EE589 - Project in Space Technologies

Sustainable missions to the Moon

Sustainable ISRU and Human Development on the Moon

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Autumn Semester: Academic Year 2024 – 2025

Contents

1 Acknowledgment

Thank you Mathieu for your guidance, your presence at E2M meetings and your support during the most challenging phases of this project. You kept me motivated until the end, of this not-so-simple semester project.

2 Introduction

This document summarizes the key information that led to the creation of another document called "Approaches to Mitigate Sustainability Risks for Long-Term Lunar Developments: 11 *Risks to the Moon's Sustainability".*

Since the beginning of the Space Age with the launch of Sputnik 1, on 4 October 1957, only a few hundred people have been to space and just 24 have left Earth's orbit to the Moon's, of which 12 have walked on the lunar surface. As such, many would find it difficult to identify with the space environment, because it is beyond their personal experience [2].

Less than a century as passed since the first satellite launch, and yet many manmade debris are now in space. This goes from the more than 40 thousands $\geq$ 10 cm size debris orbiting the Earth [28], to the ones found on the surface of the Moon or Mars. This pollution is the result of the non-regulation of space exploration; in the case of Earth orbit, uncontrolled objects are now tracked to avoid their collision with operating spacecraft, while lunar or Mars debris may well have contaminated the surface of these planets, either by the debris themselves or by bringing terrestrial bacteria with them. The consequences for scientific tasks are significant: terrestrial observation systems are obstructed, access to terrestrial orbits is more difficult and results of experiments to detect life on other planets have to account for potential contamination by previous missions [2].

As the history of space exploration shows, a sustainable strategy is unlikely to emerge spontaneously with further exploration or development. This is because companies' budgets are limited, which tends to mean that they only do what they have to do to meet technical specifications, government policy or other defined requirements. If sustainability is not identified as a requirement, it is unlikely to be taken into account [2].

However, given the current problems with the space environment introduced by previous missions, various space stakeholders are pushing to agree on an international sustainable strategy to guide future scientific exploration, industrial development and space tourism. As expressed earlier, because most people have no experience with the space environment, this is no easy task. Whether such guidelines or regulations are published or not, it is also the responsibility of this generation to not compromise the space environment left to future ones.

Finally, human exploration of space has always been seen as a mean of pushing back the boundaries of science, technology and knowledge. The ingenious solutions that will be developed to maintain humans on the Moon are also expected to have returns on society, with potential applications on Earth. Nonetheless, literature shows that there are also environmental limitations to this endeavor [13]. As such, the current great challenge for the next 25 years is to develop a permanent human presence on the Moon, combining scientific research and the appropriate use of local resources in an international collaboration, while preserving the local environment.

3 Background

This student project is part of an initiative from the association EURO2MOON, which brings together European actors in the space economy, with the main goal to foster European interest in the context of economical development on the Moon. As we will see later in this document, the European community is aiming to extract resources from lunar regolith anywhere on the lunar surface, while the United States wants to extract water, supposedly present in large quantities and in frozen form, at the South Pole.

The current goal of EURO2MOON is to answer fundamental questions regarding the economic viability of In-Situ Resource Utilization (ISRU) on the Moon by 2050. In this context, a first study evaluated the O_2 demand between almost zero to almost 40 kt/year, depending on the set of assumptions made with respect to future developments on the Moon. It should be noted that the market size was only based on the production of O_2, expected to be a good ballpark value as it is the necessary combustive for any propellant [1].

Analyzing the results of the study, we see that most of O_2's production needs come from refueling for trips between the Moon and the Earth, transporting non-propellant resources or human passenger.

The association now consists of 11 member companies, each of which has to pay an annual subscription fee. The people are divided in working group, e.g. marketing & communication, technical, sustainability,... each consisting of $2-3$ people from the member companies, and they dedicate part of their time to EURO2MOON.

4 Problem Statement

The economic potential of Moon-based propellant was the first point of interest for the different members of EURO2MOON. However, with the ambition to not reproduce the environmental mistakes made on Earth, the next goal is to define 'sustainability' from a Moon point of view. Ensuring that ISRU on the Moon is *"Moon sustainable"* is also an important step for such missions to be accepted by the general public.

As there is no knowledge of sustainability on the Moon within EURO2MOON, the first task is to list the key-points of a Moon propellant production infrastructure which could have impacts or consequences on the Moon environment (or potential Moon colonies). Studying the factors to be taken into account when developing sustainable ISRU lunar missions could also help anticipate future, potentially restrictive, lunar regulations.

5 Abbreviations

- **COPUOS**: Committee on the Peaceful Uses of Outer Space
- **E2M**: EURO2MOON
- **HEU**: Highly Enriched Uranium
- **ISRU**: In-Situ Resource Utilization
- **LCROSS**: Lunar Crater Observation and Sensing Satellite
- **LEU**: Low Enriched Uranium
- **LEO**: Low Earth Orbit
- **LRE**: Liquid Rocket Engine
- **LRO**: Lunar Reconnaissance Orbiter
- **PSI**: Plume-Surface Interaction
- **PSR**: Permanently Shadowed Regions
- **RTG**: Radioisotope Thermoelectric Generator
- **SOFIA**: Stratospheric Observatory For Infrared Astronomy
- **SRE**: Solid Rocket Engine

6 Moon environment

The Moon is the Earth's only natural satellite, orbiting at an average distance of 384400 km. This celestial body is the very object of the current project, and basic knowledge must be presented.

6.1 Lunar atmosphere

The Moon's exosphere is far too thin to produce weather conditions as we know them on Earth. In fact, lunar weather comes directly from space, and is made up of solar winds, galactic cosmic rays, coronal mass ejections and micrometeorites [29].

The absence of meteorological conditions has numerous consequences for future missions to the Moon. Firstly, the aforementioned events can be dangerous for the people living there, and the absence of weather conditions also means that there is no self-rebuilding mechanism on the Moon.

6.2 Lunar craters

Due to the Moon's unique geometry, sunlight never illuminates the bottom of certain craters located near the Moon's poles. These areas are known as "Permanently Shadowed Regions" or PSRs. The LEND instrument on the Lunar Reconnaissance Orbiter detected fewer neutrons near the Moon's poles, indicating the presence of hydrogen in the form of water. This seems to indicate that water can remain frozen in PSRs for long periods, unlike free hydrogen that would escape the Moon's gravity even at cold temperatures [30].

PSRs and their potential water content are a primary focus of the American lunar base program for the production of oxygen. It should be noted that the steep lunar crater slopes and the harsh conditions of PSRs, similar to those of a lunar night, pose significant obstacles for missions.

At the poles and next to some of the PSRs, there also exist peaks of eternal light on the rim of some craters. These places are not constantly under the light, but more than the 50% normally encountered on the Moon.

6.3 Lunar mascons

Mass concentrations, or mascons, are regions of higher-than-average density within a celestial body's crust, causing variations in its gravitational field. First discovered on the Moon, these anomalies are most often associated with large, ancient impact basins where dense mantle material uplifted and mixed with surface debris. Mascons significantly affect the orbits of spacecrafts, making accurate mapping essential for missions.

A map of the variation in the lunar gravitational field was obtained from the Gravity Recovery and Interior Laboratory mission from NASA, which flew the two spacecrafts Ebb and Flow. These spacecrafts were orbiting at a distance from each other, the difference in the gravitational field of the Moon increased or decreased this distance thereby giving information on its gravity field. The spacecraft were literally ebbing and flowing.

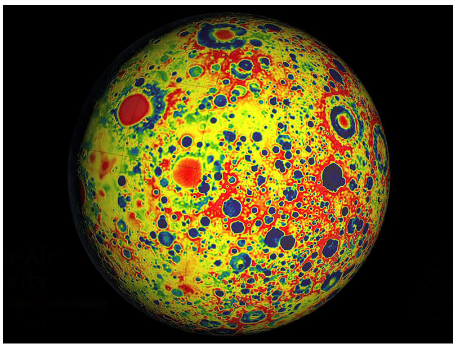


Figure 1: Variations in the lunar gravity field. Source: NASA

6.4 Lunar night

Most people know that the Moon always presents the same face to the Earth. In fact, the Moon's rotation period corresponds to its orbital period, so it always presents the same face to the Earth. There are two sides to the Moon: the visible side and the far side, sometimes called the dark side of the Moon. It's important to understand that the dark side of the Moon is not always at night, but simply never faces the Earth. In fact, the Moon's solar orbital period is about 29.5 days, half of which is daytime, followed by the other half at night.

Lunar night is a major challenge for lunar missions, most of which do not survive the duration and extreme temperatures. In fact, typical lunar daytime temperatures can reach 121°C, falling to −133°C at night [29].

6.5 Lunar regolith

A thick layer of regolith, a fragmented and unconsolidated rock material, covers the entire lunar surface. This layer is the result of the continuous impact of large and small meteoroids and the constant bombardment of charged particles from the Sun and stars. The regolith is generally 4 to 5m thick in mare regions and 10 to 15m thick in highland areas, and contains materials of all sizes, from large boulders to submicron dust particles. Beneath the regolith is a region of large boulders, large-scale ejecta and brecciated rock, often referred to as "megaregolith" [31].

Regolith is abrasive and so small that it can be deposited anywhere, which can have an impact on astronauts' health. It also darkens surfaces, considerably increasing radiant heat transfer.

This content of the Moon's soil is important, as not all the contents of the lunar regolith can be used to extract oxygen, depending on their size, composition and the process used.

7 History / Issues

7.1 Earth

As introduced, the document does not focus on sustainability issues caused to Earth, but rather on sustainability issues on the Moon. Indeed, numerous documents already exist on the subject of Earth's sustainability, which is currently a hot topic with the expected massive increase in the number of launches, following the development of the new space economy.

In fact, the space sector has been excluded from major environmental agreements that apply on Earth due to its relatively small global impact [12], people are now worried that the foreseen increase in launches by 2050 may lead to huge environmental impacts of the space sector. However, due to lack of scientific data and knowledge gaps, the effects can only be estimated [13].

Nevertheless in the present project, we believe that knowing the sustainability problems encountered on Earth is the first step to avoiding reproducing similar ones on the Moon.

7.1.1 Space debris

Satellites at an altitude of 500km will remain in orbit for a few years to a few decades, while the majority, above 800km, have orbital decay periods measured in centuries [5]. The number of manmade orbital debris threatens the sustainability of all scientific and commercial pursuits in near-Earth space. These debris includes satellites that have reached the end of their lives, launch vehicle stages, hardware accidentally released by astronauts, as well as the remnants of spacecrafts and launch vehicles which have exploded or been hit by other debris. Although much of these debris will eventually re-enter the Earth's atmosphere and burn up, as long as these are in space, they remain threats to the viability of operational satellites and the sustainability of commercial applications [2]. It should also be noted that spacecraft can only avoid catalogued debris if they are equipped with maneuvering capabilities [5].

The *"Kessler Syndrome"* is a theory that the orbital debris population could reach a critical density beyond which cascading collisions between debris could become self-sustaining even without additional launches, ultimately rendering the space environment unusable for hundreds or even thousands of years. The phenomenon can be seen as a planetary boundary that must not be surpassed [13].

7.1.2 Reentry issue

A common practice in the context of space debris mitigation is to voluntarily deorbit spacecraft by re-entering the Earth's atmosphere when they reach their end-of-life, in order to reduce the population in orbit. However, particles from these burning spacecrafts (e.g. aluminum) could have harmful effects on the ozone layer or the climate. Particles of several metals resulting from the re-entry into the atmosphere of thousands of satellites from large constellations would far exceed injections of natural origin such as meteorites, but the resulting effects are yet largely unknown [13].

Although purely hypothetical at this stage, it is possible that at a critical rate of objects entering the atmosphere, the resulting pollution could reach a level that would attract the attention of political decision-makers [13].

7.1.3 Ozone depletion

With the projected growth of the space sector, the contribution of rockets to ozone depletion will inevitably increase in the future. There will be a growing risk of regulation of rocket exhaust compounds in the name of ozone protection. The uncertainty of the data, combined with the fact that the Montreal Protocol lacks adequate measures to effectively control rocket emissions, makes this risk even greater. If left unregulated, rocket emissions could, by 2050, deplete ozone more than ozone-depleting substances ever have [13].

Over the lifecycle of complete space missions, launch has been reported to contribute almost 100% of the ozone depletion potential. Ozone is mainly destroyed by highly reactive radicals (oxides of chlorine, nitrogen, bromine and hydrogen), with a single molecule capable of destroying up to a hundred thousand ozone molecules. Ozone depletion by solid rocket engine (SRE) particles has always been the main concern, as liquid rocket engines (LRE) exhaust contains less reactive chemicals and particles, and is therefore responsible for an order of magnitude less ozone loss than solid rocket engines [13].

7.1.4 Black carbon

Hydrocarbon-based rockets emitting black carbon (e.g. kerosene-fuelled LREs or most hybrid rocket engines) and alumina-emitting SREs are responsible for most of the impact of rockets on the climate. These black carbon particles accumulate in the stratosphere and absorb a fraction of sunlight, causing the stratosphere to warm up. Alumina, on the other hand, displays a more complex behavior, reflecting incoming radiation into space and absorbing radiation rising from the Earth. This also results in a warming of the stratosphere. At the same time, the reduction in solar flux caused by this accumulation of particles in the stratosphere leads to cooling of the lower atmosphere and ground. As a result, studies that only take CO2 emissions into account when assessing the contribution of rockets to climate change underestimate it by several orders of magnitude [13].

7.1.5 Marine pollution

Debris jettisoned during launch can have the following effects on the marine ecosystem: direct impact on wildlife, underwater noise and disturbance on impact, toxic contaminants (e.g. fuel, batteries), debris ingestion, smothering of the seabed and addition of hard substrate. As shown by the case of the now decommissioned Russian Rockot launcher, which was propelled by a hypergolic propellant (a highly toxic chemical that poses potential risks to the environment) new propellants must undergo detailed assessment before their use is authorized, to avoid the release of toxic substances into the natural environment [5].

7.1.6 Growing constellations

In addition to jeopardizing the sustainable use of the space environment, large constellations can, by reflecting sunlight back to Earth and emitting radio signals, have a negative impact on the visibility of the night sky and interfere with professional astronomical observations. After the launch of SpaceX's first Starlink satellites, many astronauts reported satellite trails, sometimes visible to the naked eye, interfering with their work [13].

Figure 2: Peter Beck with the "Humanity Star". Source: Rocket Lab

In addition to these satellites, other proposals have included artificial moons to light up a Chinese city, or orbital billboards to advertise in the night sky. In 2018, the launch the *"Humanity Star"* surprised the astronomical community and was even described by some as a space graffiti, it has reentered the atmosphere since then. The pristine night sky is a common heritage of humanity: the changes evoked could have, in addition to repercussions on stargazing and scientific research, unforeseen effects on wildlife, human health and cultural or religious practices. Without greater caution, the unregulated action of private interests in space could lead to the tragedy of two common goods: the near-Earth orbital environment and the night sky [13].

7.2 Moon

Once the first spacecrafts were put into orbit around Earth, the next obvious target of scientific interest was the Moon, simply because of its relative proximity to the Earth. While most spacecraft take several months to reach the nearest planets such as Mars and Venus, the Moon is only three days away [2].

It should be noted that the Moon was, and is still considered by some people, a big rock orbiting the Earth, with limited scientific interest. Moreover, as the Moon is the first extraterrestrial ground we want to colonize, all the mistakes that will occur will serve as lessons learned for future explorations, to Mars or beyond.

7.2.1 Guidance and navigation system

It will be necessary to install an orbital infrastructure around the Moon such as ESA's Moonlight initiative, for at least, communications and localization, allowing for safe surface operations. A Moon constellation will raise the same issues as the many objects currently orbiting the Earth. But will be needed to allow for communications on the lunar surface and to Earth, which is also important to keep people mentally sane.

7.2.2 Rocket impacts on the Moon

In the past, it was acceptable that ~13-tons S-IVB third stages of the Saturn V rocket should be targeted at the Moon [2]. Between the Apollo 13 and 17 missions, all the S-IVB stages intentionally collided with the Moon to trigger *'moonquakes'*, enabling the structure of the Moon to be studied [6]. These were recorded by seismometers placed by astronauts on Apollo's (12 to 17), which were contained in the Apollo Lunar Surface Experiments Package (ALSEP) of those missions. It should be noted that Apollo 7 which did not use Saturn V, stayed around the Earth and impacted its S-IVB in the Indian Ocean. During Apollo 8, 9, 10 and 11, the S-IVB velocity was decreased to go around the trailing edge of the Moon, sending it into solar orbit through a slingshot maneuver [7]. Apollo 12 failed to place the S-IVB in a solar orbit, as planned, and the resulting orbit was a high-apogee ellipse [7]. This stage is thought to be the unknown J002E3 object, which cycles between an heliocentric and geocentric orbit [6]. The ascent stage of the lunar module was planned to impact the Moon on Apollo 12, 14, 15, 16 and 17. However, it was jettisoned in lunar orbit on Apollo 11 as well as 16 due to attitude control issues [7]. Those stages eventually impacted the Moon at uncontrolled locations.

Figure 3: Example of the titanium alloy sphere carried aboard Luna 2, from [10]

The first ever spacecraft to impact the Moon was Luna 2 on 15 September 1959. The mission's main intention was to deliver a political message, in fact, the spacecraft carrier a ball made up of 72 pentagonal sections designed to survive impact and scatter Soviet medallions on the Moon [9]. While Luna 1 missed the Moon, it also carried a ball of pennants with the inscription *USSR JANUARY 1959* and was probably meant to impact the lunar surface. Luna 2 had engraved *USSR SEPTEMBER 1959* [9].

The impact that has attracted the most criticism is that of Lunar Prospector, which aimed at the Moon's south pole in 1999 with the aim of creating a plume of water molecules from presumed polar ice deposits. Not only was it not sterilized or actively decontaminated, it also carried the cremated remains of lunar geologist Eugene Shoemaker, which some have argued is hardly compatible with the search for drinking water [2].

Although there are no regulations on the sustainability of space, common sense would suggest that crashing spacecraft on the lunar surface or leaving them uncontrolled in lunar orbit is not a behavior compatible with the presence of humans on the Moon. As of today there have been more than 120 spacecraft impacts on the lunar surface, some at known locations, others at unknown locations [8]. Similarly, the planting of flags or the scattering of medallions could be reproduced by private companies, through advertising for example, and could be used to claim territory.

7.2.3 Sterilized spacecrafts

Some worry that the planned missions risk damaging the environment they seek to explore, by contaminating the surface before potential life forms have been discovered.

Indeed, false positives due to poor sterilization techniques could harm scientific exploration, not only by giving false hope to those searching for signs of extraterrestrial life, but also by potentially closing off a region to further research (and thus affecting the sustainability of scientific exploration) [2].

The potential for confusion is also important, see the case of the camera of Surveyor 3 returned by the Apollo 12 crew. We still don't know if the bacteria survived two years and seven months on the Moon, or if they were introduced when analyzed back on Earth [2]. More recent missions such as the Israeli Beresheet crashed on the Moon carrying genetic samples and tardigrades, the latter of which could potentially have survived the impact. The Chang'e 4 mission, carried seeds and insect eggs to test whether they could grow in low gravity, inside a mini-biosphere.

The presence of humans on the moon and the scheduled regular trips between the Earth and Moon could result in forward contamination by contaminating the Moon, or backward contamination by contaminating the Earth. Therefore, it is important to have clear guidelines to ensure that the environment is not disturbed, and is preserved in the currently existing conditions to allow for the search for life.

7.2.4 Debris re-orbiting

Unfortunately, a debris-generating mechanism not known from Earth orbit may operate in lunar orbit. Due to the relatively low gravity of the Moon's surface and the absence of an atmosphere, debris that hit the surface at high speed can potentially be thrown onto high-altitude trajectories, or "reorbit". Observations made by the Galileo probe orbiting Jupiter have indicated that small natural debris produced in this way could be found orbiting the Jovian moons Ganymede, Callisto and Europa [2].

Meteoroids, which strike the lunar surface vaporize particles on impact and project large clouds of lunar dust into space. The absence of an atmosphere means that these particles follow purely ballistic trajectories and, unless they are ejected at above orbital velocity (1.6 km/s), they will travel through space and fall back to the Moon. New studies indicate that the Moon has a permanent dust cloud generated by constant meteoroid impacts, as measured by the Lunar Atmosphere and Dust Environment Explorer (LADEE) [18].

With the high energy impacts of past Apollo Saturn stages, some lunar orbital debris population may already exist. However, in the absence of Moon-based radar systems similar to those on Earth, we have no way of knowing [2]. Those orbiting debris may damage lunar orbiting spacecrafts [27].

7.2.5 Lunar dust

Considering that a single Apollo mission temporarily doubled the Moon's total atmospheric mass, due to rocket engine emissions, it takes little imagination to predict the environmental impact of sustained exploration and development of the Moon. In fact, an industrial development on the Moon could create a *"lunar atmosphere"* of engine exhaust products [2].

NASA analyses have shown that rocket exhaust plumes from the landing stages can induce high injection velocities from the top layer of the lunar surface. The model predicts a sheet of blown material at an angle of between 1 and 3 degrees elevation above the local terrain on all sides around the landing spacecraft. Due to the high velocity of these particles and the absence of atmosphere on the Moon, the particles continue to travel until they hit the lunar surface at a great distance, some almost circling the Moon before impact, while the smallest particles can even be sent into a heliocentric orbit [27].

Plume-surface interaction (PSI) is an important issue for future lunar soft landers. For the reasons given above, but also because ejected dust could directly damage the lander or its vision capability [32].

7.2.6 Moon's surface and fragility

While scientists will characterize chemical compositions or search for traces of life, future inhabitants of the moon may wish to exploit the resources or construct all kinds of buildings. The problem is that the lunar environment is far more fragile than the Earth's, because it has no atmosphere, no weather and no self-repair capability, and any change to its barren surface is practically irreversible [2]. Therefore, using the same definition as on Earth, the usage of any Moon resource would be considered unsustainable.

7.2.7 Debris and trashes

While we have seen that spacecraft impacts on the Moon can scatter a lot of debris on its surface, the end-of-life of rovers can also lead to the creation of lunar debris. In fact, over 70 spacecrafts remain on the Moon for the simple reason that they are too heavy and not worth bringing back. They account for most of the mass left on the Moon [34].

Figure 4: Memorial to Fallen Astronauts. Credit: NASA

But that is not all, some of the waste dumped was food wrappers, wet wipes and 96 packets of human urine and excrement. They also dumped tools, television equipment... all so they had more weight available to bring lunar samples back to Earth.

Sometimes, the reasons for leaving objects on the Moon were more sentimental or ceremonial. There is a family photo of Apollo 16 astronaut Charles Duke, American flags at each of the Apollo landing sites, Gene Shoemaker's ashes carried by the Lunar Prospector space probe, a feather and hammer from a TV experiment by Apollo 15 astronaut David Scott, an aluminum sculpture by a Belgian artist: the *"Fallen Astronaut"*, golf balls and clubs, etc [35].

7.2.8 Health threats to crew

Humans on the Moon are subject to various health risks. Many risks exist on the Moon as in space: radiation, isolation, distance from the Earth (a sensation that could be even greater on the far side of the Moon), low-gravity fields that can have an impact on astronauts' bodies, and the very closed environments of spacecraft and habitats to protect against the hostile environment [37].

However, there is one human health risk that we encounter on the Moon and not in free space: lunar dust. Indeed, these tiny particles are virtually impossible to keep away from humans, and it has been reported that in 1972, astronaut Harrison Schmitt suffered a brief attack of sneezing, red eyes, itchy throat and congested sinuses in response to lunar dust. Other astronauts have also experienced the harmful effects of lunar dust on their bodies [38].

On Earth, preparations for mitigation protocols of the lunar dust can be carried out using lunar dust simulants. Furthermore, while the characteristics and formation of Martian dust are different from those of lunar dust, advances in research about lunar dust toxicity, mitigation and protection strategies may prove strategic for future Martian operations [38].

7.2.9 Radioactive and dangerous materials

Nuclear power on the Moon, as envisioned by NASA's Fission Surface Power Project, offers a promising solution for sustaining long-term exploration and operations on the lunar surface. A small nuclear fission reactor could provide reliable power during the lengthy lunar nights or in PSRs where solar energy is unavailable, supporting habitats, scientific experiments, and rovers [39].

However, using nuclear power on the Moon also introduces risks and concerns. Ensuring the reactor's safety, particularly in managing radiation exposure and shielding, is a top priority. Potential system faults, fuel management, and heat rejection must be addressed to prevent accidents [39].

8 Regulations

8.1 Existing treaties

There are four main space treaties signed by the major space-faring nations. All these treaties are administered by the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS).

The only space treaty that regulates the space environment is the Outer Space Treaty, signed in 1967. The treaty is broad and if regarding specific topics, it can be largely open to interpretation. In short, the Outer Space Treaty states [36]:

- The exploration and use of outer space shall be carried out for the benefit and in the interests of all nations and shall be the province of all humankind
- Outer space shall be free for exploration and use by all countries
- Outer space is not subject to national appropriation or ownership
- States shall not place nuclear weapons or other weapons of mass destruction in outer space
- The Moon and other celestial bodies shall be used exclusively for peaceful purposes
- Astronauts are regarded as representatives of humanity by all nations, and shall be given all possible assistance in the event of accident or emergency
- States shall be responsible for national space activities, whether carried out by governmental or non-governmental entities
- States shall be liable for damage caused by their space objects
- States shall retain ownership and jurisdiction over any object they launch into outer space
- States shall avoid harmful contamination of space and celestial bodies.

These statements could be interpreted in a way that supports sustainable behaviors in space.

The other three space treaties deal with the consequences of space activities on Earth: the *"Rescue Agreement"*, the *"Space Liability Convention"* and the *"Registration Convention"*. As far as the Moon is concerned, the United Nations' attempt to bring the Moon under international law through the *"Moon Treaty"*, has not been ratified by the major spacefaring nations.

The Moon Treaty of 1979 was produced due to concerns about the lunar environment and the realization that it should be protected. However, this document was not ratified by any main spacefaring nations [4].

8.2 The Artemis Accords

More recently, with the development of the Artemis program, the Artemis Accords were signed. It should be noted that these agreements are non-binding, meaning that they are preliminary discussions on the expected norms to be followed in outer space. The signatories do not include important spacefaring nations such as China or Russia. The accords focus on 9 norms for the peaceful exploration of the Moon: *transparency, interoperability, emergency assistance, registration of space objects, release of scientific data, preserving outer space heritage, space resources, deconfliction of space activities* [33].

It should be clear by now that it is difficult to impose regulations on all nations. Here, the concerns of the documents presented relate to the success of the mission, which is a key point for the safety of astronauts and the peaceful use of space. Yet we note that it is difficult to reach agreement on these important points, so what can we expect from agreements on sustainability?

8.3 Existing recommendations

Recommendations published by NASA to protect the historical Apollo site can be translated to protect other assets on the Moon [27].

9 Sustainability

9.1 Definition

While there exist many definitions in the terrestrial context, 'sustainability' was defined for outer space by the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS) in 2018 [41]:

"The long-term sustainability of outer space activities is defined as the ability to maintain the conduct of space activities indefinitely into the future in a manner that realizes the objectives of equitable access to the benefits of the exploration and use of outer space for peaceful purposes, in order to meet the needs of the present generations while preserving the outer space environment for future generations"

We find in this definition concepts from the Outer Space Treaty and from the original definition of sustainability for Earth published in 1987 by the United Nations. Moreover, an improvement to the above definition for outer space was agreed on by the Environmental Task Force of Space Scotland [41].

9.2 Discussion

With the growing importance of sustainability in our daily lives, consideration of the impact of our presence on the Moon is of the utmost importance. Careful consideration of known risks will help shape a more sustainable future in space, and increase public acceptance of space exploration.

In addition to their potentially serious impact on the environment, the economic, energy and material requirements of some proposed space projects, such as space colonization and Earth-to-Earth transport, could be prohibitive. They could also become increasingly socially unacceptable and ethically questionable. Moreover, the space-based solutions proposed to overcome energy and material issues on Earth (e.g. large-scale space solar power and asteroid mining) are irrelevant to the timescale of the transition to meet climate targets [13].

Looking at the date of publication of certain articles concerning the environmental fears of human activity on the Moon, some published about 25 years ago. It is reasonable to wonder about the real possibility of such measures being put in place, and the length of time it would take to make them. However, it seems essential that space professionals learn more about the history of the solar system exploration, its detrimental effects, and develop an awareness of the potential for future environmental damage [4].

For over 50 years, concerns have grown about the impact of human activities on the Moon, dating back to the first Apollo landings. Today, virtually all articles on the subject emphasize the urgent need for regulations to govern lunar activities. Despite this, efforts to define and enforce such rules remain in their infancy, leaving the issue largely unresolved.

A significant obstacle is the lack of scientific data necessary for life cycle assessments (LCA) to evaluate the environmental impact on Earth resulting from lunar operations. Furthermore, the concept of Moon sustainability is itself poorly defined. What does it mean for activities on the Moon to be sustainable? Some propose adopting the idea of "planetary boundaries" similar to frameworks used on Earth, to establish clear, quantifiable limits on the impact of human activities on the Moon.

Regulations imposed by governments could one day limit the possibilities of exploitation on the Moon, and space stakeholders should consider anticipating them.

9.3 Scientific exploration

The key requirement for sustainability of scientific exploration of the space environment is the protection of that environment (which includes the surfaces, sub-surfaces and atmospheres of the planetary bodies as well as interplanetary space). This is because space science is predicated on discovering what there is in the natural space environment, not the effect we have had on it [2].

9.3.1 Human presence

The sustainability of lunar science must itself be balanced against the safety of future lunar scientists [2].

9.4 Industrial developments

While the main interest on this project is to make projections based on the production of O_2, it can be expected that as the industrial development of the Moon evolves, other minerals will be sought. If the mineral is not available easily on Earth, a number of launches will be necessary to bring it back to Earth.

9.4.1 Volumes of regolith processed

Typically, minerals deposited by solar wind (such as Helium-3), can be found in the first three meters of lunar regolith across the whole lunar surface [2]. However, the concentration is only of several parts per billion, and to extract a significant amount, extensive volumes would have to be displaced.

9.4.2 Cooperation on the lunar surface

International collaboration is expected to play a significant role in the early stages of lunar exploration, particularly during the development of key technologies by various partners. However, this cooperation may not last indefinitely.

As missions progress, individual nations or organizations could choose to pursue independent projects, as seen with the ISS, where Russia has announced plans to build its own space station. Such shifts could lead to fragmentation in lunar activities, with each party focusing on its own goals. Individual developments on the Moon could potentially overlook the interests, and perhaps even the rights, of other lunar users.

9.4.3 Second life of space objects

An interesting idea to keep in mind for future lunar rover development is to imagine the second-life use of the components of the rovers. Such components could be made compatible between very different lunar technologies so as to promote their reusability. As of today, there are no regulation or general solution regarding the end-of-life of lunar equipment.

Idea of guideline: however, to avoid issues similar to LEO, it seems necessary for all lunar missions to have an end-of-life plan for their equipment. What's more, the equipment should be in a place where it could potentially be recovered easily and safely, using technologies already available at the time it was created. We should have a place where we can find standard spare parts.

9.5 Natural aspects

9.5.1 Current trashes

What should be done with the current garbage on the Moon? Do we need regulations to address it, or can anyone clean it up? Another question is whether the discarded parts left on the lunar surface still legally belong to the states that originally placed them there. These unresolved issues highlight the complexity of managing the remnants of human activity on the Moon.

9.5.2 Lunar regolith

The lunar dust is an issue for its abrasiveness, but coupled with the low gravitational field of the Moon, for its volatility. In the context of future large lunar settlements on the Moon, the issue of loosing control over the lunar dust is large. We should not wait for technological solutions tackling this problem to raise awareness and write usable guidelines to guide future mission designs.

9.5.3 Pristine beauty

The lunar surface was described as *"a magnificent desolation"* in Buzz Aldrin's words, however this beauty is at risk. The Moon has no self-repair capability, and any change to its surface it practically irreversible.

As ISRU production increases, enormous volumes of regolith will have to be processed to extract the materials. Depending on the mining technique, this will have an impact on the aesthetic of the Moon, both from its surface and potentially as seen from Earth. Therefore, if not banned, mining on the nearside of the Moon could be limited by future regulations.

1. Irreversible lunar damages.
2. Aesthetic impact, visible from Earth.

9.6 Technological challenges

Proper navigation systems are essential for guiding rovers on the Moon. Historically, issues with inadequate systems have highlighted the need for reliable solutions to ensure successful missions. One proposed approach involves deploying a constellation of satellites to enable precise navigation across the lunar surface.

However, such constellations could create conflicts with other lunar interests, particularly radio astronomy. The physical presence of these objects and the electromagnetic radiation they emit could interfere with sensitive observations, posing challenges for balancing exploration and scientific endeavors on the Moon.

9.6.1 Reliability of space project

Space projects carry an increased risk of failure, which can result in the creation of waste on the lunar surface and in orbit. Failed missions often leave behind debris, including non-functional equipment and worn materials, that contribute to long-term environmental challenges.

9.6.2 Landing sites of Apollo missions

With the footprints of Armstrong and Aldrin still being visible on the Moon, those sites are of cultural importance. Typically, old rovers and lunar equipment still present on the surface could be coveted by trophy hunters and stolen (it happened to Egypt, so it could happen on the Moon) [2].

9.6.3 Space tourism

With development of infrastructures and industries on the Moon, a next step will be space tourism. However, there is nothing preventing those tourists from degrading the environment. As similar harsh environment that is littered frequently on Earth is Mount Everest.

Commercial human spaceflight is still generally considered an experimental activity, in which participants take part under an informed consent regime. However, as commercial human spaceflight becomes more common, there will be a need to document and codify safety practices, including lessons learned [26].

10 Moon base

10.1 Why are we going?

The reasons why we are going to the Moon is at the intersection of scientific, inspirational and national posture goals. An extensive list of reasons is available in this document [16]. Regarding the importance of sustainable lunar activities, it is inevitable that we will become an interplanetary species, so we should work together to do it right.

Eventually, it will be an economic decision whether we do ISRU on the Moon or take the resources from Earth. Whereas on Mars, there is no other choice than doing ISRU. Therefore, because of the lowering of the prices of transports from Earth, we will have to see where ISRU reveals to be more economical [23].

10.2 Potential telescope on the Moon (dark side)

The radio quiet far side of the Moon is a unique location to take sensitive measurements of the dark ages of the universe [16]. This is partly because the moon is tidally locked, meaning that its far side always faces away from the Earth. It is also because as the universe expands, many distant signals are shifted to longer wavelengths, impossible to detect by terrestrial telescopes [17].

A telescope placed in a crater would benefit the natural coldness and the lack of atmosphere.

10.3 Oxygen extraction

10.3.1 Presence of water on the Moon

Many international space actors are aiming at the poles where potentially large quantities of water could be found. In 2009, the LCROSS spacecraft first discharged a projectile into a crater and flew through the debris of the impact to analyze its composition, before impacting the Moon itself while the LRO spacecraft observed [19].

In 2018, the analysis of the Indian Chandrayaan-1 datas confirmed the presence of water in shadowed regions, while in 2020 data from the SOFIA observatory revealed water in the sunlit surface of the Moon [19].

However, there is currently no evidence of the quantity of accessible water in those areas. Indeed the LCROSS impact estimated a 5.6 ± 2.9 wt% H_2O, which may be a high value not representative of the PSRs in general, the depth of the distribution is unknown [14].

10.3.2 Reasons to look for water

Water is expected to be the most important resource on the Moon in the short term, both for in-situ resource utilisation (ISRU) and for the eventual development of a cis-lunar economy, due to its wide range of applications. It is essential for life support, personal hygiene, energy storage in fuel cells and as a solvent in various industrial processes. In addition, water can provide oxygen, which is vital for sustaining life and serves as an oxidant in rocket fuel. It also provides hydrogen, which can be used as rocket fuel and as a reducing agent in industrial applications [14].

For those reasons, while NASA wants to reach the poles, European space companies are focusing their efforts in extracting O_2 from the regolith itself, which is not only located at the poles and contains around 40% wt of O_2.

We focus on oxygen production because in hydrolox or methalox engines, the oxygen takes up the most part of the weight. As an example the Space Shuttle carried ~ 616500 kg of liquid oxygen and ~ 102600 kg of liquid hydrogen [20]. Moreover, hydrogen and carbon are not easily available in regolith. Although produced oxygen could also be used by astronauts to breath, this usage does not justify by itself the ISRU production of O_2. Based on requirement for the ISS, a three-person crew would require 1000 kg/year of O_2 on the Moon for life-support [14].

10.3.3 Technological challenges

It should also be considered that rovers operating within PSRs would need to be able to survive total darkness and cryogenic temperatures for long periods of time which poses significant engineering challenges.

10.4 NASA's plan at the south pole

This summary of the future activities at the south pole comes from [21].

10.4.1 Constraints

Operating at the south pole is no easy task, the rovers extracting water from the PSRs will operate at very low temperature (25 K to 70 K). In addition, the supply of solar energy to the rovers operating inside the PSRs poses problems. Finally, we still know very little about this region: obtaining more data on conditions within the shadowed regions is vital to the design of lunar ice processing plants [21].

What's more, unlike terrestrial mining operations, which use heavy machinery to move resources, the mass constraints of a lunar mine are very restrictive because of delivery costs. Other difficulties relates laws that do not define who owns what on the Moon [21].

Technical challenges for the rovers operating in the craters of the south pole are the very steep slopes (up to 40°) over a rugged terrain. None of these sites is in Earth Line of Sight for communications, which means that relays will be needed (on the surface or in orbit). When drilling, the temperature should remain sufficiently cold to prevent volatile loss [21].

Also, the technologies that will be used on the Moon needs to be tested on the Moon, because there may be unknown surprises there. If there is no human presence, the operating rovers will be limited in speed as there is nobody to unstuck or fix it. As an example, the Curiosity rover on Mars travels at an average speed of 30 m/h [22]. The presence of human would allow a more aggressive exploration, allowing not only repairs but also upgrades and retrieval of rovers directly on the planet [23].

All those constraints are to keep in mind when developing prospective lunar missions.

10.4.2 Customers

The O_2 produced on the Moon will be delivered on the surface, but also in cislunar space. Indeed satellites orbiting the Earth could be refueled in LEO, while future Mars missions could be refueled in lunar orbit.

10.4.3 Business

To make the lunar facility economically viable, the value of resources it produces must exceed its cost, including the costs of development, launch, installation and operation. Moreover, the price of lunar products will always be limited by the price of materials sent from Earth (which is expected to decrease as more reusable launchers are developed) [21].

10.4.4 Future infrastructure

The idea is to extract water from regolith by sublimation, heating ice to convert it into water vapor without going through the liquid phase. Thus no extraction of bulk icy regolith is done, it is sublimated in place. The vapor which escapes from the surface is captured by a dome-shaped tent (a tent has a low mass) covering the heated surface. The vapor in the tent is vented through an opening and transported to a central processing plant to extract O_2 and H_2 [21].

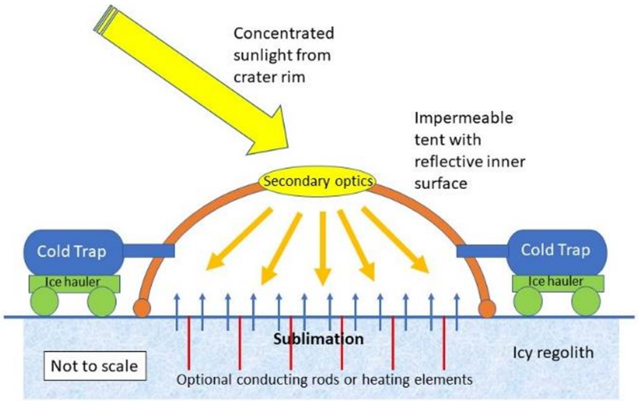


Figure 5: Thermal mining concept. From [21].

A suggested idea, rather than carry dedicated storage tanks is to entirely store the propellant in used propulsive stages. This means to fill the stages in the places they land, without moving them or creating pipelines. The need for tanks in cislunar space will however be needed. Also, the storage of propellants requires heaters to preclude freezing and cryocoolers to eliminate or minimize boil-off. The use of multi-layer-insulators (MLI) is also nedded to reduce the heat load from the Sun, Earth and Moon that reaches the tank outer wall. Hydrogen with its 20.28 K boiling point is the hardest propellant to keep from boiling [21].

The two main possibilities for power production is solar power or nuclear power. Currently, only kilo-power reactors have been NASA's recent focus, while solar power is difficult to operate in regions of extended shadow. Two private companies, Atomos Nuclear and Space and USNC, however, are working to develop space reactors with power levels from 150 kW to 1000 kW and mass around 5000 kg [21].

With solar power, the difficulty is that in most cases the distance between the rim of the crater (nearly constantly illuminated) down to the mining and processing infrastructure in the PSR bottom are in kilometers. Solar arrays must be supplemented with energy storage devices, such as batteries, to maintain operations while blocked from the Sun. Different technologies of solar power are possible, including solar panels, concentrator or solar dynamic. Some are lighter or have more efficiency [21].

The wire power transmission makes sense for small craters where the mass of the conductor can be minimized, but the ability to lay the wires down the steep slopes creates its own deployment challenges. Power beaming can transmit power wirelessly using microwaves or laser transmission. An heliostat tracks the sun in two axes and concentrate sun light to a small-aperture receiver, however when the distance between the heliostats and wokstation exceed a certain range, the system efficiency may diminish quickly. Other possibilities include batteries or robots with onboard RTG systems [21].

Although nuclear reactor can be promising, current restrictions are not pointing towards their utilization. At low power levels (up to approximately 100 kW) Highly Enriched Uranium (HEU) usually produces smaller and lighter reactor than Low Enriched Uranium (LEU), however the use of HEU is a national security concern because it is the simplest nuclear material to use for an improvised nuclear device. Security, proliferation concerns and costs associated with procurement and processing of restricted materials have been the key failure point in the US adoption of space nuclear. The Article VI of the Outer Space Treaty makes the US government legally responsible for its domestic, commercial space operations, once again demonstrating that the use of nuclear technologies is likely to prove difficult [21].

While some energy could be extracted from the heat produced by a reactor, moving an electrical cable is far simpler and introduces less risk than trying to deploy and shift plumbing with reactor coolant [21].

The architecture of the commercial lunar propellant system is being designed without a requirement for human presence. This means that all phases of the operations (building the landing site, the power plant, the extraction facility, the processing and storage facility) must be executed by robotic means. The OffWorld company develops a universal platform with modular attachments to make robots with different functions. Another solution includes robots elevated on a track which moves above the regolith [21].

ISRU only works if we can make rendez-vous in space to transfer propellant to customers. Thus it is important to perform low-cost rendez-vous, which can be achieved by lowering the system's complexity if the gateway posseses a retrieval tug responsible for all sensing, thrusting, rendezvous and berthing operations [21].

To support the lunar propellant production, it is important to have a communication and navigation infrastructure. Earth-based capabilities only provide service to the nearside of the Moon, thus relays are needed for the lunar far side and polar regions [21].

Landing on the Moon using rocket thrusters causes significant regolith ejecta, including dust, sand, and rocks. Mitigation strategies include placing landing zones in craters or behind hills, constructing berms (though their effectiveness is uncertain), and building durable landing pads. Curtains and fences may be problematic due to placement constraints. Ejecta effects could be more severe in Permanently Shadowed Regions (PSRs) due to less compacted regolith, influenced by reduced thermal cycling [21].

Lunar regolith is abrasive, damaging components like joints and tires, which may require new vehicle designs or elevated track systems. Navigating dark crater bottoms poses challenges, highlighting the need for improved transport routes. Proposed solutions include compacting or laser sintering the regolith to create roads, using chemical binders, or building elevated tracks to reduce regolith contamination, simplify navigation, and provide vehicle power [21].

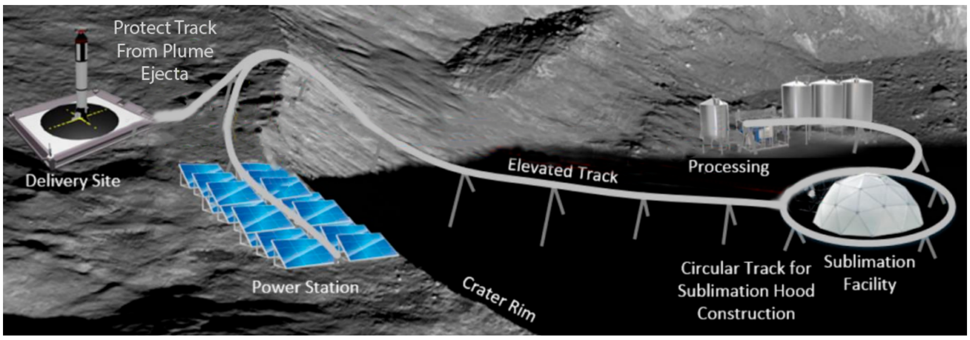


Figure 6: Polar base schematic. Modified from [21].

Shipping lunar ISRU propellant to cislunar space, particularly LEO, is costly due to the 6.2 km/s Δv requirement. Traditional chemical rockets consume most of the propellant in the process, requiring over 6 kg of lunar fuel to deliver 1 kg to LEO, making it very inefficient. Promising alternatives include "propellantless" methods such as electromagnetic launch and rotary sling-tethers, which could reduce costs [21].

In-space commodity prices will be limited by competition from Earth. As launch costs decrease, the value of lunar propellant will drop, preventing commercial lunar miners from selling their products at prices higher than Earth-supplied alternatives [21].

A key question is what happens to equipment left unused on the Moon if a lunar company goes bankrupt, potentially creating debris?

10.5 Lunar Exploration Plan

10.5.1 Discussion

In this section the goal is to perform an estimation of lunar energy required per kg of O_2 produced, based on the current technologies developed by the members of E2M. In case of missing informations for one component of the value chain, the value will be estimated based on basic principles or taken from NASA's plan at the south pole.

The objective is to have a better representation of what the production of 40 kT/year means. Indeed, while the business cases for lunar ISRU have been well-considered, the scale of the mining operations required to produce the projected amount of oxygen has received less attention [24]. The value obtained will be useful to estimate the required size of a solar panel field, or the potential need for nuclear energy. The upper-bound for the price of the energy per kg of $\mathrm{O_2}$ can be estimated as the price it would cost to ship $\mathrm{O_2}$ from Earth. The requirement to produce 40 kT/year will allow to estimate the operating mass rate of the mine operation, which is not known in great details and can have large impact on the equipment and lunar landscape. Moreover the scale of operations is important as it defines whether to operate on a continuous or batch basis [24].

It should also be noted that two of the most significant uncertainties in the ISRU value chain are the material properties and the spatial variability of the regolith. It is thought that so far, this has impeded the rigorous engineering design of reactors, transport mechanisms and excavation technologies [24].

Additional parameters to consider may include boil-off losses during storage, issues related to changing or refilling tanks, and challenges in relocating processing facilities. These factors will likely depend on variables such as the size and cost of the equipment involved.

Key data points to consider include the energy required per kilogram of output, the total weight of the infrastructure in its current version, and the system's expected lifetime. Understanding what the system is designed to achieve is essential for evaluating its feasibility and efficiency. Alternatively, financial considerations may suggest that the system should operate for a minimum duration to justify its cost.

Key existential questions arise regarding the operation of the system. Should it function continuously, or only during the lunar day when solar energy is available?

Another critical aspect is the operational availability of the lunar infrastructure, which is influenced by the lunar day/night cycle and the working hours of personnel, assuming human involvement is necessary (which is likely). In most studies, it is typically assumed that only 7.5 hours are productive out of an 8-hour shift. This limitation must be factored into the planning and efficiency calculations of lunar operations [24].

10.5.2 Mining zone

The choice of mining zones raises several important questions: Where should mining take place? What concentration of resources is ideal? And how does solar illumination affect the process?

These factors largely depend on the specific method chosen for extracting oxygen. The extraction process will determine the best locations and conditions required for optimal efficiency.

10.5.3 Drill rover

You need to account for preparing the mine area by removing boulders, smoothing out small craters and preparing roadways [24].

10.5.4 Refine factory

The article studies hydrogen reduction, but the concept behind the refining is the important part [24].

Refining, also known as beneficiation, is the process by which particles of a raw material are separated according to certain properties of the material, including size, density, conductivity, magnetism and surface chemistry. This refining step has been generally oversimplified or completely overlooked. This is likely a mistake as refining will help improve system reliability and efficiency, with a feedstock from which fine and coarse particles are removed (limits blockages, material handling issues, abrasiveness and dust) and regolith is decontaminated [24].

Removing the coarse particles (> 1 mm) which can cause blockage and the fine particles ($< 90\mu$m, difficult to measure their size below 90μm) which are considered to be too fine to be processed, leaves only 26.2% of the mined regolith for further processing [24].

Agglutinates are considered the most abrasive part of the feedstock and should not be handled extensively as it will rapidly cause extensive equipment wear. Furthermore, the glass (SiO_2) fraction is likely to cause issues in the high-temperature furnace due to sintering. Removing the glass and agglutinate fractions of the mined regolith reduces the usable part of the mined regolith to 20.9% [24].

NASA's ROxygen demonstration reactor observed that at temperatures above 800°C, the regolith particles clump together, which can lead to poor mixing and sintering, permanently fouling the reactor. In larger-scale experiment the O_2 yield was 4 times lower due to the scaling of the heat transfer to the reactor [24].

The O_2 yield given a particular grade of ilmenite (ilmenite content) in the feed is also a great unknown, but should be considered when estimating the mass rate to be mined to produce a given amount of O_2 per year [24].

The important trade-off with the processing unit is that if we require a high ilmenite content for the reactor, the feedstock mass rate is low, but the mined tonnage rate is very high. An oxygen-producing reduction furnace treating less than half a kilogram per hour of high-grade, sized feedstock will be smaller, lighter and less energy intensive than one treating a kilogram per hour of unsized regolith. But this is a complex technical and economic trade-off [24].

Refining directly (entirely or partially, for example only sort the size) at the mining site could lower significantly the amount of material which must be transported to the refining, processing and storage unit [24].

The process reactors are designed to operate with an ideal feed: a certain mass concentration of material, size, ... in order to operate at the highest oxygen production efficiency. However, there is little research on how these feeds would be produced in-situ, and how this would feed into the reactor and these technologies have not yet been developed for lunar applications [24].

It is surprising that no company at E2M is currently focusing on this issue, as there are significant technological challenges to address. Sorting the lunar regolith is not an easy task, and overcoming these hurdles is essential for successful operations on the Moon.

10.5.5 Process factory

While over 20 technologies have been proposed for this step, the four main being considered by NASA and ESA are: [24] [14]

- Hydrogen reduction of ilmenite, $< 2\%$ yield, ~ 900°C, in presence of H.
- Carbothermal reduction of silicates and iron oxides, $\sim 10\%$ yield, > 1600°C, in presence of CH_4.

- Molten regolith electrolysis, 20 – 40% yield.
- Molten salt electrolysis (also known as FFC Cambridge process), < 1000°C.

The yield is defined as the mass fraction of oxygen which can be extracted from the mined bare regolith.

The molten salt electrolysis was chosen by Airbus in the development of ROXY [40].

Some of these processes require an external feed of hydrogen or methane for the reaction to happen. Likewise some of these require oxygen to be bond to specific atoms, such as hydrogen reduction which primarily (not only) depends on the ilmenite ($FeTiO_3$) content. This limits the regions of the Moon where such regolith content can be found (a map of the Moon and its mineral content can be found in [24]), and limits the quantity of oxygen that can be extracted, from a theoretical mass content of 40%, less than 2% can be extracted. Finally the temperature at which thoses processes take place can pose technical feasibility issue.

10.5.6 Other

For solar panels, the key value of interest is kWh/m^2, as the dimensions play a crucial role. Additionally, other solar technologies should be explored. Batteries and cables are also essential components to consider for efficient energy transportation.

When it comes to transporting primary materials, options such as rovers or pipelines need to be evaluated. Cryogenic couplers for material transfer should also be factored into the planning process.

10.5.7 Estimates

The goal was to ask each member of E2M to provide interesting data per kilogram of regolith that their equipment processes: kg of equipment/kg, energy/kg, ... In such a way that the whole chain could be sized to achieve the required production of 40 kT/year. A second goal was to estimate the price of O_2 deliveries coming from Earth, so that we could have extracted a maximum price per kJ.

However, two major obstacles were encountered: firstly, the refining stage does not seem to be targeted by any member of E2M, and secondly, none of the companies responded nor shared their equipment data.

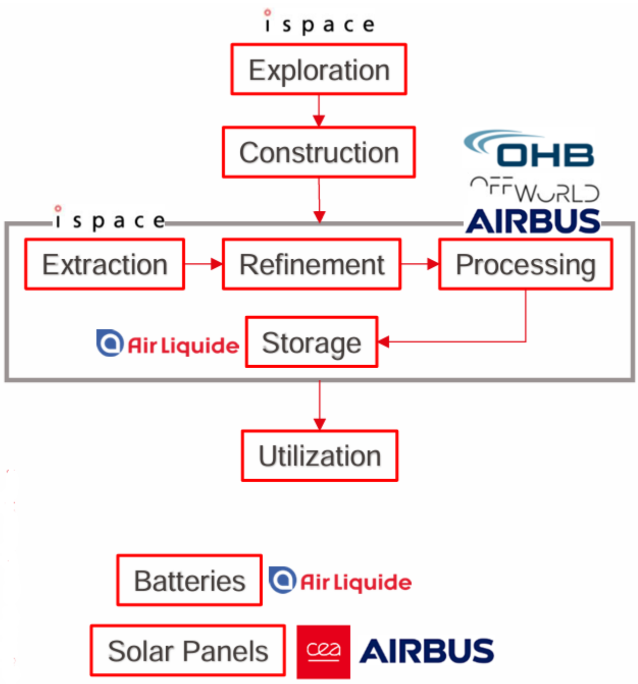


Figure 7: O_2 Value chain of E2M

11 Guidelines

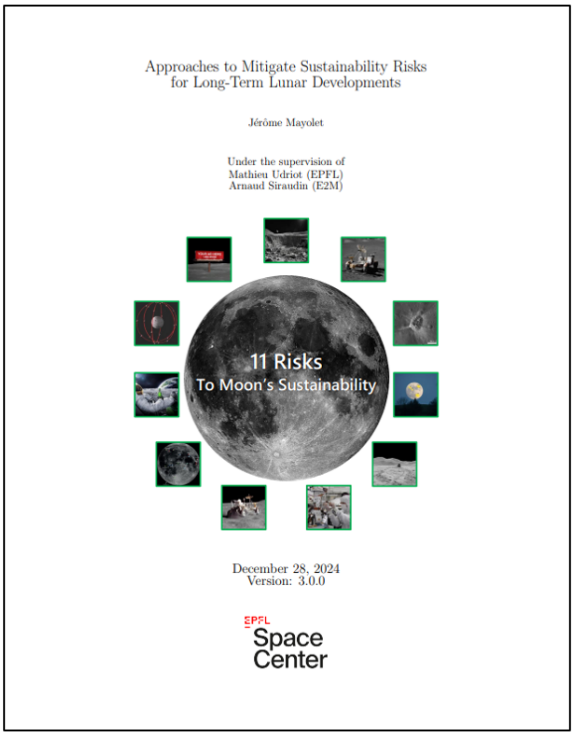
Although the drafting of guidelines was not pursued, as a risk analysis was preferred, we report here some thoughts on the subject.

Ideally, guidelines should be technology-independent, in the sense that they should be formulated in such a way as to impose constraints rather than solutions. For example, a guideline should sound more like *"The spacecraft must not make hard landings on the Moon"*, rather than *"The spacecraft must have retrorockets"*. Nonetheless, knowing about existing technological solutions can help to write technology-independent guidelines.

12 Risk analysis

Based on the content of the current document, which is the summary of an in-depth literature search, E2M asked to identify issues related to Moon's sustainability and to perform a risk analysis, which led to the writing of another report, presented in Figure 8. Different feedbacks were received to improve the document.

Beyond the risk analysis itself, this new report serves as a summary of valuable resource of ideas to foster discussions on lunar sustainability, and can be seen as a mean of presenting the results of the literature review by highlighting the causes, consequences, factors and best practices to reduce the risk of the issues.



Approaches to Mitigate Sustainability Risks
for Long-Term Lunar Developments

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December 28, 2024
Version: 3.0.0

EPFL
Space
Center

Figure 8: Front page of the risk analysis document.

12.1 The 11 Issues

The risk analysis highlights 11 issues which are ranked according to their risk, and each item within each issue is listed in alphabetical order. An effort has been made to ensure that all the issues are Mutually Exclusive and Collectively Exhaustive (MECE). In addition, the best practices respond to a defined formulation, as they have been classified into 4 groups. The word "best practices" is used instead of "guidelines", as imposed by E2M.

To improve consistency of the document, all the causes, consequences and best practices that are shared by different issues were phrased exactly the same. The word *"collision"* was used instead of the word impact, when referring to the spacecrafts surface collisions. Furthermore, we chose to have a grading system on a scale of 3 because of the limited information available to date on the Moon's environment, and we feel that a scale higher than 3 would have resulted in a more subjective rating. Overall from the feedbacks received, everyone agreed on the grade for the probability and impact on activities and the environment given to each issue.

Finally, the document was designed to be accessible to a wide audience, including non-technical readers. It is self-contained, with the main ideas presented in a clear and straightforward manner. Feedback received has confirmed its readability and clarity.

The 11 issues are the following:

Issue 1 - Lunar dust: pollution of the lunar environment caused by airborne lunar dust or regolith.
Issue 2 - Orbital congestion: high number of objects orbiting the Moon, both active and debris.
Issue 3 - Spacecraft surface collisions: spacecraft impacts on the Moon, accidental or on purpose.
Issue 4 - Biological contamination: biological contamination of the Moon by Earth living organisms.
Issue 5 - End-of-life of lunar assets: generation of a debri after the end-of-life of a lunar asset.
Issue 6 - Human-generated wastes: waste rejected by the human presence on the moon.
Issue 7 - Site utilization: conflict between stakeholders over the use of the lunar space.
Issue 8 - Moon's fragility and traces left by human activities: visual damage caused by human activities to the naturally pristine lunar landscape.
Issue 9 - Resource extraction: large quarry required to extract lunar resources.
Issue 10 - Visual pollution: visual pollution, altering the Moon's appearance as seen from Earth.
Issue 11 - Advertisement: advertising and the utilization of lunar sites for an unnecessary activity.

12.2 Late remarks

As a late received feedback suggests, biological contamination of the Moon is not necessarily as significant as that of Mars, as living organisms are not expected to be found on the Moon. After discussion with a COSPAR member at the Swiss Space Sustainability Research Days, this is the principal reason why there are already scientific regions defined on Mars and not on the Moon.

Nevertheless, the concept of conflict with science, and the fact that some sites on the Moon must remain unexplored to provide science with a pristine environment, remain important. While the science at the poles are of great interest because of the presence of PSRs and peaks of eternal light, the geology of the Moon is still largely unknown, and likely the main topic of science on the Moon [42].

12.3 Removed analysis

The analysis presented on the following page has attempted to see what the outcome of the risk analysis would be if all the best practices suggested in the document were implemented. While this seemed like a good idea, it was difficult to know whether best practices that keep areas pristine or prohibit access to them are complete solutions, based on the current grading system. Also, the effectiveness of a best practice is difficult to measure at this stage, as a single best practice could, if assumed to be a perfect solution, resolve an entire issue.

After carrying out the exercise of re-grading all the issues 4 times, and assuming that all the best practices had been applied, 4 very different results were obtained. This variability was too important to be left in the main risk analysis report, and it was therefore decided to remove it from that document to keep it here.

12.3.1 Extended discussion

The following discussion highlights the effects that implementing all the best practices mentioned in this document could have on the risk of each issue. Indeed, whereas the previous analysis was based on a baseline scenario with no guidelines implemented, we repeat the analysis with them.

It should be mentioned that some of the guidelines are limiting, such as the one to limit the lunar growth to a manageable rate. Still we assume that every best practice is followed and applied perfectly. It should also be noted that best practices that limit the impacts to specific sites, are not easy to transpose into the current grading system. For the purpose of this extended discussion, it is assumed that such best practices are satisfying solutions to the impacts.

For the activities risk, and compared to the previous analysis: we see that only issues 1, 6, 7 and 8 have not seen their probability reduced (last row). And that only issues 1 and 3 have not seen their impact reduced (last column). On the other hand, issues 4, 5, 10 and 11 have seen their risk reduced to the lowest value.

Finally, the risk of issues 1, 6, 7 and 9 are unchanged. The main reason is that the efficacy of the innovative best practices to limit the lunar dust are difficult to assess, for the site utilization, conflicts to use a site are still expected to occur but the attribution is realized by a third-party entity, while for the resource extraction, it is hard to quantify the result of the best practices on the size of the mines.

Table 1: Activities risk table, baseline scenario.

	Low Impact	Medium Impact	High Impact
Low Probability	Issue 4, Issue 5, Issue 10, Issue 11		Issue 3
Medium Probability	Issue 2	Issue 9	
High Probability	Issue 6, Issue 8	Issue 7	Issue 1

In terms of environmental risk, issues 4, 5, 10 and 11 have the lowest risk, and no more issues have a high impact (last column). Issues 1, 2, 6 and 9 have a medium to high probability and impact, which indicates that these are likely to stay important environmental impacts under the current best practices.

Table 2: Environment risk table, best practices scenario.

	Low Impact	Medium Impact	High Impact
Low Probability	Issue 4, Issue 5, Issue 10, Issue 11	Issue 3	
Medium Probability		Issue 2, Issue 9	
High Probability	Issue 7, Issue 8	Issue 1, Issue 6	

Under the current grading system, some issues have not seen their risk significantly reduced. Issues still classified as medium to high risk in either table indicate that the depth of the issue is significant, and that new ideas for mitigation need to be developed.

13 Outlook

From the project's start to the decision to conduct a risk analysis, its goals were never clearly defined. Each day presented the challenge of determining where to focus and which ideas to develop further. The decision to do a midterm presentation during the semester aimed to establish a clearer direction, with the help of people from eSpace. Given E2M's interest in producing a tangible outcome, the risk analysis was imposed. Therefore, envisioning a future project with a well-defined goal remains a significant challenge.

Ideas could be to continue on the basis of the risk analysis and complete the points that have been left as "TBD", in order to provide an answer (whether qualitative or quantitative). Another thing to do, would be to link the risk analysis with more historical events and existing regulations to make the concerns raised by the issues more credible. Finally, although likely difficult, discussing the subject with people interested by the issues or experts is of interest. Two people met a the Swiss Space Sustainability Research Days could be contacted.

14 Conclusion

The scope of the work accomplished has been substantial, beginning with the initial meeting with E2M, where members encountered disagreements about ISRU technologies on the Moon, particularly confusing the extraction of oxygen from regolith with that from polar water. Subsequently, an intensive effort was made to build knowledge on lunar sustainability through an extensive literature review while also proposing ideas for advancing the project. Finally, the week of the midterm presentation proved pivotal, as the decision to focus on a risk analysis was taken, providing the project with a clear and defined direction.

The project was not without its challenges. A major hurdle was the limited interaction and feedback from E2M members, which significantly affected efforts like estimating the scale of future ISRU lunar infrastructures. Additionally, the lack of publicly available information on long-term lunar projects posed further difficulties, likely due to their early development stages and companies' reluctance to disclose sensitive data. It is strongly recommended that future students avoid projects heavily reliant on external data, opinions, or feedback, as they may encounter similar obstacles.

In conclusion, this semester-long project culminated in a risk analysis outlining 11 key risks for long-term lunar developments. The work provided valuable insights into the lunar environment and the challenges mankind may face in the coming decades. I hope that this foundational knowledge will serve as a cornerstone for future student projects in the field of lunar sustainability, especially as the Artemis program continues to advance.

15 Declaration of Competing Interest

While the cooperation with EURO2MOON provided a scope to focus on, the content within this scope was developed independently, ensuring no conflict of interest.

This report was submitted on 10/01/2025.

Appendix

Agenda of the semester

To better plan a future student project, I tracked my weekly progress throughout the semester. These weekly notes on my work show the evolution of the project on a week by week basis.

Date	Tasks
09.09.2024	First meeting with Mathieu, defining the scope of the project. First E2M meeting: they did not know about sustainability on the Moon, and knew very little about the Moon. Starting literature reseach on "Sustainability on the Moon".
16.09.2024	Continuing literature research on "Sustainability on the Moon". Received documents from Mathieu and E2M. Summarizing main concepts in the report.
23.09.2024	Review of the documents read, sort my ideas and prepare presentation slide for E2M meeting (including ideas of project subject). Preparing questions for "WG Value Chain".
30.09.2024	Choosing the project subject (estimate the number of launches to setup 40 kt/year of O_2 production). Meeting with Pascal, started block diagram, E2M meetings postponed (Arnaud + WG).
07.10.2024	Attended 2 EPFL conferences and read the prospective American Architecture on the Moon (180 pages).
14.10.2024	Meeting Arnaud (E2M), to explain the chosen subject, agreed but also wanted guidelines. Dive into ISRU chain, first model + paper on importance of sorting before processing. ROXY literature (found online) + IAC in Milan.
Autumn Break	Meeting with "WG Value Chain", uninteresting, only welcomed a new member. Re-contact Pascal and Pierre-Alexis to get useful documents, and contact other participants of the WG meeting for documents on the value chain.
28.10.2024	Draft ideas of guidelines for Moon Sustainability. Learning about existing guidelines and regulations. + Received ROXY literature from Pierre-Alexis, same as the one found online previously...
04.11.2024	Preparing slides and practicing midterm presentation, because of a need for ideas, following almost no answer from E2M. After the presentation it was decided to define the end of the project as 2 weeks of technical review, 2 weeks guidelines writing and 2 weeks for E2M review and report writing. Then meeting with Arnaud: unhappy with the work done so far. He wants a risk analysis, a weekly email showing that the work is done and meeting every 2 weeks.
11.11.2024	First draft of risk analysis (17 pages).
18.11.2024	PDF feedback from Arnaud and release of the second draft of the risks analysis (29 pages). + Meeting with Arnaud.
25.11.2024	Third draft, includes the analysis of the results (34 pages).
02.12.2024	Arnaud sent the report to E2M. I sent it to eSpace. Project report writing during the week, Arnaud meeting postponed at the last minute.
09.12.2024	All feedbacks received (1x E2M, 2x eSpace), integration in the report. Wrote Python code to sort the items in the analysis. Arnaud meeting postponed at the last minute.
16.12.2024	Continuing to include the feedbacks in the risk analysis. + meeting with Arnaud.
During Exam period	Writing of the main report, perfecting the risk analysis, developing the slides and preparing for the oral presentation. + SSS Research Days.

Table 3: Tasks Done During the Semester

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