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Inhabiting Space: A journey towards human settlements outside the Earth

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Abstract

Historically, inhabiting other planets has been a topic of fascination and scientific inquiry. There are numerous challenges the human race would face in this eventuality, but this quest also entails opportunities for exploration, cutting-edge scientific testing and discovery, and resource exploitation. The first attempts have been made possible thanks to the International Space Station, which has provided space agencies with a wealth of data to establish parameters for keeping humans alive and healthy for long periods in the harsh environment of space, where the most challenging issues are represented by ionizing radiations, long-term exposure to micro-g conditions, and psycho-physical health.

Within this context, the Moon has been one of the most discussed targets for human settlement, due to its proximity. With the advent of the new space race enhanced by the private sector, several ambitious projects have attempted to replicate off-world dwellings conditions as closely as possible to test the limits of human endurance. In this article, the author will mainly review the advantages as well as the drawbacks of inhabiting an extra-terrestrial lunar environment, and the future space missions working toward this goal.

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1 Introduction

Inhabiting other planets has been a topic of fascination and scientific inquiry for many years. Due to their proximity and morphological conditions, the Moon, and Mars are currently two of the most discussed near-future targets for human settlement. Numerous challenges come with colonizing other planets, such as political, social, cultural, and technological. But there are also scientific discovery, resource acquisition, and exploration opportunities.

Up until now, the human species encountered several difficulties in planning, designing, and carrying out manned space missions, e.g., [1], [2], [3], [4], and [5]. As space missions can be considered catalysts of unique scientific conditions, it is essential human life is preserved efficiently within off-world settings, especially against cosmic radiation and space-related conditions such as adaptation syndrome, spatial memory, visual motor performance, bone loss, psychological impacts of living in confined spaces, and many more.

It is common knowledge that for the next decades, many companies will set the goal of extending the capacity of human beings to live and work in a sustainable environment beyond Earth, as well as investigating the radical changes humans can experience on a biological level. [6] In addition, the opportunity to make scientific discoveries and perform project research beyond Earth entails mostly the promise of a technological advance from which people can benefit heavily, as it has already been seen throughout the years, e.g., [7], [8], [9], and [10].

2 Space Colonization Overview

Space colonization refers to the concept of establishing self-sustaining human settlements that could thrive and expand over time beyond Earth's atmosphere. Several reasons define space colonization as more than a possibility. The most popular regards access to new resources and opportunities for scientific exploration and discovery. Also, it could provide a practical long-term solution to overpopulation or a catastrophic event in the long period. But, there also are several challenges associated with space colonization, such as the high cost and technical difficulty of creating self-sustaining habitats. Material transport and management, maintenance, ionizing radiation, lack of oxygen, and extreme temperatures are just some main challenges off-world dwellings would face in the eventuality of creating viable colonies. Also, humans' expansion on other planets raises ethical questions that must be addressed as well.

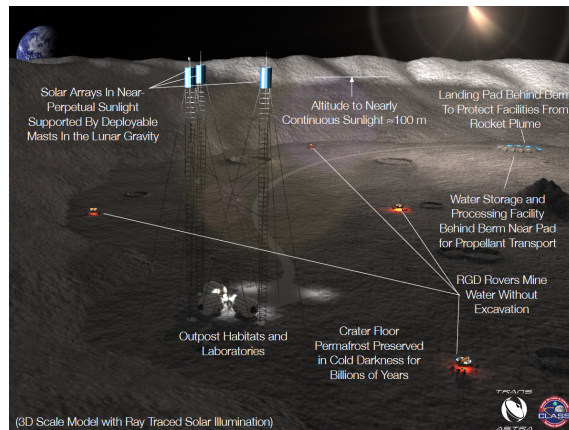


Figure 1: Example of a propellant Moon mining outpost. TransAstra Corporation's concept would ideally solve the affordable lunar polar ice mining propellant production problem. [11]

Despite these challenges, there are several ongoing country initiatives among both private and public agencies, e.g., [12], [13], as well as proposals for space colonization, e.g., [14]. It remains to be seen whether space colonization will become a reality shortly and how feasible its planning and management are going to be, but it is undoubtedly an area of active research and development that should be explored thoroughly. The next subsections will address the topic of past, present, and future attempts of colonizing off-world planets, and the greatest challenges humans would face to carry out the colonization of Earth's natural satellite, i.e., technology, economic sustainability, food cycles, and survival issues.

2.1 Past Field Colonization Tests

One of the early conceptual definitions of Moon colonization was addressed by the Soviet Union, e.g., Zvezda Moon base [15] and NASA, e.g., Horizon Project [16] and [17]. At that time, the latter had to: develop tools and procedures, define and set communication systems, design and assemble lunar rovers and extravehicular space suits, train their astronauts to land on the moon as well as gather surface samples to be returned to Earth. As mission costs skyrocketed over the decades, now, companies would never choose to prepare candidates for short-term 384,400-km long-trip missions, which would also include subsequent landing and extravehicular activities. The idea is to save mission costs by conducting remote field trips at remote locations chosen because of geology, terrain, or favourable characteristics to conduct experiments. As a means of example, in 1963, NASA sent Buzz Aldrin, Neil Armstrong, and Michael Collins on a preliminary GFT, i.e., Geology Field Trips, at Cinder Lake near Flagstaff, Arizona. The three former military pilots practised sample collection with special tools and used state-of-the-art communication systems. The GFTs continued over the years with different companies, crews, and targets, such as rock formation identification, sample cultivation, survival training, and communication techniques. [18] Both Apollo GFTs and lunar missions provided valuable data for the next generation of space exploration. However, new target requirements and technological advances demand new GFTs, called *analogue missions*. Many remote and harsh locations are still used for today's testing missions. To date, analogue locations include Arizona, Hawaii, Utah, Antarctica, Israel, and Spain.

2.2 Current Field Colonization Tests

Space missions have always been tailored to meet specific requirements. Analogue testing on Earth arises from the fact that space exploration is inherently risky. The costs involved are usually part of public state funding [19], and the potential dangers mean that astronauts must be adequately trained and equipped to deal with any kind of situation. Present-day analogue missions are conducted to train or test short- and long-range mobility, advanced systems, extra-vehicular spacesuits, operations, and local resource power conversion or storage. They can also help scientists to understand how the human body responds to extreme environments. The design requirements involve many disciplines, e.g., signal processing, electronics, biology, and many more. Design iterations are inevitable since the process depends on analyses, simulations, experimentation, and technological compromise. The first step is to define mission targets and expected costs and determine the success probability for each one. Thus, design phases may undergo numerous and significant modifications throughout the process. Collateral targets, e.g., social nature, are also taken into consideration.

Analogue missions usually observe the following main design path [20]:

- Concept exploration, i.e., the initial study phase, which involves the main milestones.
- Detailed development, i.e., the detailed definition of the system requirements.
- Production and deployment, i.e., the hardware and software supply chain.
- Operations and support, i.e., the system maintenance, dismissal, or recovery.

In this context, analogue space simulation missions play an important role in the testing of space technology on Earth. The aspects covered also consider the simulation of narrow living habitats for the crew and their interaction. Numerous analogue space simulations have already been carried out in different places on Earth:

- Hawaii, US, i.e., HI-SEAS Mission, a research station on an isolated Moon-like site on the Mauna Loa volcano on the Big Island of Hawaii. [21]
- Utah, US, i.e., Mars Desert Research Station, a simulated Martian habitat located in the Utah desert. [22]
- Negev Desert, IL, i.e., Austrian Space Forum’s recent AMADEE-20 Mission setting. [23]
- Florida, US, i.e., NASA Extreme Environment Mission Operations mission, where astronauts live in an underwater habitat that simulates long-duration missions in weightlessness conditions. These simulations help astronauts understand how to execute daily operations in a simulated partial gravity environment. [24]

The limitations are many, such as the inaccurate harsh conditions that astronauts are likely to experience or the simulated isolation and confinement experienced during an analogue mission. Nevertheless, they provide a valuable platform for preparing for actual space missions and advancing space exploration. Many more are currently underway, and they mainly involve Isolation and confinement [25], bed rest simulations [26], radiation testing [27], in-situ resource utilization [28], and many more.

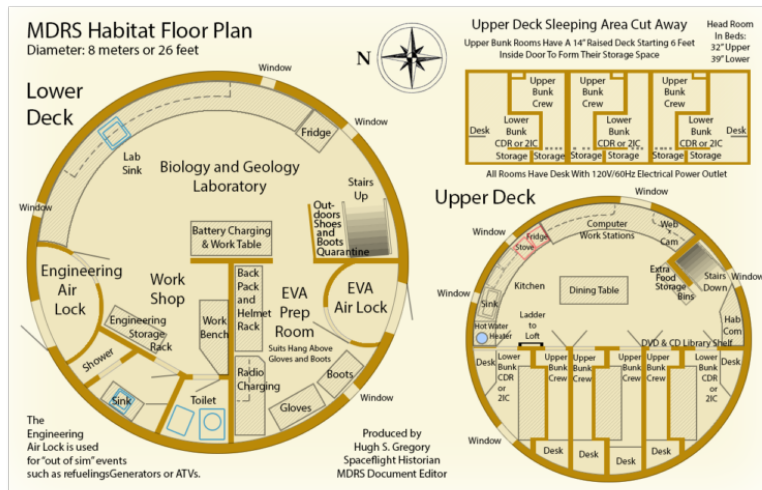


Figure 2: Analogue research station example. [22]

3 Inhabiting the Moon and Its Implications

As space exploration advances inexorably, the possibility of exploiting resources beyond the atmosphere of Earth becomes increasingly appealing and factual. There are several potential resources in outer space, such as minerals, water, and even energy. The idea of resource exploitation in space has been discussed for decades. Many missions have been able to complete orbits around asteroids [29], or excelled in returning samples of asteroid matter back to Earth, e.g., [30], [31], and [32], to prove the feasibility of the process and set common goals for the next endeavours. The next sections will briefly examine the potential benefits and drawbacks of inhabiting Earth’s satellite, as well as the challenges related to exploiting its resources.

3.1 Main Aspects

The Moon is the closest and largest body to Earth. Its main features include its typical orbit, the high surface thermal excursions, i.e., from around $T_{Moon} = 100K$ to $T_{Moon} = 390K$ [33], its irrelevant atmosphere [34] (which determines the lack of cosmic radiation and objects shielding, as well as life in general), i.e., which ranges from $P_{Day} = 10^{-7}Pa$ to $P_{Night} = 10^{-10}Pa$, and its morphology (which involves craters and depressions) [35], as well as its composition, predominantly constituted by silicates minerals [36] and harmful dust. [37]

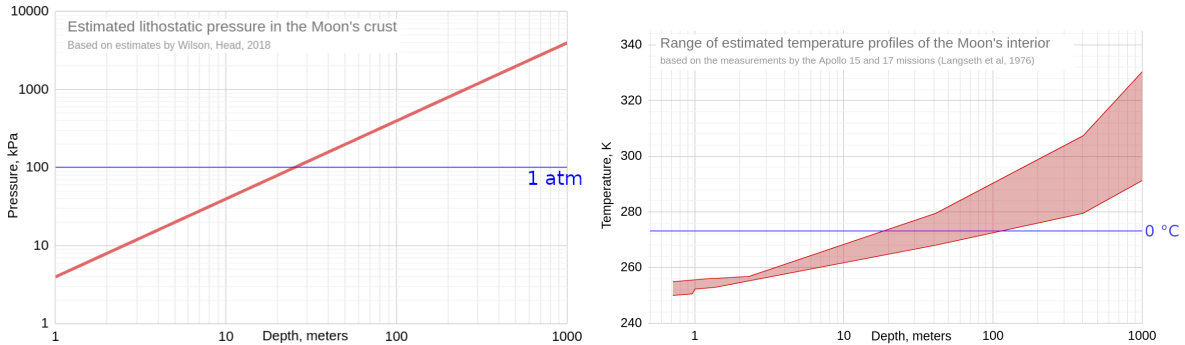


Figure 3: The estimated Moon’s (a) lithostatic crust pressure. [38] (b) internal temperature range profile. [39]

In the eventuality of placing a colony on Earth’s natural satellite, the lunar ecosystem would provide exceptional challenges for humanity. The first considerations mostly involve the cost per unit mass of launching cargo to/from the satellite, even if in the latter case the work and propellant required would be much less. The costs vary and are difficult to predict or address, as the cost impact relies on future technological improvements and its supply chain. There have been considerable efforts to address the issues over the years, e.g., [40]. Some authors [41] proposed non-rocket approaches involving the use of electromagnetic resource launchers. Rough manufacturing costs are esteemed to be approximately around 600M\$. [42]

Existing launch providers are currently lowering their costs as well as the level of acceptable risk to carry out missions. Usually, the risk level comprises different parameters related to the damage occurrence probability within a given framework. As a means of example, the launch cost to the ISS has been reduced by a factor of 4. [43] However, costs still represent a major issue in this sense in terms of flight operations, hardware, software recurring costs, operations capability development, facilities maintenance and operations, launch operations, engineering, spares, and logistics. [44]

One of the most effective ways to meet safety levels is to carry out thorough risk assessments. The process is an integral part of the design phase, and it is strictly related to the positive outcome of the mission goals; thus, periodic revisions are compulsory. To perform a proper risk assessment, the engineers should consider the regulations or standards that apply.

Space ventures such as the one described, if not entirely addressed, entail high risks, with long lead times and large capital investments. Suitable design modifications must be implemented to improve the robustness against such failures without violating system constraints and requirements for launchers or vehicles. Typical examples involve rotating elements, high-pressure valves, propellant feed lines, injectors, and thrust chambers. Even the failure of a single element can propagate downstream and may affect elements severely, resulting in mission failure or worse. Whenever it is not possible to reduce the risks directly, contingency plans should be considered. It is not carried out to prevent errors or dangers from happening, but to define a rapid countermeasure that could immediately respond to the considered escalating situation.

Ventures could be funded through private or government investments. It can be profitable for a commercial enterprise as long as the revenues earned are greater than the total costs. Within the mining venture context [45], the costs that should be considered are research and development, expenses planning, infrastructure construction and maintenance, environmental, and time. In this context, humanity appears still far from solid economic exploitation of lunar resources.

3.1.1 Hosting Structure

The long-term human presence concept on the Moon can be traced back to the late 1950s, e.g., [46], [16], and [17], and has often been revisited since then. Potential hosting structures must withstand harsh conditions and are subject to many boundaries in the long term, i.e., gravity, internal pressurization, and shielding from outer natural agents. Good structural design practices imply the correct assumption of useful materials, their structural behaviour, the environmental loadings, and the inherent structural uncertainties.

Functional aspects involve efficient In-Situ Resource Utilization units. While early attempts have focused primarily on consumables, the last decade has seen an exponential increase in research on ISRU for manufacturing. [47], [48], and [49] In particular, it has been shown that many resources available on the lunar soil can be successfully utilized through various Additive Manufacturing techniques, allowing the Moon to serve as a source of building materials. Also, rare earth elements are essential for many modern technologies, and the ability to extract them from extra-terrestrial settings could reduce the dependence on imports from countries with limited reserves.

Table 1: Lunar surface chemical composition. [36]

| Compound | Formula | Maria Composition | Highlands Composition |
|------------------|--------------------------------|-------------------|-----------------------|
| Silica | SiO ₂ | 45.4% | 45.5% |
| Alumina | Al ₂ O ₃ | 14.9% | 24.0% |
| Lime | CaO | 11.8% | 15.9% |
| Iron (II) Oxide | FeO | 14.1% | 5.9% |
| Magnesia | MgO | 9.2% | 7.5% |
| Titanium Dioxide | TiO ₂ | 3.9% | 0.6% |
| Sodium Oxide | Na ₂ O | 0.6% | 0.61% |

Recent studies [50] resulted in a basic plan for a lunar outpost near one of the poles of the Moon to permanently house astronauts in six-month shifts. These studies were made before the discovery of water ice ($5.6 \pm 2.9\%$ by mass) in a nearby polar crater. Other locations considered included the rim of Peary Crater near the lunar North Pole and the Malapert Mountain region on the rim of Malapert Crater.

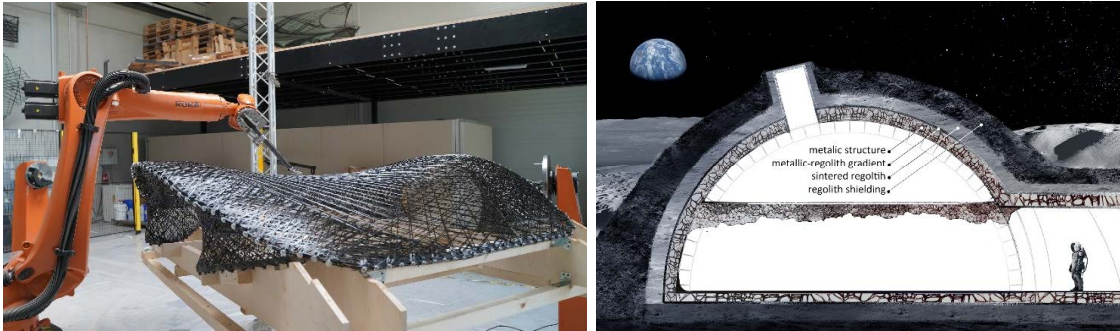


Figure 4: (a) 1:10 Large-scale structure fabrication demonstration (b) Multi-layered lunar habitat example.[51].

Other important topics include lunar temperature cycles and building material fatigue, structure embrittlement due to low-temperature effects, steel/alloy outgassing due to space vacuum, and frame buckling/stiffening due to the forces involved in pressurization. In particular, consistent safety factors accounting for the early design/construction process undoubtedly need to be considered for the lunar environment. In this regard, to prevent hypothetical base costs from reaching exorbitant values, Lunar lava tubes¹ have been extensively proposed as enclosures for early human habitats. [52], [53], and [54] These natural tunnels would theoretically protect from thermal excursions, cosmic radiation, solar radiation, meteorites, micrometeorites, and ejecta from impacts.

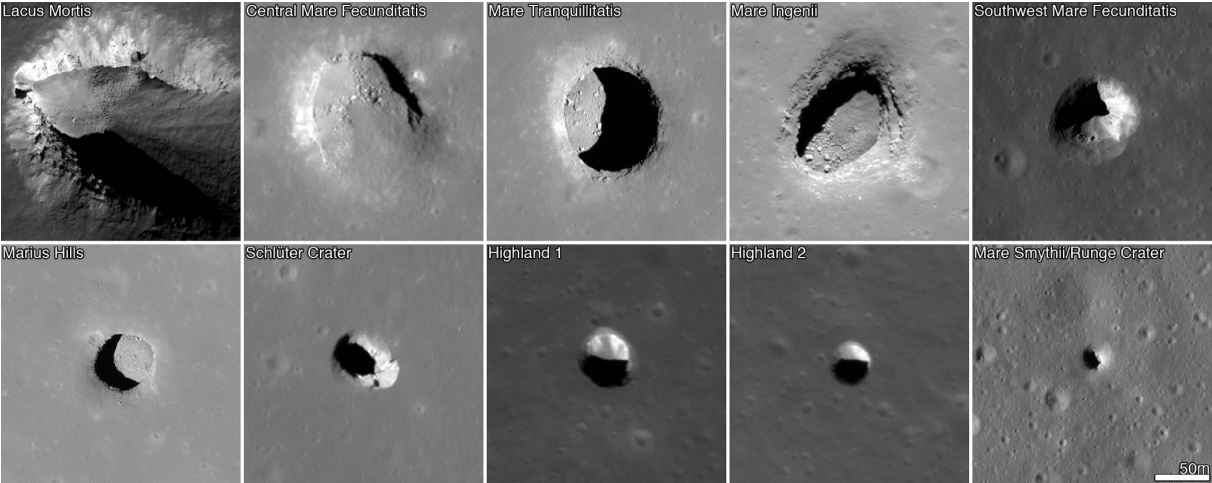


Figure 5: Known lunar mare and highland pits. [54]

¹Subterranean tunnels of modest size that form as a result of lava flows, and appear to extend for long distances beneath the Moon’s surface.

These morphological features are typically found along the boundaries between lunar mares and highland regions. This would give ready access to: elevated regions, for communications; basaltic plains, for landing sites and regolith harvesting; and eventual underground mineral resources. [55] At last, to enable an independent lunar settlement, infrastructures should be designed to be easily deployed and functional, whether through remote assembly or autonomous systems, providing the basis for possible habitat self-maintenance.

3.1.2 Nutrition and Physical Health Aspects

Water and food production at low cost and high yield rates have become increasingly significant. The former grows scarce in many World parts. In this sense, another potential benefit of resource exploitation involves mining a potential new source of water for Earth on a functional outpost [56] such as the Moon. Recent evidence [57] suggests direct evidence for surface-exposed water ice in the lunar polar regions. But, water extraction from the lunar poles entails complex infrastructure to achieve it. For what concerns the latter, Future missions will require long-life nutritious food. [58] In the eventuality of growing crops on the Moon, astronauts would face long nights, extreme surface temperatures, exposure to solar flares, soil poor in nitrogen, and so on. Due to the lack of atmosphere on the Moon, plants should be grown in sealed chambers; electricity would need to make up for the natural cycle plants would experience on Earth. [12] Many concepts have been proposed both for sustainable Lunar in-situ food production [59] and agriculture [60], including the use of fast-growing crops and microalgae. [51] Early attempts at plants grown in lunar regolith [61] have proven successful; The extent to which plants can enhance human life support on other worlds depends on the plants' capability to thrive in extraterrestrial environments.

Safety precautions against space threats are essential. Not only do astronauts need special clothing, but they also need to be notified immediately of any damage to the suit or the hosting structure. The biological consequences of radiation exposure mainly relate to altered neurogenesis [62], oxidative damage [63], and radiation-induced bone loss [64]. Also, The acceleration due to gravity on the surface of the Moon is $a = 1.625 \frac{m}{s^2}$, i.e., about 16.6% that on Earth's surface; it may be vital to fetal development and long-term human health. Many factors determine the extent of direct and indirect damage to genetic material, e.g., type of radiation, age, and gender. Different strategies can be addressed to reduce radiation exposure: water shielding [65], magnetic shielding [66], and electrical shielding [67]. A thorough prevention would require significant suit improvements. Although suit models retrace NASA efforts, there are several private and public entities developing their prototypes for future missions, e.g., The ESA Pextex Project² [68], the Austrian Space Forum Suit [69], Roscosmos's updated version of Orlan-MKS suit [70]. At the moment, the most advanced studies for the improvement of fabrics concern shape memory alloys, i.e., fabrics that can be assimilated to springs. However, one critical limitation of these materials is the recoverable deformation limit [71] and self-healing properties. [72]

²Which involves fabrics with self-healing and dust repelling functions.

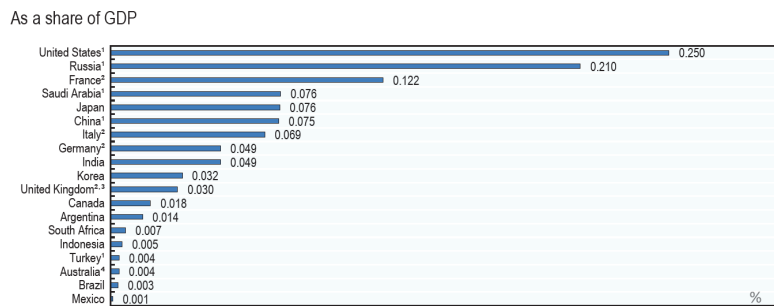
3.1.3 Psychological Aspects

In preparation for extra-terrestrial missions, astronauts must prepare themselves to live in an isolated micro-society whose balance is strictly dependent on its members' intense and frequent interaction. Withdrawal from known society determines the loss of variety and identity in social relationships where compliance, influence, and independence play an important role in group dynamics. [73] It has been observed that people forced to live in confined settings show impairment in at least one of the following: Thinking, perception, mood, and impulse. [74] Therefore, it is important to rely on effective individuals when selecting the astronaut crew. The optimal group performances may be highly influenced by group heterogeneity and individual attitudes, common tasks, and duration, leading to a favourable mission outcome.

To maximize astronaut performance and minimize the risks associated with fatigue, sleep disturbances, altered sleep-wake cycles, and desynchronization of body rhythm, their activities should be varied [75], but they should be left to operate autonomously. [76] The individual understanding capability can result in a thorough success of the mission. It is essential to develop systems that can help humans cope with information, or at least identify the key points necessary to limit errors. A successful model improvement would require a clear understanding of the domain requirements, the interfacing system, and the environmental factors. [77] For future space missions, it should not be excluded threats posed by capable but untrained individuals might arise, leading to a disruptive outcome of the crew cohesiveness and targets.

3.1.4 Economic Viability and Sustainability

The impacts of the recent crises on government space investments and activities are evident, i.e., many missions were delayed or postponed in many countries. [78] However, troubling times often contribute to highlighting how space technologies can support societies during a crisis. The interest in specific economic domains of space programs is growing, such are the contributions to innovation or entrepreneurship. In this regard, agencies are increasingly supporting start-ups and entrepreneurship in the space sector. As a means of example, ESA is supporting business incubation centres (BIC) and their commercialization in its member states, having resulted in more than 500 company creations. [79] As space budgets grow and diversified in many countries, decision-makers need now to track the implementation and impacts of investments in the space sector. Cooperation between public and private investors might be the key to a successful implementation of a thriving lunar economy.



Notes: Budgets include data for civil and defence programmes, when available. The figure does not include the aggregate budget for the European Union.

1. Conservative estimates.
2. Includes contributions to the European Space Agency and Eumetsat.
3. Includes for non-European Union members their specific contributions to EU space programmes (i.e. Copernicus and Galileo/EGNOS).
4. Includes only civil R&D.

Figure 6: G20 government space budgets for 2020. [80]

The rising interest in the Moon associated with the rise of private actors and the need for space agencies to save money by subcontracting to private contractors are paving the way to establish a human presence on the Moon and create new potential businesses. However, every stakeholder, government, policy-maker, and commercial actor must measure the economic value and benefits of private companies generating change in the overall lunar economy. Further economic and industrial frameworks are currently undergoing to better evaluate the economic impact of such endeavours. Collaboration between governmental and private enterprises at an international level will make the economic assessment easier. As seen with the ISS, the lack of international cooperation on economic data sharing makes economic evaluation even more difficult. Microeconomics and macroeconomics indicators should be carefully selected, and initiatives on how to bring the two together should be put in place.

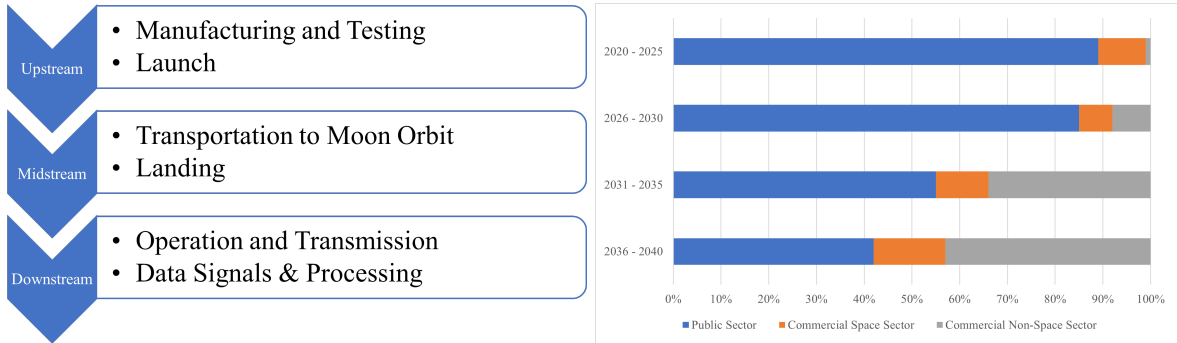


Figure 7: Elaboration from PwC’s Lunar market assessment [81] of (a) Lunar market value chain (b) Estimated overall global future transportation market value.

Long-term economic conditions on the Moon would require filling the current technology gaps. To achieve that, stakeholders need to understand where there is potential for technology development or business opportunity, as well as policy issues regarding consensus and engagement. PwC’s assessment predicts the lunar market will surpass a value of €142 billion [81] by 2040 and identified three key areas to measure its fallout:

- **Transportation between Moon and Earth.** Reliable and low-cost transport and supporting infrastructure are crucial to support supply chains and people transport.
- **Communication and navigation systems** to cover technical data for mission preparation and research. Long-term dwellings need a reliable, large-scale network to provide capabilities to support surface exploration and transport.
- **Resource utilization.** It represents the most feasible technology when considering settlements. Economic viability would be facilitated by the capability to extract, process, and utilize lunar resources, i.e., lunar regolith, water, and volatiles. Autonomous processing and additive manufacturing are expected to fill the existing technology gaps.

Besides the economic effects, a lunar economy can have far-reaching societal impacts besides the economic effects. Future political agendas might reflect the lunar economy progress due to strategic opportunities, while the leap for scientific progress has the potential for discoveries.

4 The Immediate Future of Space Colonization

The new Space Era is currently at its earliest peak. There are many reasons to be optimistic about the prospects for space colonization in the coming decades. Many discoveries from life-science research, e.g., [82], [65], and [64] to behavioural and sociological sciences, e.g., [83] and [73] have been promising so far. Many upcoming missions, e.g., [84], [85], and [86], present a whole set of important challenges, such as the development of cutting-edge lightweight structures or fighting the long-term health effects of living outside Earth, while the cost of space travel is decreasing steadily. In this context, the Asian market (as opposed to Western countries) is currently addressing the development of reusable rocket engines aggressively. [87]

Overall, the future of space colonization is likely to be shaped by a combination of scientific and technological advancements, economic and political factors, and the creativity and ingenuity of the people working in this field. Hopefully, this would result in organizational cultures becoming more transnational, each influenced by their counterparts in other countries. [88]. Nations and private companies are investing in space exploration and colonization, recognizing the economic and strategic benefits of having a strong presence in space. [89] One of the most studied areas of research in space colonization is the development of sustainable habitats that can support human life in space. This includes the development of advanced life support systems that can recycle air and water, as well as the production of food and other essential resources, and the protection from the harmful effects of radiation.



Figure 8: NASA proposed model of an inflatable module. [90]

4.1 Artemis Program

Formally established in 2017, The Artemis program is a collaboration of government space agencies, i.e., NASA, ESA, JAXA, CSA, and private spaceflight companies, whose main joint goals are to establish a self-sustaining presence on the Moon, lay the groundwork for private companies to build a lunar economy, and ultimately send humans to Mars. It incorporates several major components from previously cancelled missions. [91] The program is organized as a series of planned Space Launch System missions [92]:

- Artemis I mission (2022), to demonstrate the reliability of Orion’s SLS and core systems, including the service module, in preparation for manned flight, and to test the heat shield in a high-speed re-entry.
- Artemis II (2024), planned as the first crewed test flight of SLS and the Orion spacecraft. The crew members will perform extensive testing in Earth orbit, and Orion will then be boosted into a free-return trajectory around the Moon. Then, re-entry and splashdown are also scheduled.
- Artemis III (2025) is the planned first crewed lunar landing. The mission depends on a support mission to place a Human Landing System³.
- Artemis IV (2028), docking with the Lunar Gateway⁴ in any future yearly landings on the Moon thereafter.
- Artemis V (2029), the third planned crewed lunar landing. It will deliver the European Space Agency’s ESPRIT module [95] a robotic arm system [96], and a Lunar Terrain Vehicle. [97]

Under the Commercial Lunar Payload Services program [98], scientific instruments such as habitat modules and rovers will support the crew on the lunar surface. However, some internal NASA observers note that the program cost and timeline are likely to be delayed due to the inadequate management of contractors. [99]

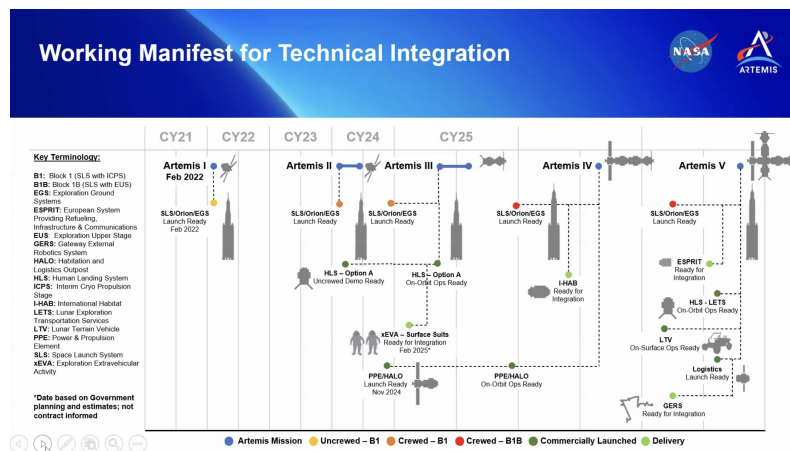


Figure 9: NASA’s Artemis integration roadmap. [100]

³A spacecraft that conveys the crew to the lunar surface, supports and returns them to orbit. [93]

⁴A small space station orbiting the Moon to support the campaign investigations, e.g., lunar and planetary sciences, life sciences, and fundamental physics. [94]

4.2 Final Considerations

Life on Earth evolved in unique conditions and is not duplicated anywhere else in the solar system. In 2015, United Nations Member States agreed on a new set of goals to end poverty, protect the planet, and ensure prosperity as part of the 2030 Agenda for Sustainable Development Goals. Space technology can support many of these targets, such as agricultural planning, biodiversity protection, telehealth, and disaster management. [101] As the space frontier grows, it is also imperative to harness the advantages of space to reduce inequalities. However, the public seems to have accepted the assumption that human migration into space is inevitable. In this context, SDGs are believed they will have substantial repercussions on how the potential future society on other planets.

There are significant challenges associated with inhabiting the Moon or other planets. The harsh environmental conditions make it challenging to sustain human life, e.g., different sizes, lack of atmosphere, extreme temperature variations, radiation, and meteorite impacts. The long-term effects of these conditions are not known, but they would likely include muscle degeneration and bone loss. Also, inhabiting other planets raises ethical considerations. Influential authors, e.g., [102] consider both asteroid and planet mining to be a necessary foundation for establishing humanity as a spacefaring civilization; others, e.g., [103], remain sceptical or critical, or propose a more cautious approach. [104] For humanity’s development, it is essential to address the social and economic effects and implications of international cooperation on this matter. Although space mining efforts seem promising, no company has been able to achieve solid or crucial mining results yet. The reasons are many: legal, funding, design complexity, and general investing sector uncertainty. But many public and private companies have a technological profile or a dedicated roadmap to set the goal of space mining. In the eventuality of a well-established space mining future, governments should provide a clear regulatory regime for celestial bodies’ mining rights in a way to prevent market monopolies (if the current agreements on outer space resources such as [105] were to exist no more in the future), but, also, not hinder investments in this sector. The current deal does not address private mining efforts. [106]

Finally, at least in its early days as multi-planetary species, humanity could limit the contamination of other planets with Earth organisms, as this could compromise scientific discoveries and potentially harm any autochthonous life that may exist.

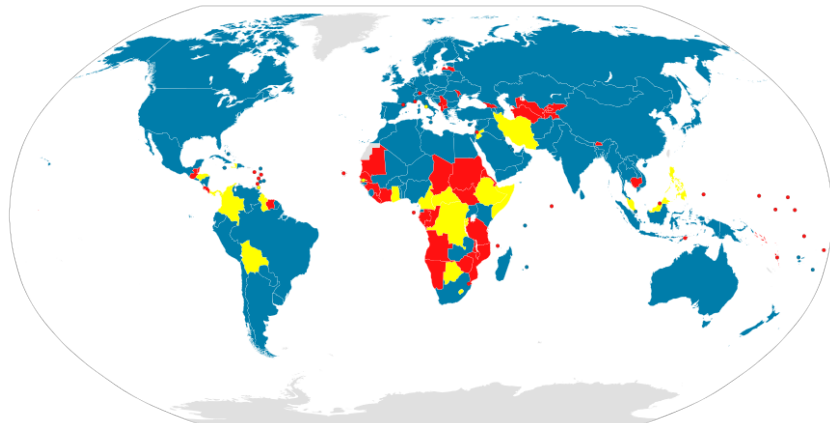


Figure 10: Party countries of the “*Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies*”. Non-ratifying or non-signatory countries are highlighted in yellow and red. [107]

Conclusions

Space exploration attracted the brightest minds over the last seventy decades. Becoming a multi-planetary species could help humanity reach its full technological potential as well as protect the future of the human race, and entail a complete disruption of whole economic sectors. Investment increasing in the space sector is a precondition to ensure research development with an excellent chance of high multiplier effects. It will be desirable to create robust demand with the promise of high revenues, to build confidence in investors, and help companies raise larger rounds, following the common investment roadmaps. One of the most exalting possibilities is the exploitation of resources beyond Earth's atmosphere. But outer space is still vast and largely unexplored; due to the distances involved, deep space missions will not be able to waste any resources nor involve excessive payload. With the advancement of technology, new promising feasible techniques to extract potable water, mine minerals, and harness energy off-world have been theorized. Therefore, system efficiency and reliability are essential to carry out missions thoroughly. However, these conditions raise several questions about the implications of such activities for the future of space exploration. Beyond the technological challenges, human presence within deep space turns into a philosophical question that regards high-value, near-term technological spinoffs as well as the economic promises of resource exploitation.

In conclusion, off-world resource exploitation represents a great opportunity for humanity, but it does not come without drawbacks. The economic benefits and potential solutions to Earth's shortage of resources are significant. Before proceeding, it would be necessary to weigh the consequences of human actions. Also, the impact on the still untouched alien environment as well as the potential geopolitical conflicts over resources must be carefully avoided, and, possibly, oriented toward international cooperation.

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