Regolith mining in Shackleton Crater: Propellant, building materials and vital resources production for a long duration manned mission

Regolith mining in Shackleton Crater: propellant, building materials and vital resources production for a long duration manned mission

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Abstract

The return of humans on the Moon is strongly endorsed by the International Space Exploration Coordination Group (ISECG) as a fundamental step in the journey to Mars. Lunar and Cislunar exploration has the potential to unlock a whole new domain of advancements and opportunities that would benefit life on Earth and on other worlds. In this framework, In Situ Resource Utilisation (ISRU) is among the most important objectives to be addressed in order to enable permanent presence on other celestial bodies.

The baseline for this paper is LUnar Propellant Outpost (LUPO) mission, whose aim is to produce liquid Oxygen and liquid Hydrogen from Lunar South Pole regolith water hydrolysis to refuel spacecraft. The first objective of the present work is the resizing of the extraction and production systems to match the establishment of a permanent crew of 20 people. The design of the plants is then analysed to satisfy the water and oxygen demands of crew habitats and manned elements operating on Lunar surface. On top of this, new ways of utilizing resources are analysed. Propellant production from regolith has as waste product a huge amount of dehydrated regolith (DR), given that approximately 9000 tons of regolith are needed to extract 1400 tons of water. An evaluation of a DR processing strategy in preparation to applications as building material is performed. Furthermore, molecular hydrogen from water hydrolysis can be, when not used for propulsion purposes, considered as a valuable reducing agent in more advanced processes that can be established in the next future, such as regenerative air revitalization units from CO2. Finally, an evaluation of the possible volatiles that can be extracted while producing water is performed.

Results show how the overall resizing and improvements implemented increase both production volumes and system efficiency, while simultaneously increasing the autonomy of lunar elements. This, along with the opportunities related to DR exploitation, consistently optimizes a basic architecture of lunar ISRU activities and benefits the related economical aspects.

Keywords: In-Situ Resource Utilisation (ISRU), Propellant, Consumables, Building Materials, Volatiles

Acronyms/Abbreviations

AHP	Analytic Hierarchy Process
CTV	Crew Transfer Vehicle
DR	Dehydrated Regolith
ECLSS	Environmental Control and Life Support Systems
EVA	Extra-Vehicular Activity
FoM	Figure of Merit
ISRU	In-Situ Resources Utilisation
ISS	International Space Station
LCR	Large Crew Rover
LCROSS	Lunar CRater Observation and Sensing Satellite
LEO	Low Earth Orbit
LH	Liquid Hydrogen
LLO	Low Lunar Orbits
LOX	Liquid OXygen
LUPO	LUnar Propellant Outpost
NASA	National Aeronautics and Space Administration
NRHO	Near Rectilinear Halo Orbit
PPF	Propellant Production Facility
PSF	Propellant Storage Facility
RAPTOR	Reusable Automated Propellant TranspOrt Rocket
RASSOR	Regolith Advanced Surface Systems Operations Robot
RCS	Regolith Collection System
RTS	Regolith Transportation Systems
SEEDS	SpacE Exploration and Development Systems

1. Introduction

According to the words of NASA's Administrator Jim Bridenstine, the next steps of lunar exploration will be performed in such a fashion that “this time, when we go to the Moon, we will stay”.

As a result of the Artemis program, NASA hopes to establish a sustained human presence on the Moon by the year 2028 to uncover new scientific discoveries, to demonstrate new technological advancements and lay the foundation for private companies to build a lunar economy [1].

Being the plan to establish a human presence on the Moon and given the high cost of sending materials to the lunar surface, future missions like Artemis will have to learn how to rely on in-situ resources utilisation (ISRU).

In this framework, the Lunar Propellant Outpost (LUPO) is a mission designed by the students of the 2nd level specialising Master SEEDS (SpacE Exploration and Development Systems) aimed at producing propellant (LH/LOX) on the Moon surface from 2035 until 2050 [2]. Since the starting date of this work was 2018, when the plans of a sustained presence on the Moon surface had not been unveiled yet, the business case of LUPO relied entirely on the propellant market on lunar orbit. Given the new impulse towards a human presence on the Moon, the potential benefits of a surface ISRU market for LUPO's business case have to be analysed.

The identified needs that can be satisfied by an expansion of LUPO infrastructure are propellant for lunar ascenders and consumables and building material for habitats. Each of these three topics will be discussed thoroughly in this paper.

2. The LUnar Propellant Outpost (LUPO)

The LUPO mission aims to produce propellant on the Lunar surface by exploiting in-situ resources and utilising pre-existing systems, therefore supporting future human space exploration [3]. The propellant selected for the surface production is LH/LOX because of its efficiency when employed in transfer operations between the Lunar surface and Low Lunar Orbits (LLO). Also, it is possible to obtain LH/LOX from the electrolysis of the water present inside the permanently shadowed regions of the craters in the Lunar South Pole. In particular, from the recent analysis of the Chandrayaan-1 M3 data [4], inside the Shackleton crater the regolith is expected to be mixed with ice in quantities from 5% to 30% in weight.

The iced-regolith is extracted inside the crater through the Regolith Collection System (RCS) [5] which is based on the NASA's Regolith Advanced Surface Systems Operations Robot (RASSOR) design. The regolith is collected by the Regolith Transportation Systems (RTS) and transported outside the crater to the Propellant Production Facility (PPF). Here, the water is separated from the regolith as water vapour, which is then condensed into liquid water, filtered and finally electrolysed into gaseous Hydrogen and Oxygen [3]. The gasses are then cryocooled and stored in the Propellant Storage Facility (PSF).

The mission envisions a Spaceport where the customer's vehicles can dock and refuel. If the customer prefers to be refuelled in LLO, the Reusable Automated Propellant TranspOrt Rocket (RAPTOR) can refuel on the Spaceport and transport the propellant to the refuelling orbit. This would be beneficial for those missions which have different destinations other than the Lunar surface [6].

At this stage of the preliminary design, there are large uncertainties on both the actual ice percentage inside the extracted regolith and the realistic market's request for propellant on the lunar surface or cislunar space. To accommodate these uncertainties, the ISRU segment is designed enhancing a strong modularity. The modular approach is also able to dramatically reduce the cost of the ISRU segment by the advantage of the learning curve, while providing an easier operational set-up and the possibility to increment the business within the mission timeline. In particular, following the preliminary mission timeline [3], LUPO will address the on-orbit market in 2037, two years after the implementation of the first ISRU modules.

Although the capability to address the on-orbit market would largely enhance the propellant request, thus increasing the total revenue, the preliminary business case analysis suggests that on-orbit refuelling could be not so profitable [7]. This is due to the intrinsic limits of the price for the propellant refuelling determined by the cheapest way of reaching a customer's destination. The propellant price is evaluated to be lower for refuelling in LLO (nearly 10 M$/t) than on the Lunar surface (about 30 M$/t) [7]. Furthermore, RAPTOR has to consume propellant to reach the refuelling orbit and land again on the Spaceport, with an estimated gear ratio of 4 (3 kg of propellant are employed to deliver 1 kg of propellant in LLO). Thus, from the investor's perspective, the on-orbit market is less attractive because the propellant price has to be lower and 75% of the propellant produced is wasted in the transport.

From this perspective, the best solution to solve the LUPO business case would be a strong surface market, such as the one related with a permanent Moon Settlement. Such an infrastructure would indeed require a huge amount of propellant to provide transport service of astronauts and goods between lunar orbits (LLO or NRHO) and the surface.

In the following chapter, the potential presence of a human permanent lunar outpost will be taken into account and its relationship with LUPO will be investigated.

3. A lunar surface market

As mentioned above, the ambitious goal set by NASA with its Artemis program is to establish a sustained human presence on the Moon by the year 2028. Even if it does not mean to set instantaneously a permanently inhabited human colony on the lunar surface, this will likely happen sooner or later within this century.

As a case study, a lunar base permanently hosting 20 people is assumed to be operative on the lunar South pole within the LUPO time-frame. The analysis of its positive impact on the propellant outpost will be performed, starting from the identification of the basic needs of such settlement which are likely to be satisfied by in-situ resource utilisation.

First of all, the limits imposed by radiation exposure will drive the amount of time that each astronaut will be able to spend in the base. In order to make some speculations on this topic, 1-year permanence is assumed. This means that an affordable way to bring astronauts back and forth from Earth will have to be present in the overall architecture. The transport system can either bring the propellant from Earth, or it can buy it from LUPO on the Moon surface.

A prolonged human presence in space will also need consumables, in particular water and Oxygen. The amount requested will depend on the technological capability to close the loops of these two resources.

Furthermore, the structures and the radiation shields of permanent habitats will represent a huge percentage of the overall mass of the base. This is why a lot of research on lunar ISRU for building material is currently being performed. There are a lot of possible ways to process regolith to obtain different building resources. A selection of the most promising materials which can benefit from LUPO architecture has to be performed.

Finally, the volatiles extraction and their potential applications will be investigated.

3.1. Propellant

For the sake of the discussion, the transport to the lunar outpost is assumed to be split into two vehicles, one performing the trip from Earth to the Lunar Gateway and back to Earth and the second from the Lunar Gateway to the base and back. Something similar may be studied in case of a direct Earth-Moon transfer with Starship-Super Heavy.

Focusing on the reusable lander/ascender, to perform a lunar ascent to the lunar gateway and back on the surface would require a total Delta-V of 5500 m/s [8]. Assuming a dry mass of 11.4 t, as the LUPO Crew Transfer Vehicle (CTV) [2] and a specific impulse of 450 s, a typical value for LH/LO2 engines, the overall amount of propellant calculated with the Tsiolkovsky equation would be 29 t. If the vehicle has a crew capacity of 4 people, the astronauts' shifts will be 5/year and a total propellant request of 145 t/year would be present. The surface market is sized by considering that the cost to ship from Earth to the lunar surface with Starship will be approximately 30 M$/t [7]. This would mean a potential income of about 4 B$/year.

Being the LUPO propellant production facility modular, the change of the demand would not translate into a re-design of the plant and extraction modules: the PPF would only require an additional module. It is clear that this would increase the efficiency of the mission without affecting its complexity.

The second case would be a Moon-direct with SpaceX Starship-Super Heavy.

Data about Starship-Super Heavy are still unconfirmed and the Delta-V to perform the transfer LEO - Moon surface and back are not easy to predict, because it is probable that aerocapture in LEO will be employed. These two facts impede to perform a precise calculation on the amount of propellant that Starship-Super Heavy would require on the Moon surface, but it is clear that having the possibility to refuel on the surface can be attractive from the SpaceX perspective, since it can lower the total number of refuelling operations in LEO. Furthermore, the refuelling would consist in Oxygen only, hence the benefit for LUPO would be high, because it would not require any change in the original architecture. In fact, LUPO is already producing approximately 250 t of Oxygen more than it can sell, given the selling mixture ratio of LH/LOX engines of 1:6 and the production stoichiometric ratio of 1:8.

A critical topic related to this kind of market is the so called "abort-to-orbit" requirement for crewed vehicles. In fact, if they will have to be capable of aborting the landing at any time of the mission and return to a safe orbit as safety requirement, no surface refuelling option would be feasible. Nowadays, a definite answer is impossible to obtain, that is why this option is worthy to be evaluated and maintained open, until a better understanding of safety regulations will be available.

3.2. Consumables

Designing a manned outpost on the Moon that can host 20 people would be a crucial point for the human space exploration. However, by increasing considerably the size of the crew new issues may arise in terms of environmental control and life support. In fact, as compared to the International Space Station (ISS) crew size, a higher quantity of consumables would be required. Currently, the consumables are delivered to the crew by resupply from Earth, but in the near future, thanks to the new capability to exploit the lunar indigenous resources, cheaper solutions may be available.

Astronauts, as living beings, need Oxygen for breathing, potable water and food. Differently from the past missions on the Moon such as the Apollo programme, Oxygen and water needs can be fulfilled with provisions coming from the Moon surface. Considering the scenario with 20 people living permanently on the Moon surface, the daily needs in terms of water and Oxygen are presented in Table 1.

Table 1: Daily needs per crew member per day [9].

Water needs	Units	Value
Drinking Water	kg/CM-day	2.00

Food Rehydration Water	kg/CM-day	0.50
Urinal Flush	kg/CM-day	0.50
Personal Hygiene	kg/CM-day	0.40
Hand wash	kg/CM-day	4.10
Shower	kg/CM-day	2.70
Medical Water	kg/CM-day	0.50
Oxygen needs	Units	Value
Oxygen consumed in the habitat	kg/CM-day	0.83
Leakages in the habitat	kg/day	0.50
EVA Metabolism losses	kg/CM-day	0.35
EVA Leakages losses	kg/CM-day	0.43

The annual needs are then shown in Table 2. They include the total water and Oxygen required for one year as well as an initial Oxygen amount for the pressurisation of the habitat, contingency needs and a safety margin.

Table 2: Annual needs for 20 people per year.

	Water	Oxygen
Need	102 tonnes	9.8 tonnes

In case the habitat has no capability to recycle water and Oxygen from CO2, the consumables to be supplied would be equal to the needs. If the habitat features a semi-closed loop ECLSS, based on ISS technologies adapted to the Moon environment, the consumables would be much less. In fact, part of the water and the Oxygen consumed by the crew can be recovered by an electrolyser ($2H_20 \rightarrow 2H_2 + O_2$) and a Sabatier reactor ($CO_2 + 4H_2 \rightarrow 2H_20 + CH_4$) (Figure 1).

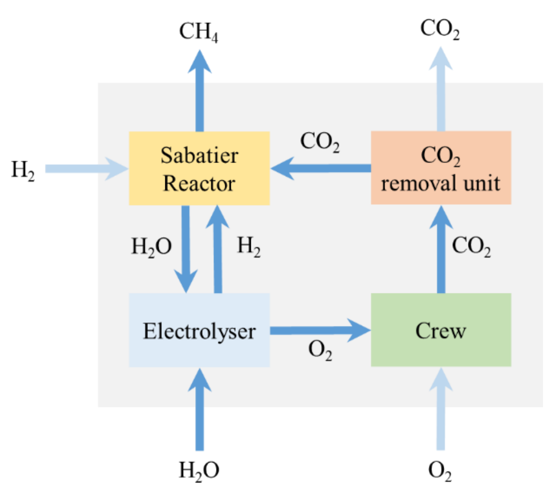

Figure 1: ECLSS schematics: the blurred arrows refer to exchanges that may not occur, according to the scenario considered.

Different resupply strategies may be applied, according to their types and quantities:

- Only water is supplied to the settlement, which has an increased capability to perform electrolysis in order to produce Oxygen and Hydrogen. The amount of water to be electrolysed can be sized according to the quantity of Oxygen required by the habitat or to the quantity of Hydrogen employed in the Sabatier reactor. In the first scenario, part of the CO_2 produced by the crew has to be vented because of a lack of H_2, while in the second scenario a surplus of O_2 is produced.
- Oxygen and water are supplied. Without increasing the quantity of water to be electrolysed, only part of the CO_2 can be reduced because of the lack of H_2. Moreover, less water is produced as a by-product of the Sabatier reaction, thus requiring more water from resupply.
- Hydrogen, Oxygen and water are supplied. A first possibility is to recover the entire amount of CO_2, thus requiring a high quantity of Hydrogen. An alternative approach could be to partially decrease the CO_2 recovered.

The different types of ECLSS are summarised in Table 3.

Table 3: Comparison between different ECLSS architectures. All quantities are expressed per year. R is the percentage of the CO_2 produced by the crew that is recovered by the Sabatier reactor.

	H_2O [t]	O_2 [t]	H_2 [t]	H_2O electrolysed [t/year]
Open loop	102	9.8	0	0
Semi-closed loops				
H_2O (R=1)	17.8	0	0	13.8
H_2O (R=0.8)	16.8	0	0	11.1
O_2+H_2O (R=0.61)	15.7	2.4	0	8.4
$O_2+H_2+H_20$ (R=1)	12.4	2.4	0.6	8.4
$O_2+H_2+H_20$ (R=0.8)	14.1	2.4	0.3	8.4

All these alternatives have advantages and disadvantages and can benefit from in-situ resources. Without performing a proper trade-off, some considerations can be offered, taking into account the relationship with LUPO.

The open loop architecture is the simplest one and LUPO would enormously benefit from it, given the huge quantity of consumables to provide. However, this solution is less probable to be adopted from a permanent human settlement.

The semi-closed loop scenarios vary in the amount of consumables required, the complexity of the logistics (water is easier to be managed than O_2 and H_2, O_2 is easier than H2) and the complexity of the system that has to electrolyse the water.

From LUPO perspective, the resupply of O_2+H_2O is the most attractive solution because of the surplus of 250 t of Oxygen that the propellant facility produces each year. From the settlement point of view, this solution is attractive for the low amount of water to be electrolysed (less mass and power involved) and for the fact that no cryogenic storage of H_2 is required. Hence, this alternative is selected.

In order to enable the water resupply from LUPO, water must be purified before being provided to the crew. According to the LUPO architecture [3], before being electrolysed to get pure Oxygen and Hydrogen, water is purified by the complex ISRU filtration system that consists of multiple ISS-derived filters. In details, the system can manage particulates whose sizes are between 0.5 µm and 120 µm. It is composed by three filters: the particulate filter, the separator filter and the start-up filter [10].

Once the water is purified, it must be mineralized in order to be used as drinking water. The solution could be to adopt the already proven mineralisation cartridges utilised on the International Space Station.

Subsequently, the logistics of resupply will be studied both for the open loop and the semi-closed loop case selected. Assuming that the habitat is located at a distance greater than 1 km from the PPF due to safety reasons, different alternatives are possible:

- Water is provided through a pipeline connecting the PPF and the habitat. Oxygen is supplied through tanks carried by the Large Crew Rover (Figure 2).
- All the consumables are stored in tanks and carried by the LCR to the habitat.

Figure 2: LUPO Large Crew Rover (LCR).

Considering that the LUPO LCR has a maximum logistic cargo transportation capability of 500 kg [2], multiple trips would be required for both scenarios to provide all the consumables to the habitat (Table 4).

Table 4: LCR trips per year.

Open loop	Water supply trips	Oxygen supply trips
With pipeline	0	20
With LCR	204	20
Semi-closed loop	**Water supply trips**	**Oxygen supply trips**
With pipeline	0	5
With LCR	32	5

Each scenario has a different complexity, which takes into account the level of closure of the ECLSS, the number of trips and the need to build a water pipeline. In case the customer does not have any recycling capabilities, a pipeline solution is recommended because of the high number of LCR trips. If the habitat includes a semi-closed loop ECLSS, the provision with the large crew rover (LCR) is suggested.

3.3. Building material

The exploitation of indigenous resources to build habitats and infrastructure is deemed critical to lower the mass and thus the cost of a lunar permanent mission [11]. The lunar surface is covered by a layer of unconsolidated debris called regolith. Its composition depends on the location, as shown in Figure 3.

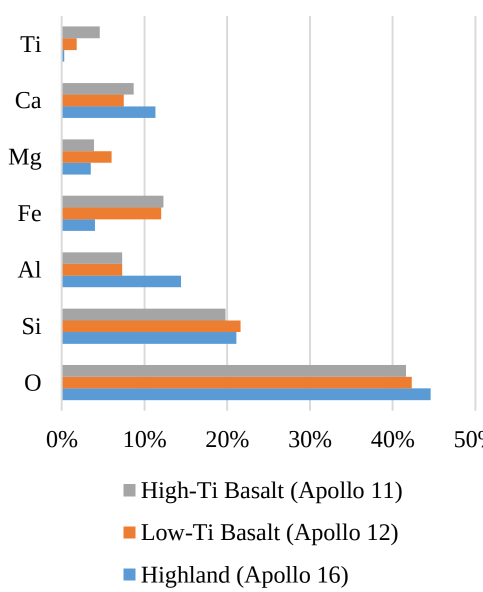

Figure 3: Chemical composition of lunar regolith [12].

The polar region, where LUPO is located, is best approximated by highlands regolith (to the best of current knowledge) [13]. This means a higher concentration of Aluminium and a lower concentration of Iron and Titanium with respect to mare regions.

The selection of the most suitable material in building applications on the Moon surface is a critical choice, since no direct experience with lunar surface structures is available. Nevertheless, a lot of research activities are ongoing, proposing new ways to process regolith for construction applications, resulting in a broad range of alternatives from which to choose when Moon structures will have to be built with indigenous resources.

The most extensive study found in literature about this topic, Happel [14], lists several potential building materials derived from loose regolith and attempts to identify which is the most suitable according to a set of criteria. Starting from that study, the trade-off is repeated with three major changes: the scores of the alternatives are updated according to the research of the last decades, the criteria identified to score the alternatives are prioritised with the Analytic Hierarchy Process (AHP) method and a family of criteria, the "Synergy with LUPO", is added.

3.3.1. Alternatives

Different materials are available on the Moon and different ways exist to process them, in order to eventually manufacture a wide set of products and assets that would in turn enable an expanding set of applications and capabilities.

A list of alternative materials has been defined according to the potential ways of exploiting lunar regolith - the most abundant and largely available material on the Moon.

Sintered regolith. Preparing regolith for sintering requires regolith compaction in a desired shape, mixed with a binder where necessary. This process have undergone extensive research over the last years and holds promising benefits in the simple, flexible manufacturing of relatively small parts that can be further assembled, such as bricks [15]. Power demands are generally low and can be sustainably satisfied by concentrated solar energy [16] or by artificial sources such as microwave [17] or laser [18]. Little or no post-processing is required.

Lunar glass. Glass can be easily prepared through simple melting and rapid cooling of lunar regolith. While different mineral compositions might influence the resulting glass properties, nonetheless this should not impact considerably the range of applications, like windows, screens and barriers. Some subsequent thermal treatments would apply. Only little beneficiation would be needed. Vacuum and anhydrous conditions can improve the properties.

Glass composites. A glass production plant could also be integrated with glass fibres production units or other types of ceramic reinforcements that could be embedded in glass matrixed to produce more robust and performing composites. Reinforcements production is however strongly dependent on the desired type and can introduce additional steps and reacting substances, as well as adding complexity to the system.

Cast regolith. Casting regolith can be relatively cheap and easy and can generate large-sized products with different shapes, like slabs, tubes, shields and frames for modular structures [14]. Moreover, almost no beneficiation would be needed, and casting in vacuum would be beneficial. Its brittleness might however require the presence of reinforcing parts.

Lunar concrete. As for sintering, many studies have been carried out to assess the potential use of lunar regolith as aggregate for concrete. Different types of cements have been theorized and analysed, either hydraulic [19] or waterless [20]. Lunar concrete would copiously benefit building capabilities and could also take advantage of recently developed automated techniques like contour crafting. On the flipside, preparation might take numerous steps, and cannot be carried in vacuum.

Lunar steel. Iron ores are found in regolith, often in the form of ilmenite ($FeTiO_3$), and could be refined via hydrogen or methane reduction among the other processes. Further carbon addition would be necessary to obtain steel and its exceptional benefits. This, along with the relative scarcity of ilmenite in the polar regions, can complicate steel production.

Other metals. Other metals can be derived from lunar regolith employing different extraction processes. Silicon, Aluminium and Titanium are the most interesting ones and could serve in solar cells manufacturing as well as for structural applications or as conductors. Metal extraction processes are usually very energy-intensive and more complex than bare regolith processes, often involving chemical reagents and many steps. The selection of a simple and well-known process is therefore critical in making early lunar metallurgy sustainable.

3.3.2. Criteria

The selection criteria are divided in four families. The first three are related to the process leading to the use of a new material in construction [14]: research and development, extraction and production and operations and utilisation. The fourth added category is the interaction of the process with the LUPO architecture. The list of the sub-criteria will be presented as follows.

Research and development: knowledge of properties, understanding of utilization, processing simplicity, imported infrastructure;

Production and extraction phase: raw material availability, process safety, operational ease, automation, maintenance level, environmental hardness, energy request, defect free production, material testing, incremental expansion, input materials.

Operations and utilization phase: versatility, ease of handling, robustness, tensile strength, compressive strength, Young's modulus, ductility, creep & fatigue, durability, thermal insulation.

Synergy with LUPO: hydrogen exploitation, dehydrated regolith (DR) exploitation, local regolith composition, utilisation of pre-existing LUPO infrastructure (PPF, set-up phase).

3.3.3. Results

The AHP method was employed to derive the weights of both the first level and second level criteria (Figure 4): the overall score of each Figure of Merit (FoM) is derived by multiplying its score by the weight of its family.

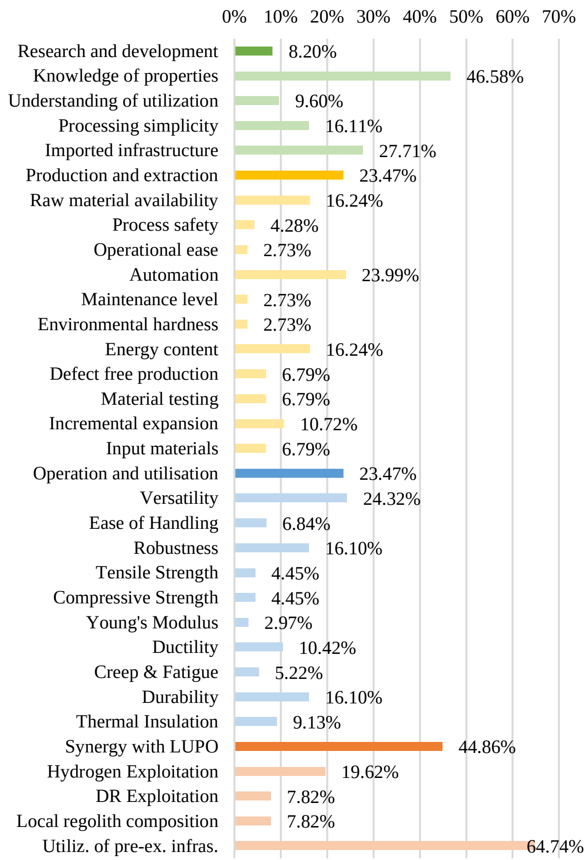

Figure 4: Figures of merit: the blurred bars refers to 2nd level FoMs, whose final weight is evaluated by multiplying its score by the one of its 1st level FoM.

To each alternative, a score is given for all these criteria. By weighting the score of each alternative with respect to the weight of each criterion, the overall scores are obtained (Figure 5).

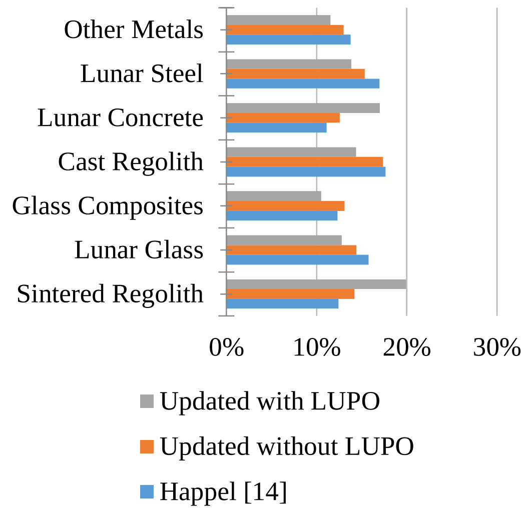

Figure 5: Materials' scores comparison

Cast regolith was the most appealing construction material identified by Happel [14], followed closely by the lunar steel. The process of updating the scores with data related to the last decades' research did not change this ranking. The most substantial variation is experienced by the lunar concrete, which benefits from the technology advancement in 3D printing and in the better understanding of its properties, due to recent studies focused on it [22], [23].

When considering the infrastructure already present within the LUPO architecture, consisting mainly in the utilisation of the LUPO set-up phase 3D printing rovers, the sintered regolith and the lunar concrete become the most appealing building materials.

The results of the trade-off show that a new revenue stream can be identified in the construction of lunar habitats and infrastructures of a surface lunar base with sintered regolith and/or lunar concrete. Nonetheless, the economic benefits of this potential revenue stream are difficult to be evaluated because of the high number of variables that come into play.

3.4. Other resources

Other resources found on the Moon can increase sustainable ISRU opportunities and valuably impact a settlement capabilities and development. Some of them can be successfully derived by the described infrastructure, eventually requesting simple and minor adjustments.

The permanently shadowed regions of the lunar craters are cold traps where volatiles and substances other than water may be found. Analyses of the ejecta plume of the Lunar CRater Observation and Sensing Satellite (LCROSS) impact in the Cabeus crater revealed the presence of chemical compounds in relevant concentrations [24]. Assuming that similar concentrations can be found in the Shackleton crater and knowing the annual production of water from icy regolith according to LUPO architecture [3], the amount of volatiles that can be extracted is estimated Table 5.

Table 5: Volatiles abundance [24].

Compound	% Relative to H_2O	Amount [kg]
H_2O	100,00	1357800
H_2S	16,75	227432
NH_3	6,03	81875
SO_2	3,19	43314
C_2H_4	3,12	42363
CO_2	2,17	29464
CH_3OH	1,55	21046
CH_4	0,65	8826
OH	0,03	407

These compounds could be easily separated and collected upon water extraction from regolith at the propellant production facility by means of fractional distillation [25]. Their applications would be several. The most abundant volatile is Hydrogen Sulphide, which can be employed to recover elemental Sulphur with the Claus process. On Earth, Sulphur is used for manufacturing sulphuric acid, medicine, cosmetics, fertilizers and rubber products, but the first application in a future lunar outpost would be being mixed with loose regolith to produce waterless concrete [21]. In this case, the best mechanical properties would be obtained with a sulphur content about 35 % by weight [20], that means that up to 600 t of concrete may be produced each year.

Ammonia and carbon dioxide could be used in greenhouses or as chemical reagent in scientific experiments. Sulphur dioxide can be reduced to obtain again sulphur or oxidised to obtain sulphur trioxide and subsequently reacted with water to obtain sulphuric acid for ilmenite reduction [26]. Carbon-based compounds could be employed for organic chemistry experiments or to produce small quantities of chemical fuels or polymers.

Finally, recycling capabilities shall be seriously considered and eventually implemented on the site. On Earth, aluminium recycling is far more energy-convenient than production via conventional metallurgy. Recycling parts from expendable landers delivered to the surface for set-up or resupply purposes would recover significant amounts of material that could be formed with lower needs for pre-processing or pre-treatment. This would in turn decrease the energy and minerals demands while reducing waste, improving overall the sustainability of the architecture.

4. Conclusions

There are many possible opportunities for in-situ resource utilisation, which will be more or less important according to how the Moon will be visited in the future. From the analysis performed in this paper, the propellant production seems very attractive, in particular if a human presence is established on the Moon surface. In fact, the surface market is much more convenient than the orbit one, since no propellant is wasted to reach the customer in orbit and, at the same time, it is much more valuable there.

Furthermore, a lunar propellant production facility will enable many other possibilities. The consumables demand can easily be satisfied with the same infrastructure, being water and Oxygen the main needs required. Nevertheless, the technology improvements will tend towards close ECLSS loops, which will decrease the amount of consumables required, thus diminishing the importance of an in-situ production. The infrastructure employed for propellant production may be expanded in order to process the dehydrated regolith, producing lunar concrete and sintered bricks at first, then cast regolith, metals and even glass. Moreover, one of the easiest integration with the LUPO water extraction is the volatiles extraction, because they are very abundant in the craters regolith with respect to other locations of the Moon surface.

Unfortunately, none of the aforementioned resources are valuable enough to justify its collection and transportation back to Earth. Hence, the role of ISRU will likely be relegated to propellant production until a permanent base on the Moon surface will be present. From that moment on, ISRU will be employed as “import replacement” of goods which are easy to manufacture and/or heavy to transport, such as consumables, structures and radiation shields. Finally, with the evolution of the settlement, more and more needs will drive the collection of resources and volatiles will start to be employed.

As regards the economic viability of these options, especially from a private investor point of view, it is hard to understand whether profitability may be achieved within an acceptable level of risk of the investment. A lot will depend on the governments’ plans and their efforts in paving the way to the future lunar economy.

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