Research Article

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Moon-Earth: Prospects for a lunar-centric scenario for space development after 2030

Abstract

Gerard K. O'Neill's idea of large habitats built from outer space resources in his 1974 Physics Today article "The Colonization of Space" resulted in a flurry of speculation and research and development work aimed at use of lunar resources to build large-scale solar-power satellites (SPS) to generate revenue to pay for space colonization. As the enormity of the technical and financial challenges to achieve space colonization became apparent, research interest began to wane with declining funding that came with the realization that the U.S. had reached the Moon before the USSR, removed the drive to achieve more. Nixon canceled Apollo Missions after 1972. As the U.S. faced the Oil Embargo and growing domestic concerns NASA fought to retain its budget, develop the Space Shuttle and the International Space Station (ISS). Now after decades of technology development and much greater knowledge of lunar resources conditions have been created where a lunar centric model of space development appears increasingly feasible offering the possibility of not only more rapid development in outer space, but also to impact long term sustainable development on Earth by reducing the need for terrestrial resources for industrial development in Earth orbits, cislunar space and the Moon. In effect, lunar industrial development can contribute increasingly to achieve sustainable development on Earth. This, however, will raise challenges to address governance of space traffic and of resource access and use on the Moon. Unlike 1974 many countries are developing the capacity to reach and operate in cislunar space and on the Moon.

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Introduction

Until NASA's Artemis program gained support in the U.S. and growing support among western-friendly governments the Moon was not a widely accepted destination for space exploration and associated development. The Mars Society and later Elon Musk saw little need to invest in lunar exploration and development. Decades earlier Gerard K. O'Neill had advocated mining the Moon to build large space habitats from lunar resources which activity would be paid for by space-based solar power (SBSP) in geosynchronous orbit, which would also have been largely built using lunar resources. O'Neill's vision proved too large to finance in the late 1970s with then available technologies. By 2011 asteroid mining started gaining attention with visions of trillion-dollar asteroids like Psyche grabbing interest at ISDC and other space activist conferences refocused attention on the potential of space resources. President Obama chose to challenge NASA with Mars and bypassing the Moon in his 2011 address to NASA staff by 2015 he signed the Space Act that declared that under U.S. law space resources could be sold after extraction. SPSB was also starting to attract attention from John Mankins who demonstrated that lower cost power-sats could be robotically assembled from identical small modules thereby significantly lowering assembly costs. Mankins largely ignored lunar resources and saw the feasibility of SBSP with components launched from the Earth and assembled in orbit.[1]

Key assumptions of lunar-centric space development:[1]

i. The Moon is the low-cost site for materials for space manufacturing. Many important materials are on or near the surface, and the vacuum and fractional gravity of the Moon promises launch costs from the Moon that are a fraction of launch from Earth.

ii. Military / national security needs drive initial technology development notably the DARPA NOM4D program.

iii. Sustaining drivers of orbital industrial development are needs for sustainable development of Earth with an emphasis on SPSB for Earth and in-space energy needs, and space tourism evolving into space settlement as increasingly large habitats become permanent residences for increasing numbers of people.

iv. Lunar industrial development can make important contributions to developments in Mars orbit. The delta-v of shipment to Mars orbit from the lunar surface is less than launch from Mars. Industrial development in Mars orbit using lunar materials can lower costs and improve effectiveness of operations on Mars.

v. It will become increasingly urgent to limit launch of spacecraft to LEO from Earth as congestion from satellite mega constellations increases and suborbital intercontinental transportation takes off following the model proposed by Elon Musk.

vi. Climate change is a threat to all countries and urgent action is called for to limit or eliminate large scale resource extraction on Earth, as well as to limit launches through the atmosphere.

vii. Billionaires can speed up development but international cooperation is critically needed to demonstrate the feasibility of self-sustaining lunar industrial development.

viii. A framework that encourages strong international cooperation in space exploration and development for the benefit of humankind and the protection of our planet and its biosphere is necessary.

These assumptions could drive the creation of a financial model that would permit the calculation of the size of the space economy by 2050 given these assumptions. Alternative scenarios where these assumptions are not widely accepted, could range from collapse of industrial civilization to a range of rates of growth of the space economy based on orbital services and continuance of space exploration. The tragedy of the time horizon continues to limit investment in space development. Widely accepted forecasts show a space economy somewhat larger than $1 trillion by 2040. Given breakthroughs in the use of lunar resources to build large space structures in Earth orbits and cislunar space creation of a $10 trillion space economy becomes thinkable beyond 2040 given sufficient international cooperation and agreement on space traffic management and access to space resources and rules for their extraction and use.

Manufacturing and assembly of large structures in space

A space resources-based space economy depends on breakthroughs to economically build large structures in Earth orbit and cislunar space which can lead to large-scale industrial and commercial development in Earth orbits, cislunar space and the Mars orbits.

Construction of ISS required more than $150 billion investment over more than a decade.[2] A Lessons have been learned in the process of constructing ISS, however continuing to launch large extremely costly assemblies to space dramatically limits what could be built to what can be launched with existing spacecraft. John Mankins proposed a space manufacturing solution to dramatically lower costs for SBSP. Such approaches with robotic assembly of large numbers of identical components offers a way forward for antenna and solar collector arrays in Earth orbit. The DARPA NOM4D programs is aimed at more general solutions which could include assembly from Earth or lunar launched materials and components, as well as new materials and assembly processes.[3]

Distinct from DARPA is the work of private industry notably Orbital Assembly, which has developed assembly techniques that promise dramatically lower costs for orbital assembly. Orbital Assembly was recently renamed Above: Space and has proposed to construct a large space hotel by 2027.[4]

Advantages of assembling large structures components in space

Structures launched to space are limited by maximum weight, physical size that fits within the space faring and preparation of payloads for the stresses of space launch. By assembling large structures in space from small, highly standard components the end-assembly can be arbitrarily large and final testing can be done in orbit significantly lowering the risks and costs of large satellite launch. Assemblies as large or larger than ISIS can be assembled in orbit. Novel approaches such as Al Globus's "Space Settlement: an Easier Way"[5] look to building structures larger than ISS faster and at relatively low cost.

Technologies required for manufacturing and assembly in space

DARPA's NOM4D program contract awards address key enabling technologies to enable construction and assembly of large structures in space.[6] Bill Carter summarized the design philosophy "space systems are built off-Earth using designs optimized for the space environment, shedding launch constraints. This would enable enhanced capability, improved robustness, operation in higher orbits, and future cislunar applications."

These materials technology improvements coupled with advances in autonomous robotic assembly has the potential to dramatically lower the cost of antenna arrays and large-scale SBSP.

Importance of SPSB to development of lunar-centric space resources economy

While Gerard K. O'Neill saw SBSP as the funding mechanism for space settlement climate change and the present global energy crisis demand rapid reduction in carbon emissions yet with increasing per-capita energy use as development continues. China, UK, India, Japan, the EU and ESA have active SBSP programs. There are compelling applications for SBSP particularly for disaster relief where power could be beam to rectennas on aerostats to power large cities whose power has been cut-off due to natural disasters which are forecast to rise in frequency and intensity with climate change. Losses in trillions of dollars are expected in coming decades where SBSP could play a major role to provide electricity to millions facing prolonged power interruptions. Remote military sites are also a prime application of beamed power from space where terrestrial solar may be at a disadvantage. Amory Lovins, an advocate for decentralized terrestrial solar power views SBSP as of limited as costs for terrestrial continue to decline and decentralized power generation with energy storage fills more and more needs suggesting a more limited outlook for power beaming to Earth. Power needs for in space manufacturing, lunar industrial development and large space habitats could be met through SBSPs scaled for the purpose.

Lunar resources and materials

Ian Crawford has demonstrated the availability of many materials required to build large structures in space on the Moon starting with basalt in regolith in equatorial zones and anorthosite in highland zones suitable for the production of e-glass. Other industrially useful concentrations of many metals and oxygen are widely available.[7] The challenge will be to lower the cost of extraction and to build large-scale space launch capabilities for manufacturing materials launched to Earth orbit and eventually Mars orbit to build large space structures in those areas. A very important resource of the Moon are its great advantages for research in multiple disciplines. Astronomy stands out as a discipline likely to emerge as a driver for lunar exploration and development including of large structures on the lunar surface or in deep craters shielded from solar radiation favoring infra-red astronomy. The lunar far side, that is always facing away from radio frequency signals from Earth, may be a uniquely advantaged location for radio astronomy in the Solar System as described by professor Crawford in his recent article. Building telescopes on the Moon could transform astronomy – and it's becoming an achievable goal.

Advantages of using the Moon as a low-cost site for materials for space manufacturing

Since the Moon has 1/6 the gravity of Earth and has no atmosphere many launch technologies can work there that require much less energy than launch from Earth. In the 1970s O'Neill proposed mass drivers. Heinlein in his 1966 novel The Moon is a Harsh Mistress[8] proposed catapults to launch cargo to Earth. Michael Turner proposed use of slings made from basalt fibre produced from lunar regolith as a low lost solution to deliver cargo from the lunar surface to LEO.[9] Notable about Turner's concept is his emphasis on orbital assembly and manufacturing as a key market for lunar resources. Basalt fiber is very strong, light weight and has excellent thermal barrier properties leading to it being the material of choice for the USSR for intercontinental ballistic missile nose cones. Basalt fiber is highly versatile material, widely available in lunar regolith across the lunar surface, with the potential to emerge as a structural material for large structures to be built in Earth or lunar or Martian orbits. Anorthosite, which is also widely available in surface regolith inf lunar polar regions can be used to produce e-glass, a fiberglass material suitable for building light and strong structures.[10]

Lunar industrial development can enable sustainable development on Earth with a large human population increasingly drawn to space settlement as climate change disasters increase in frequency and intensity. Extractive industries on Earth need to be restricted to sustainable limits as climate change coupled with the growing stresses from a large human population with high standards of living amplify environmental stresses as sustainable development goals are met for increasing numbers of people (Figure 1).

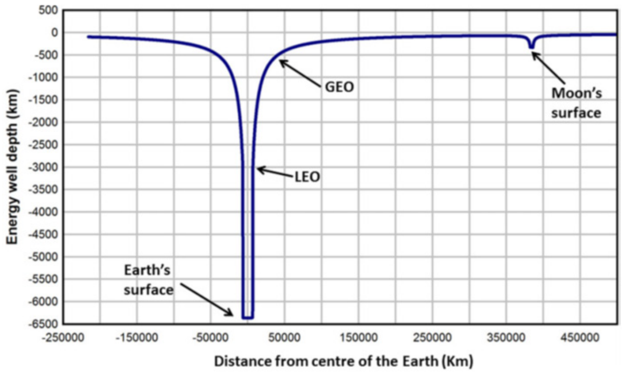

Figure 1 The diagram represents the energy well of the Earth relative to that of the Moon.

The delta-v from the lunar surface to LEO and other Earth orbits is less than from Earth with an even greater advantage for lunar materials and lunar materials processing. The same is true relative to launch from the Moon to Mars orbits. Similar calculations work for water sourced from deep lunar craters per the Commercial Lunar Propellant Architecture study.[11] Far more energy is required to launch from Earth with its dense atmosphere than from the 1/6 gravity and vacuum at the lunar surface (Figure 2).

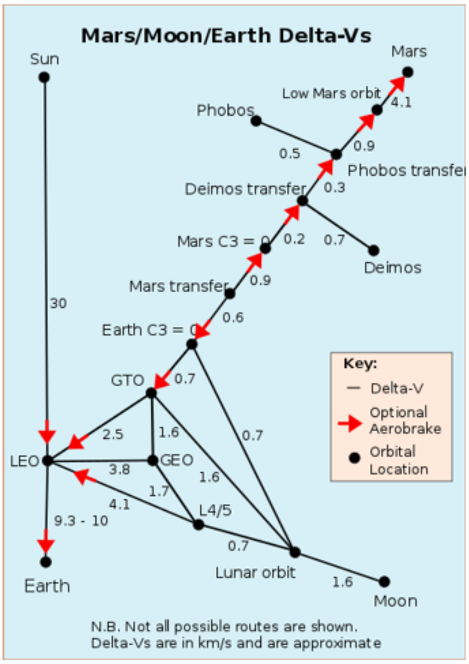

Figure 2 Mars/Moon/Earth Delta- Vs.

Delta-v symbolized as Δv as used in spacecraft flight dynamics, is a measure of the impulse per unit of spacecraft mass that is needed to perform a maneuver such as launching from or landing on a planet or moon. The delta-v from the lunar surface to Mars orbit is less than from the surface of Mars. While delivering payloads from the Moon to Mars orbit would take considerable time, if lunar industry has developed to meet demand from Earth orbital and cislunar industrial and commercial facilities meeting the additional needs of developing industrial capacity to serve needs of relatively small numbers of settlers on the Mars surface might be better met from manufacturing and assembly operations in Mars orbit using lunar materials than attempting to launch from Earth or building materials processing and manufacturing on the Martial surface.

Industrial development in Mars orbit could significantly lower the cost of Mars settlement by building habitats in orbit for people as well as locating engineering and assembly operations for equipment to be used on the Martian surface in orbit. Additionally, positioning satellites, communications satellites, computer server farms to serve needs in orbit as well as on the surface could be constructed in orbit from lunar materials since the Delta V from the lunar surface to Mars is less than from the Martian surface to Mars orbit. Well-developed industrial operations on the Moon could play a significant role in the settlement of Mars.

Importance of lowering costs and improving effectiveness of operations on Mars

If we accept that settlement of Mars is necessary, then any means to decrease what is shipped to Martian surface will carry benefits. Habitants in orbit as well as manufacturing facilities and possibly agricultural operations could lower the costs of settling and operating on Mars. Food for settlers could potentially be grown in orbital facilities at lower cost than on the surface where soils with perchlorates in the surface would eliminate to growth of plants such as potatoes commonly consumed by humans.[12]

Need to limit launches to LEO from Earth

Building large structures in Earth orbits could require thousands of launches. If materials with similar functional properties can be launched from the Moon to Earth orbits there will be increasing advantages to do so. Launch from the Moon would avoid the tyranny of the space faring due to the vacuum on the lunar surface. The cadence of launches from Earth to LEO is already rapidly increasing even though structures larger than ISS are not yet being constructed in Earth orbits. If large structures are to be built in Earth orbits the rate of launches could be orders of magnitude higher unless needed materials can be sourced from the Moon.

Limiting launches to LEO from Earth is becoming an urgent issue. Tipping points associated with climate change and with space traffic management and space debris suggest that if material can be shipped to Earth-orbits from the Moon or NEOs much of the launch activity could be reduced ultimately launching only people and payloads that can only be sourced from Earth.

The growth of suborbital intercontinental transportation may increase the urgency of reducing launches to LEO through the atmosphere. There is also growing urgency to limit large scale resource extraction on Earth due to climate change and the need to meet UN Sustainable Development Goals including improvements in the quality of life of all people. If material can be mined on the Moon or asteroids and shipped to orbital industries that will become increasingly attractive.

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Evolution of space tourism to space settlement

Space hotels as proposed by Above:Orbit could become very attractive if launch-to-LEO costs could reach $100/kg which at present appears thinkable. The proposed hotel has over 400 rooms but is not likely to be favored for permanent residency. Larger size and greater diversity of interiors would be favored for permanent residency. There is a substantial share of the population that could afford to finance a residence in a space habitat and whose work could be neutral as to location or even favor a location in outer space. Additionally, medical conditions may favor locating where gravity is less than 1 g. Long-term financing with 100-year mortgages may be affordable to a sufficiently large number of people that mortgage financing could emerge as an important way to finance space settlement.

Rules based governance of use of lunar resources

At present rules for the exploitation of lunar resources have not been established. An attempt was made in the 1970s to negotiate the Moon Treaty to establish a basis for internationally agreed rules for the use of lunar and other cosmic resources. Under the leadership of Neil Hosenball, NASA General Counsel, the text of the Moon Treaty was finally agreed to by UN COPUOS and approved by UNGA in December 1979.[13] Unfortunately, the U.S. Senate failed to ratify the treaty that the U.S. had championed for nearly a decade. While a small number of states became parties to the Treaty, the fact that the U.S. did not ratify resulted in the cessation of progress on internationally accepted policies for the use of outer space resources. By 2015 interest in the use of space resources was elevated by acceptance of the possibility of asteroid mining. The informal Hague Working Group on Space Resources was established which submitted its reports to COPUOS, but these had no legal force. Finally in 2023 the UN COPUOS Working Group on the Legal Aspects of Space Resources[14] [15]was established with a five year mission to develop a document that could be adopted by COPUOS and recommended for approval by UNGA. Whether this Working Group will be more successful is unclear due to the emergence of power blocs[16] with differing interests in outer space. Dennis O'Brien's review of the work presently underway by the Working Group recognizes the forces at play suggesting that there is a basis for optimism for the development of rules to govern access to and use of lunar resources.[17]

There is an emerging security dilemma in cislunar space with the potential for conflict or competition to arise among different actors operating in or around the Moon.[18] This could include government agencies, private companies, or other entities with interests in lunar resources or access to space. The impact of the security dilemma on a lunar-centric space development strategy could be significant. Here are a few potential scenarios:

Resource competition: As lunar resources become more valuable and in demand, different actors may compete for access to those resources. This could create tension and potentially lead to conflict, as each actor seeks to secure their own access to resources.

i. Military competition: As different countries or private companies establish a presence on the Moon, there is potential for military competition to arise. This could involve efforts to establish military bases or weapons systems on the Moon, or to gain strategic advantage over other actors.

ii. Regulatory disputes: As different actors operate in cislunar space, there may be disagreements over regulations and legal frameworks. This could involve disputes over ownership of resources, liability for accidents or damage, or other legal issues.

These scenarios could impact a lunar-centric space development strategy in a number of ways. For example:

i. Increased competition for resources could make it more difficult for companies or governments to secure the materials they need to advance their space development goals.

ii. Military competition could create instability and potential conflict, making it more difficult for actors to operate safely in cislunar space.

iii. Regulatory disputes could create uncertainty and unpredictability, making it harder for companies or governments to plan and invest in space development.

iv. To address the security dilemma in cislunar space, it will be important for actors to work collaboratively and establish clear regulations and legal frameworks for lunar activity. This could involve diplomatic efforts to establish norms of behavior, as well as regulatory frameworks that address issues like resource ownership and liability. Ultimately, a collaborative approach to lunar development is likely to be more sustainable and effective than one characterized by competition and conflict.

Conclusion

Lunar-centric space development can accelerate progress and make space settlement feasible earlier in large habitats inspired by Gerard K. O'Neill's vision.

Without internationally agreed rules broad international cooperation towards industrial development of the Moon cannot emerge and progress would be limited.

Acknowledgments

Neil Hosenball, NASA General Counsel who negotiated the Moon Treaty on behalf of the United States created an instrument that was misunderstood by space advocates and many in the space industry that may yet emerge as the key to enable the development of the governance necessary for industrial development of the Moon. https://iisl.space/s-neil-hosenball-1925-2009/

Conflicts of interest

The author declares that there is no conflict of interest.

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