	Atlas 551	RHL 004								100	145	150	205	125					725
15	Human Habitat #1	Heavy Lift	CL 02								50	350	630	870	900	800				3600
16	Human Lander (reusable)	Heavy Lift	HL 01							100	400	500	800	850	900	950				4500
17	First Human Mission (cost for P/L)	Heavy Lift										25	100	100	100	175				500
18	Ore Excavator/Hauler #2	Atlas 551	RHL 005								50	100	100	100	175	200				725
19	Water Processor #2	Atlas 551	RHL 006							50	100	100	100	150	100	75				675
20	Water Electrolysis #3	Atlas 551	RHL 007											100	100	325	200			725
21	Human Habitat #2	Heavy Lift	CL 03											60	150	375	375			960
22	Human Mission 2	Heavy Lift												50	150	200	100			500
23	Human Mission 3	Heavy Lift													50	150	200	100		500
24	Human Mission 4	Heavy Lift													50	150	200	100		500
25	Unpressurized ISRU Lab	Heavy Lift	CL 04												50	200	600	600	450	1900
26	Human Mission 5	Heavy Lift														50	150	200	100	500
27	Human Mission 6	Heavy Lift															50	150	200	400
28	Human Mission 7	Heavy Lift															50	150	200	400
29	Water Electrolysis #4	Atlas 551	RHL 008														100	150	250	500
30	Water Processor #3	Atlas 551	RHL 009													100	100	200	200	600
31	Ore Excavator/Hauler #3	Atlas 551	RHL 010															50	200	250
																				0
																				0
																				0
																				0
	Heavy Lift Launch Vehicle (includes Ground Systems at KSC)			100	400	1000	1200	1300	1100	1000	1000	1000	1000	1350	1350	1350	1350	1350	1350	17200
	Block 1 CEV			300	600	1200	1200	1000	500											4800
	Block 2 CEV (including TLI Stage)									200	300	425	550	550	500	500	500	500	500	4525
	Cislunar Transfer Stage							100	200	300	300	400	400	300	400	400	400	400	400	4000
	Cagro Lander										100	400	700	700	600	150	150	150	100	3050
	Technology Wedge			2475	1050	225														3750
	Undefined Mission Wedge															0	1625	2050	2200	5875
	JSC Ops Cost for 2 Human Flts/yr			40	40	40	40	40	120	160	240	240	280	320	400	400	400	400	400	3560
	Architecture Integration			10	10	10	10	10	30	40	60	60	70	80	100	100	100	100	100	890
	Totals per year			3400	3650	4950	4700	4600	4800	5000	5100	5400	6050	6650	6650	6650	6650	6650	6650	87150

Figure 5. A 31 Mission Plan to Establish a Lunar Base (Paul Spudis and Tony Lavoie)

Fortunately, in 2021 SpaceX's Falcon Heavy which can potentially launch 63.8 tonnes into LEO is already functional and SpaceX's reusable Dragon 2 spacecraft has the capacity to carrying up to seven astronauts into orbit. A four-person private all-civilian mission using the Falcon 9 rocket and the Dragon capsule is planned for the end of 2021. [28] A commercially available Falcon Heavy launcher and Dragon 2 spacecraft represents approximately 30% reduction of the development cost of the Spudis and Lavoie scenario when inserted into their concept for lunar production facility which can be used as an example for creating a manufacturing facility for solar power elements.

Using the SPS-ALPHA concept as an example, in 2016 Justin Lewis-Weber proposed that the photovoltaic power generation system would be constructed from an extremely larger number of small modular PV elements that would be manufactured in an automated factory on the Moon. [29] The key to his concept is the use of self-replicating systems (SRS's) which are small machines that would replicate themselves from lunar materials to build the factory instead of launching it from Earth. The Moon is an excellent construction site and lunar materials are ideal for use in constructing mechanical SRSs for three reasons: (1) its direct elemental composition, (2) its relatively uniform composition, and (3) ease of mining its top regolith layer (5–15 m).

This approach would result in the following benefits:

- a reduction in up-front costs by several orders of magnitude

- practically unlimited production potential with capacity increasing exponentially over time
- practically zero runtime or production cost (as space materials are free and there would be no astronauts on the Moon)
- dramatically increased adaptability to future challenges or production

For this design to work, the SSP components should be a simple as possible in terms of size and number, and they would be modular elements that would self-assemble in orbit which has been the approach to the SPS-ALPHA being developed by John Mankins which consists of these eight modular components:

1. Hexbus - basic smallsat structural unit
2. Interconnect - smallsat to bind structural components
3. Hexframe - simple deployable beams that provide the base structure for the reflectors and connect the reflector array to the power/transmitter array
4. Reflectors and Deployment Module
5. Solar Power Generation Module
6. WPT Module
7. Modular Push-Me/Pull-You Robotic Arms - used for self-construction
8. Propulsion/Attitude Control Module

The approach by Lewis-Weber consists of:

1. The SSP components will be manufactured on the Moon by means of an SRS
2. The SSP components will be launched from the lunar surface into geostationary Earth orbit by means of an electromagnetic linear accelerator or Mass Driver
3. The SSP components will self-assemble in GEO
4. The SSP will wirelessly transmit the captured energy to stations on the ground
5. Rectenna stations near population centers on Earth will receive the power and integrate it with local energy grids

While it must be acknowledged that such a Self-Replicating System does not yet exist, terrestrial scale automatic manufacturing systems do exist. Lewis-Weber estimates that the R&D cost of such a system would be on the order of $5-10 billion. Significantly, this approach would mitigate most of the cost to manufacture and launch a SPS from the surface of Earth. Recall that $10 billion is the cost to construct a 1-GW nuclear power plant and/or to build and launch a 1-GW SPS.

8 The Greater Earth Lunar Power Station

The GE⊕-LPS concept builds on the aforementioned in situ resource utilization (ISRU) approaches and adds a human element to the discussion. For space development to be successful it needs to incorporate a cultural dimension by involving the public in these endeavors. Space agencies have realized this factor and most major space missions now have programs which invite the participation of a broad segment of public. In addition to television and social media sharing the excitement of space missions with the general public, students are often given the opportunity to suggest names for missions and spacecraft, and to make essays and art works. This makes space development both relevant and inspirational.

The GE⊕-LPS is a habitable space station in lunar orbit that, in this initial iteration, is primarily designed to provide solar energy for lunar operations and, as such, could serve as a prototype for larger SPS stations in Earth orbit and even space settlement scenarios. Most SPS concepts consist of very large structures due to the fact that much surface area is needed to capture sufficient solar power in order to transmit significant levels of energy to some distant destination. A rotating toroidal space station is a classical approach to space habitat design because it can provide the occupants with artificial gravity which is important to long term periods in the space environment. Also an important criteria for a space habitat is radiation protection and this is satisfied by constructing the GE⊕-LPS with lunarcrete which has been mined and processed from lunar regolith together with a water barrier.

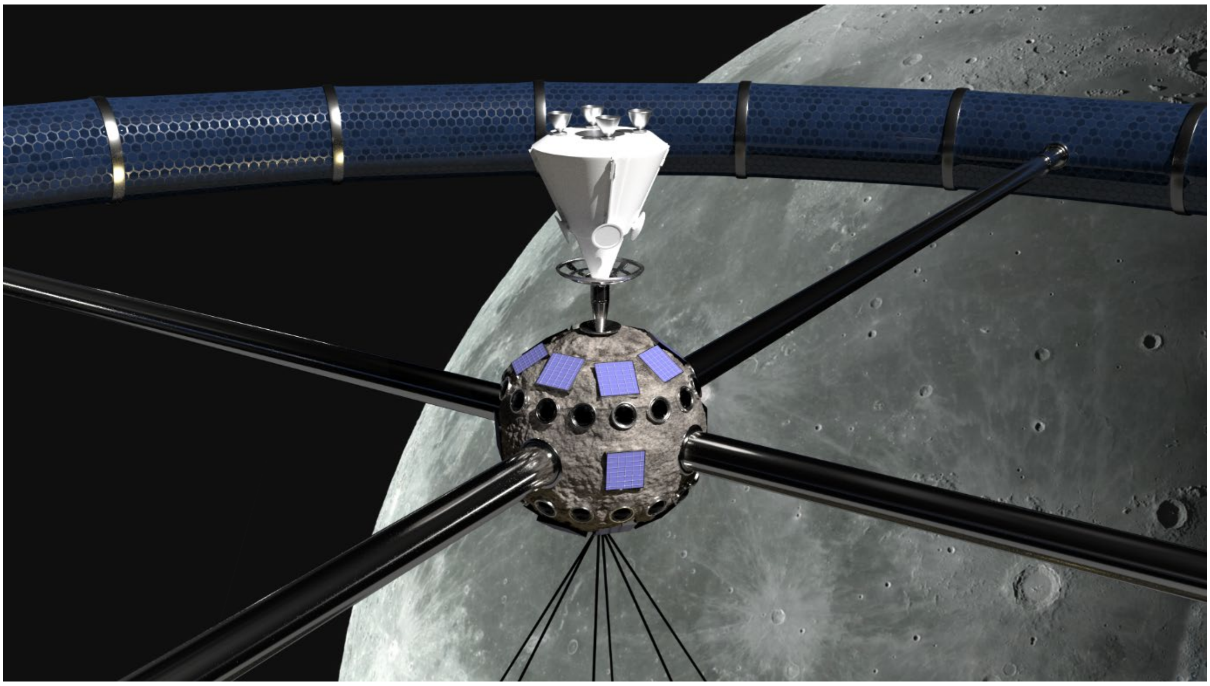

Figure 6. A Lunar Lander Docked to the Station Central Habitat of the GE⨁-LPS

First, the central habitation module of the GE⨁-LPS would be constructed in a modular manner and sent into orbit for assembly. First, using industrial 3D additive manufacturing techniques, a lightweight geometrical spherical structure – either an icosahedron or a geodesic polyhedron - would be built from metals such as aluminum obtained from lunar resource processing and sent into orbit.

The outer surface of the habitat would be covered with matching interlocking elements made from "lunarcrete" produced in a lunar factory designed for this purpose.[30] Lunarcrete would be manufactured by beneficiating lunar rock that has a high calcium content. Water would either be supplied from sources on the Moon, or by combining oxygen with hydrogen produced from lunar soil. [31] When completed the outer surface of the habitat would consist of layers of "lunarcrete" modules which, together with an interior water barrier, also extracted from the Moon, would provide the necessary radiation shielding for the habitat. Once the initial structure was completed and sealed, interior components would be integrated. The habitat module would become the central basis of the GE⨁-LPS. Additive manufacturing methods would also apply to the construction of the four main spokes of the station. Making lunar glass by melting regolith can produce building materials of extreme strength and durability; anhydrous glass made from lunar soil would be stronger than alloy steel, with a fraction of its mass. Asteroid capture may be required to supply additional materials and minerals not found on the Moon and/or needed materials may be obtained from Earth.

Likewise, the individual segments of the outer torus would be constructed using modular lunarcrete elements. This would extend the radiation protected habitable area of the GE⨁-LPS to the outer torus enabling useful artificial gravity for the crew and visitors and more living and working space. Whereas the central habitat module with its enhanced radiation protection would serve as a safe refuge in the event of a coronal mass ejection (CME) or other higher radiation event. The radiation protection also protects the crew from energy leakage from the generation of electricity the main task of the GE⨁-LPS.

The finished station elements would be sent into lunar orbit via an electromagnetic linear accelerator or a "Mass Driver" where they will be assembled into the toroidal elements of the GE⨁-LPS. The lunar mass driver concept was proposed in 1970s by American physicist Gerard O'Neill and his colleagues as a means of launching material from the lunar surface with the goal to build large orbital space colonies. Mass driver technology also has been researched and tested and used to launch fighter jets from aircraft carriers. A lunar mass driver several kilometers long should be able to deliver 600,000 tons a year to L-5, or more easily to L-2, at a reasonable cost. NASA has indicated the Moon's L1 and L2 libration points (Lagrange points) would be ideal locations to receive to assemble large space structures. [32]

An alternative to the mass-driver could be a Lunar Space Elevator, anchored on the lunar surface and connecting to the Earth-Moon L1 or L2. points Unlike earth-anchored space elevators, the materials for lunar space elevators will not require a lot of strength. Lunar elevators can be made with materials available today as carbon nanotubes are not required to build the structure. A lunar space elevator could significantly reduce the costs and improve reliability of soft-landing equipment on the lunar surface. 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. [33] [34] [35] [36]

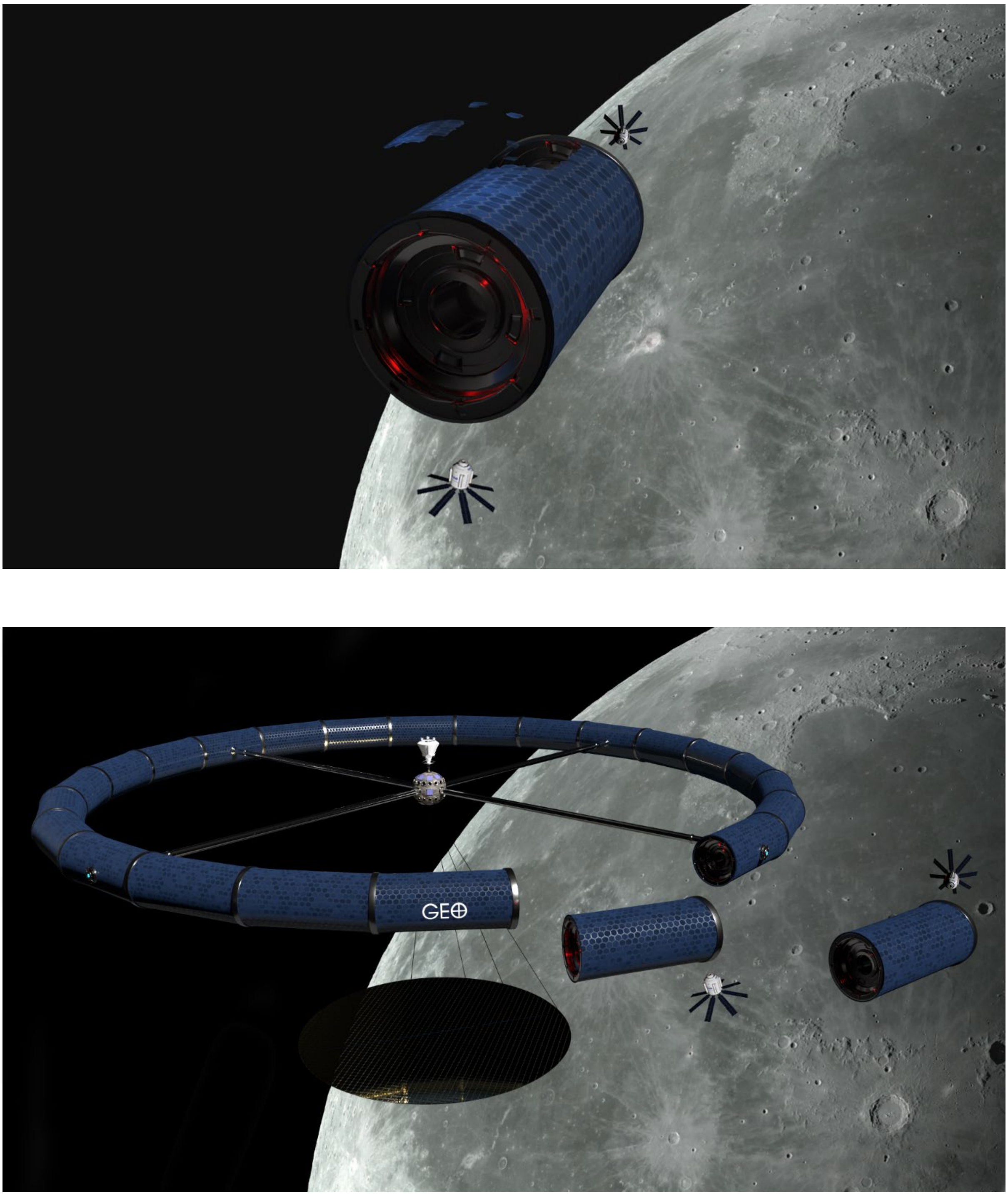

Figure 7. Assembly of the GE⊕-LPS in Lunar Orbit.

The basic technology for mass producing manufacturing photovoltaics already exists and the engineering aspects of doing this on the Moon are typical of major construction and manufacturing techniques used on Earth. Thanks to Apollo, there exists substantial information about the lunar environment. The photovoltaic modular elements produced in an automated factory on the Moon, will then be automatically assembled into the pre-programmed system onto the supporting toroidal elements. These elements would be inter-locking and their electronics would be automatically integrated into the toroidal segment. As each toroidal segment is finished it will dock with the previously completed sections until the torus is completed.

Once the torus structure has been completed and the photovoltaic power elements are activated, the electrical power will be fed to the four ion electrical propulsion units positioned equidistantly along the torus. These moveable thrusters will maintain the precise rotational spin and attitude control of the GE⊕-LPS while also providing thrust for transferring the GE⊕-LPS to other orbital locations. As the Moon is within Earth's Hill Sphere and the presence of mass concentrations or "mascons" below the lunar surface, lunar orbits are inherently unstable and constant orbital attitude adjustments will be required. The rotation will enable a centrifugal artificial gravitational environment for the habitat which will provide comfort and health attributes to the residents, workers, and tourists by providing adaptation to either lunar-G or Earth-G environments.

Figure 8. Four (ESP) ion thrusters for rotation, attitude control and maneuverability.

9 The Human Element

In addition to persuasive economic drivers, for space development to be ultimately successful it also needs powerful inspirational messages. Integrating a human element in the design of the GE⊕-LPS combines these two factors. The GE⊕-LPS is not only a machine supplying needed energy for lunar activities but it also a tourist destination, a vantage point, a way station, a refuge, an outpost, a base of operations and, most importantly – a space settlement. As such, this represents an additional revenue stream for its operators.

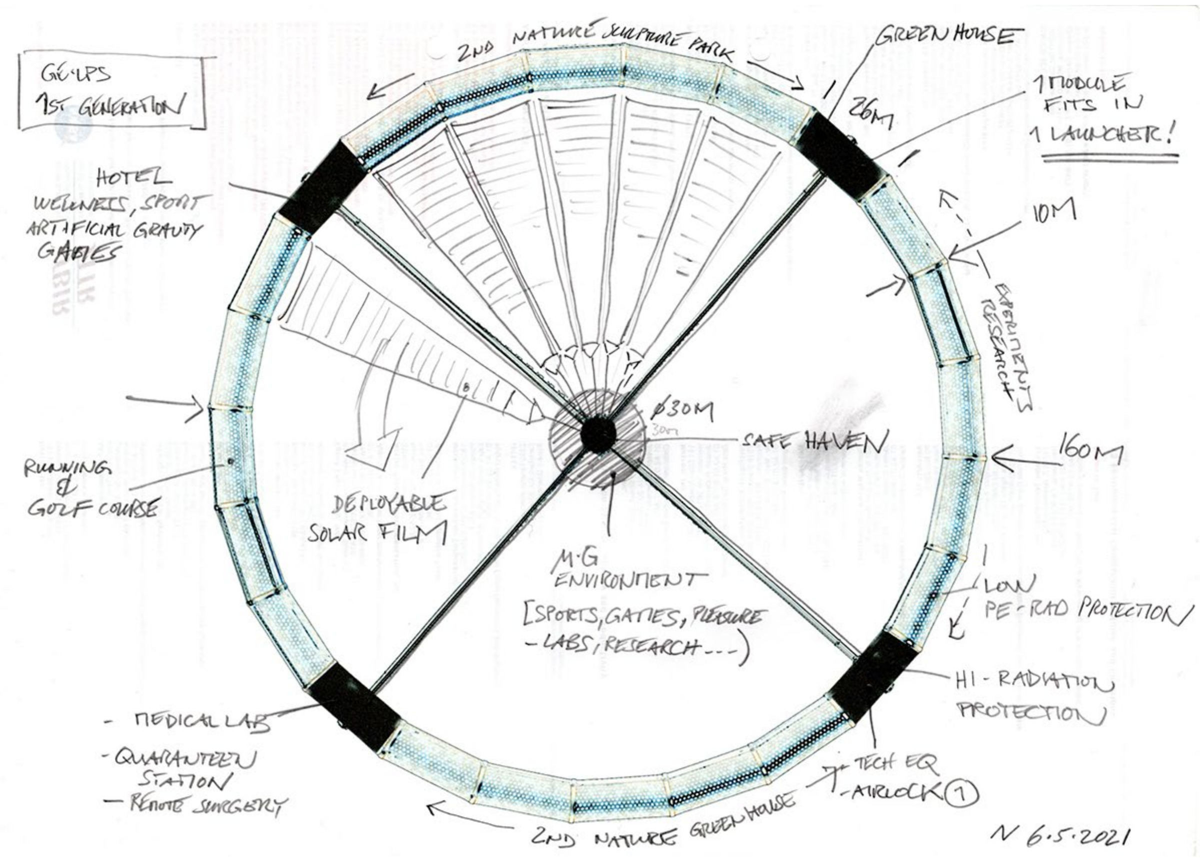

Figure 9. Brainstorming sketch by Andreas Vogler (not to scale)

In pre-Corona society, the evolution of air travel reached over 4 billion passengers a year and created a major industry employing millions of people. Space tourism was inaugurated with the first space tourists paying $20-30 million to visit the ISS. Sub-orbital tourism is poised to kick-off in 2021 with hundreds of passengers having paid $200,000 or more for a brief trip to the edge of space. The first orbital tourist mission has been announced by Space-X and is scheduled to take place before the end of 2012. Several private space operators are developing space tourist operations including high altitude balloon flights and orbital flights. Private flights to orbit the Moon have been offered at $150 million by Russian and American launch providers. Once these space tourism endeavors mature and new opportunities appear and the prices decrease, space tourism could follow the path of terrestrial tourism and become a major source of revenue for space development.

The process of building a habitable GE⊕-LPS creates an Earth-Moon economic case that can be the first step in establishing a two-planet economy. This human factor opens the project to direct participation by a large public, not only as potential tourists but also as investors. A regularly scheduled global lottery "Fly Me to the Moon" could be held which would make a trip to the GE⊕-LPS available to practically anyone on Earth and this would be a source of revenue as well. As the GE⊕-LPS concept could be scaled to larger dimensions, it also connects the promise of space development - in this case energy production – to address energy, environmental and climate issues on Earth.

Figure 10. Moon Village Association Webinar: Fly Me to the Moon

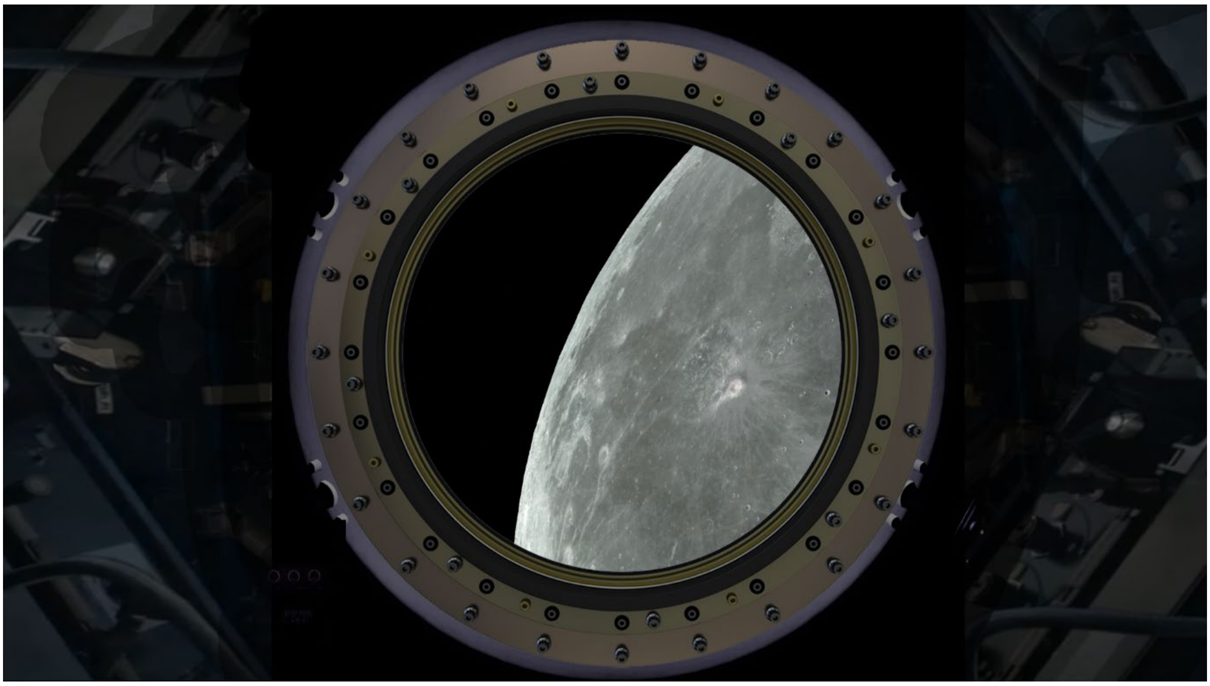

Figure 11. View of the Moon from inside the GE⊕ Lunar Power Station

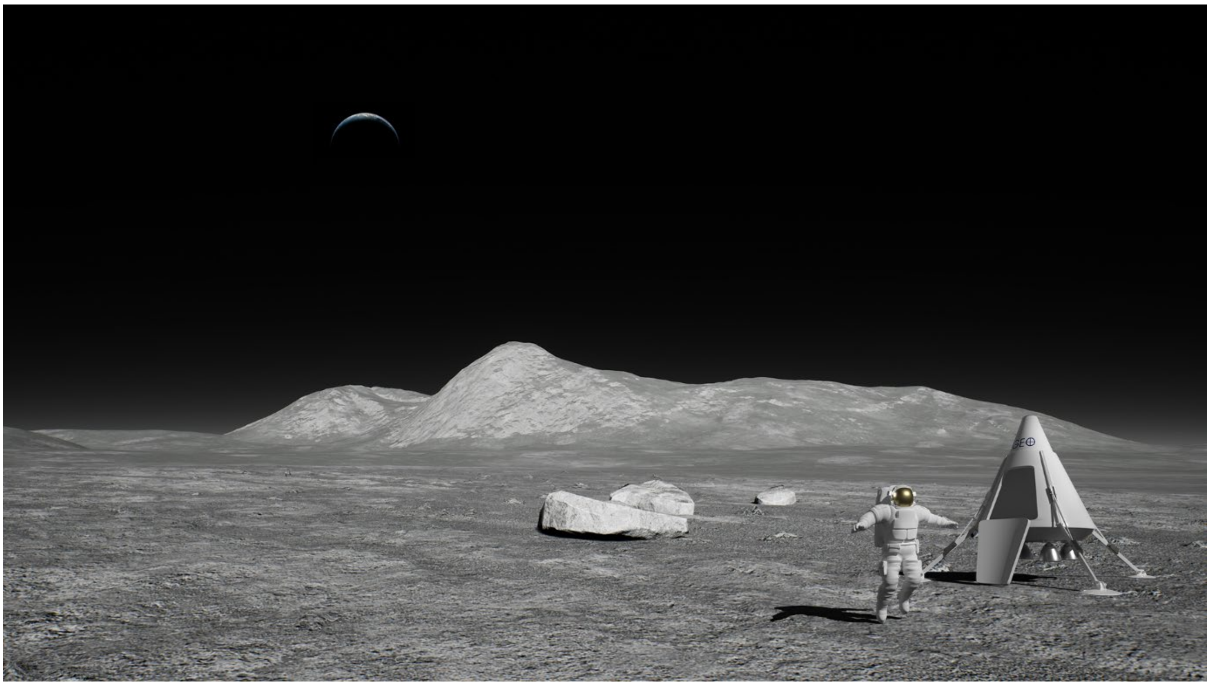

Figure 12. Lunar Tourist Excursion

10 Summary and Conclusions

Embracing the concept of Greater Earth as a new perception of our planet and understanding this as a dynamic system would be a viable strategy for merging the environmental and ecological movements with the economic goals and visions of the space community. Occupying the regions of Greater Earth including the Moon and Geolunar space is essential to the future of civilization.

Addressing the *Energy Dilemma* will require massive amounts of clean energy production for restoring the environment and meeting the energy needs of a growing population. Addressing the *Climate Emergency* will require massive amounts of clean energy production to adapt and survive a severe warming or cooling situation. Having sufficient energy would also allow our species to solve the water crisis, create new transportation fuels, reduce poverty, stimulate progress in the developing countries, sustain the world economy and to end conflict over finite energy resources.

Space tourism and energy from space are considered as main economic drivers for future space development. Tourism connects space development to the dreams of spaceflight shared by much of the human population. Energy is the largest market on Earth with an annual value of $21 trillion. Harvesting inexhaustible energy in space and equally distributing it to all people of all nations would enable the entire population of Earth to have a prosperous and hopeful future. This is in contrast with 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. Utilizing lunar resources and lunar manufacturing facilities to build the solar power satellites would contribute to making SBSP more economically feasible and thus a reality for humanity.

Thus, the GE⊕ Lunar Power Station serves two critical and practical purposes: 1. it is a novel and viable technical approach to realizing the Space Energy Option addressing the urgent energy dilemma and climate emergency issues on Earth and, 2. it provides an inspiring and practical space facility for developing humanity's lunar aspirations. Indeed, humanity's future on Earth is irrevocably linked to its future on the Moon.

11 About the Authors

Arthur R. Woods is an independent researcher and astronautical artist with two art projects successfully flown on the Russian Mir space station: the Cosmic Dancer in 1993 and Ars Ad Astra in 1995 in the context of

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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.

Andreas Vogler is a Swiss architect and director of Andreas Vogler Studio. He worked in London, TU Munich, TU Delft and as a Guest Professor at The Royal Academy of Fine Arts in Copenhagen, researching on prefabricated buildings, light weight construction and space architecture. In 1999 he did parabolic test flights with NASA Houston. In 2003 he co-founded 'Architecture and Vision', working in the fields of aerospace, art and architecture. His studio work in architecture, transportation design and robotics. Space projects include habitats and manned rovers for Moon and Mars as well as inflatables. His works are included in the permanent collections of the Museum of Modern Art MoMA, New York and the Museum of Science and Industry, Chicago.

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ACRONYMS

BP	British Petroleum
CEV	Crew Exploration Vehicle
CHF	Swiss francs
CME	Coronal Mass Ejection
EJ	Exajoule
EPC	Engineering, Procurement and Construction
EPR	Evolutionary Power Reactor
GEO	Geostationary Orbit
GSO	Geosynchronous Orbit
GTO	Geo Transfer Orbit
GW	Gigawatt
GWh	Gigawatt-hours
kg	kilogram
kWh	Kilowatt-hours

IAA	International Academy of Astronautics
IPCC	Intergovernmental Panel on Climate Change
L1,L2	Lagrange Point 1 & 2
LCoE	Levelized Cost of Electricity
LEO	Low Earth Orbit
LPS	Lunar Power System
MT	Metric Tonne
OTV	Orbital Transfer Vehicle
PV	Photovoltaic
SEP	Solar Electric Propulsion
SBSP	Space-Based Solar Power
SPS	Solar Power Satellite
SRS	Self-Replicating System
TW	Terawatt
TWh	Terawatt-hours

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