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Waste Management for Lunar Resources Activities: Towards a Circular Lunar Economy

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Abstract

Space resources activities are currently the objective of a thriving, cross-disciplinary, global effort aimed at assessing their role and potential in the future of humankind. New, innovative mission concepts, legal frameworks, and advanced technologies are being actively developed and proposed with the final goal of enabling profitable and efficient space resource utilization. The immediate location for these impacts is the Moon. In sight of this bright cohort of imminent perspectives, it’s imperative for the global community to properly assess the potential effects and consequences of the forthcoming space resources activities, with the goal of including sustainability in the foundations of the ongoing progress and ensuring its enforcement in every future endeavour. Within this context, this paper addresses the topics of Moon mining waste management and a lunar circular economy as key issues in the sustainable utilization of space resources.

The most promising technologies are considered for lunar resources extraction and processing - with special focus on water - correlating their waste generation potential to the scale of the efforts implemented and to the projected availability of the resources of interest. Importance is also given to the corollary activities of space mining - such as logistics and transport operations - for their implications in waste management.

Protocols and technologies with the lower waste generation potential are identified and further scenarios are elaborated for waste handling, reduction, reuse, and recycle, as well as end-of-life strategies for mining plants.

This report’s recommendations are proposed for the development of incremental regulation for waste management, including but not limited to the definition of common areas of non-interest for waste disposal and regulatory obligations for conducting impact assessments before the establishment of mining activities.

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1. Introduction

Space resources utilization (SRU) is one of the most fascinating and pioneering perspectives in space for its promise to disrupt the current possibilities in space exploration and to unlock entire new domains of this thriving human endeavour, beside its beneficial implications for economy, society and technology. Concrete efforts are being undertaken by nations and space agencies all across the globe. The European Space Agency has developed a clear strategy for space resources utilization [1], that aims to establish a pilot plant by 2040 to validate the possibility for human explorers to safely and robustly rely on local resources for space missions on the Moon and beyond. NASA is leading the way with the Artemis program, which is expected to re-establish human presence on the Moon starting from 2024 [2].

Similar plans are being constantly developed at the same time - in strict cooperation with public institutions - by private companies, which are designing innovative concepts and architectures for resources utilization, and are actively contributing in shaping the future of our existence in the Solar System, such as iSpace, TransAstra and OffWorld.

Beside technologies and roadmaps, a fundamental role in enabling a thriving space resources utilization future will be played by space policies at national and international levels, as wise regulatory frameworks are necessary to ensure a profitable and pacific use of space ultimately benefiting all humankind.

A big challenge for the forthcoming years, both from a technological and a legal standpoint, is represented by *sustainability*, i.e. a set of best practices and principles promoting a responsible exploitation of resources as well as a correct implementation of the related activities, in order to ensure the present and future prosperity of human endeavours in space.

A necessary condition for this is therefore a deep awareness of the environmental, societal and economic impacts of human activities in space, as the main drivers for the definition of every long-term vision and campaign for the exploitation of extra-terrestrial resources.

Waste management - meant as waste generation, collection, treatment and disposal - for space resources is a key aspect in the life cycle of future missions. However, this topic is relatively new for this field and has still been poorly explored. Being SRU at its infancy, and due to the lack of detailed regulations and compelling business cases, there is still little attention on waste management. Moreover, the extremely small number of potential actors in the foreseeable future of SRU, compared to the vastness of space and to the abundance of its resources, does not seem to contribute in generating a sense of urgency for waste management instances.

Nevertheless, SRU Waste Management (SRUWM) is not only relevant for more distant and mature scenarios, but its importance extends back to the present day: the grounds for an effective implementation of sustainable SRU activities needs to be laid down today, in order to develop and improve all the necessary know-how, technologies and practices that will be the norm tomorrow.

The present work therefore aims to assess the technical implications of SRUWM based on state-of-the-art systems and architectures for Moon mining. These premises are further expanded under the scalability and logistics aspects to better elucidate relevant limitations and opportunities in this area.

Due to the preliminary nature of this effort and to the early condition of this research field, two main types of resources will be taken as a study case, in consideration of their importance for the first SRU efforts, namely lunar volatiles and minerals.

On the base of these findings, the goal is to identify sustainable waste management strategies and critical aspects that can further serve as input for the informed formulation of standards, protocols, policies and regulations.

This study builds on the work already started by the technical panel of The Hague Space Resources Working Group [3], constituted with the same objective of supporting the maturation of the group's Building Blocks [4] with subject-specific insights alongside the socio-economical panel.

2. Mining waste on Earth and in space

Observing and understanding how mining waste is managed on Earth is a first step towards the definition of robust SRUWM practices.

A typical way of classifying terrestrial mining waste is based on its economic value, i.e. the value that the substances constituting the wasted materials might have due to the presence of a certain demand for them in a market. If this demand is actually absent, waste loses all its potential economic value, and it's therefore not considered of interest. This latter type of waste shall ultimately be disposed safely to avoid any immediate or future damage to the environment. Another classification scheme is based on the environmental hazard posed by a given waste, which in turn dictates specific norms for its treatment and disposal [5].

In space, each waste has the potential to retain some economic value at first. Due to the extreme environmental conditions and to the relevance of flexible and robust SRU practices for sustained and scalable exploration, maximizing the ability to favourably exploit locally sourced materials is imperative.

This already constitutes a strong driver for the establishment of righteous recycling, upcycling or reuse practices, which are among the guiding principles for mining waste management on Earth as well [6, 7]. Moreover, logistics and operations may benefit from reductions in the amount of produced waste having to comply with transportation and storage requirements.

A broader assessment of the potential impact that SRU ventures can have must also take into account the effect on other present or planned space missions, as well as on the surrounding environment and its sites of cultural and scientific interest. This means that SRUWM shall not only concern the specific substances discarded during a given mining process, but also the end-of-life phases of mining equipment, site management protocols and other derivative actions. Taking these premises a step further, it is here therefore argued that advancements in SRUWM are foundational for the establishment of a Moon circular economy, i.e. an economy focused on closing the life cycle of goods and products to the point where virtually no waste is produced, or only minimal input resources are required, as materials are constantly treated and recycled to produce new components. A circular economy paradigm could help generate new commercial opportunities on the Moon in the form of new products, services and capabilities, not to mention the advancements in environmental technologies the Earth would benefit from.

As previously mentioned, the following sections will examine these aspects for the extraction of lunar volatiles and lunar minerals as the most relevant resources for the next steps of SRU activities.

3. Volatiles

Volatiles found in space are the key to lowering the cost of human and robotic space activities. The development of sources of volatiles will support growing economic activities in space and enable sustainability. The surface of the Moon is home to a range of volatiles, with oxygen making up 40 to 50 percent by weight of lunar regolith found across the surface. This oxygen is however chemically bound in the material and high yield extraction may require significant energy input to produce the high temperatures needed, as will be detailed in Section 4.2. Beyond this source of oxygen, the lunar surface is also believed to hold water ice in permanently shadowed regions (PSR) in concentrations up to 30% by mass [8]. This availability of water ice provides a method to obtain water which requires less energy and regolith processing.

The PSRs reside on the Moon’s North and South pole. About 41% of the Northern PSR area and 81% of the Southern PSR area stays permanently below 110 K, which is needed to retain lunar ice over the billion-year timescales it is thought by some to accumulate via cold trapping. Beyond these large PSRs there may also be a much more vast area of tiny cold traps also containing ice [9]. There are also seasonal PSRs that sometimes receive reflected light, but most PSRs including these are low lying areas, often crater bottoms, which stay in permanent shadow from the Sun. Very near many of these polar PSRs are also high regions of near constant illumination by the Sun, called peaks of eternal light [10, 11]. The constant illumination found at the peaks of eternal light are ideal places for solar power generation on the Moon, providing potential mining operations and human habitats with constant solar output. There are many other challenges on the Moon that can be aided by special features of these polar regions. One example is thermal fatigue of Moon spacecraft which is caused by the extreme night and day temperature cycle. Having access to continuous solar power and environments with constant temperatures can assist greatly in coping with these challenges. Exploiting these environmental features wisely can also decrease the amount of infrastructure and equipment needed on the surface, further minimizing the impact of SRU activities and facilitating SRUWM.

While there are many other volatiles that can be found on the Moon and in these regions, this paper will focus on water ice due to its concentration, usefulness, and ease of conversion into useful forms. There are many ways water ice can be extracted from permanently shadowed regions, but many traditional mining technologies from Earth are not compatible. Heavy mining equipment would be impractical to ship from Earth and aspects of equipment operation that rely on Earth gravity would not function the same. Because of the unique environment other solutions have been explored for ice extraction, including two that have received recent NIAC awards for further study, thermal mining and beneficiation.

Thermal mining is a process which uses thermal energy to melt the ices found in PSRs, then cold trap the gas into ice for storage. In this process, thermal energy is typically transferred via reflected natural sunlight, generated laser, or microwave. Thermal mining also may include the use of thermal rods embedded in the surface to better direct thermal energy to subsurface ice. [12] The effectiveness of thermal mining is dependent on the nature of the regolith at the PSRs. While regolith’s characteristics can range from those of dirty snow (“dry regolith”) to frozen concrete, thermal mining is most effective when the ice is located near the surface, as it is believed to be on the moon. Studies indicate that ice concreations at 4wt% or above will allow thermal mining to be effective. [13] There is widespread disagreement on the wt% of deposits, and ground truth will be needed to verify, but some expect deposits of up to 30wt% [8]. Given the significant quantity of ice on the Moon, it follows that this technology would be able to scale to the size of a lunar economy. Moreover, since the thermal mining process utilizes cold trapping for storage of the mined H2O, the process of building a storage and supply chain for processed H2 and O2 would also easily follow.

Alternatively, the beneficiation process involves the processing of lunar material to separate ice from other materials like minerals and metals. Typically these include phase changes, which requires the transport of high power to the PSRs for use in the ice vaporization and the regolith heating, or strip mining, which requires the transport of unwanted silicates, also resulting in unnecessary risk and waste. Most recently, a new procedure called Aqua Factorem has been proposed, which would take advantage of the fine grains of the lunar surface. A grain-sorting process would be able to extract the ice, which could then be converted to solid phase and eventually, rocket propellant. This new process would take only 100 watts, as opposed to the 800 kW for thermal extraction, and does not require the amount of transit to the PSRs, making it logistically simpler. However, this technology is still under study, and does not provide a viable option to implement immediately. In the long run, the funding for such studies would likely lead to worthwhile power savings on the moon [14].

3.1 Lunar volatiles for rocket propellant production

There are many benefits to producing rocket propellant on the Moon with local volatiles. When compared to the complexity of manufacturing rocket propellant on Earth and getting it to the Moon, doing everything on the Moon is far more efficient. The alternative is producing propellant on Earth, launching it on a rocket into space, transferring the propellant over 238 thousand miles to the Moon, then using more propellant to land it on the Moon. Instead, lunar ice can be collected and electrolysis used to split it into hydrogen and oxygen, which can be used as LOX/LH2 (liquid oxygen, liquid hydrogen) rocket fuel. A great amount of propellant, and expense, is involved in getting any payload out of Earth's gravity. Because there is significantly less gravity on the Moon, less propellant is wasted in producing and shipping propellant out of the Moon's gravity well for use in space, and any ships using lunar produced propellant to leave the Moon save a huge amount of propellant that would be wasted shipping it from Earth.

Propellant can be produced on the Moon in many ways. One excellent propellant production method involves using hydrogen and oxygen made from water ice obtained from the Moon's PSRs. By replacing all or portions of rocket propellants with lunar derived hydrogen and oxygen, the costs of spaceflight can be significantly reduced. This is because all of the propellant mass that would otherwise need to be brought from Earth can instead be generated on the Moon. While LOX/LH2 propellant can be fully produced on the Moon, other propellants may still use LOX as an oxidizer, and some such as methalox may be produced on the Moon from a combination of Earth and Moon materials. By replacing all or even part of propellant constituents, the Moon's resources can provide significant benefit to cost and resource overhead.

Once water is obtained it is purified. It can then be used directly in the form of steam or plasma to obtain low to medium thrust. However, for the purpose of creating high thrust propellant, electrolysis is performed. Electrolysis uses electricity to generate oxygen and hydrogen from water. Many propellants will use the liquid form of oxygen as an oxidizer, with some using liquid hydrogen as the fuel. For LOX/LH2 (Liquid Oxygen/Liquid Hydrogen) engines this then completes the needed ingredients for propellant. For other propellants such as LOX/LCH4 (Liquid Oxygen/Liquid Methane) additional ingredients are needed, in this case carbon. Despite the Moon being relatively carbon poor, production LOX/LCH4 on the Moon with even Earth carbon and Moon derived LOX and LH2 can substantially decrease propellant cost. This is because the LOX used in the propellant accounts for up to 78% of the LOX/LCH4 mixture's mass, with hydrogen making up roughly 25% of the LCH4, meaning the carbon portion of the total propellant mass is only around 16.5%. Based on this, whether propellants capable of full in-situ production are used like LOX/LH2, or propellants are used that require other materials to be found on the Moon or brought from Earth, the use of lunar derived water is significantly beneficial [15].

With these significantly beneficial uses for Moon water ice, thought must be given to handling the minerals, metals, and other volatiles which are left after purified water is obtained. While other uses of the Moon and it's materials may not be the current target, care must be taken to protect them. While water may currently be the primary focus, the little surface characterization data we have hints that it is potentially not present in the form of pure ice deposits. Spectroscopic data of impact ejecta was obtained after a Centaur upper stage impacting the Moon's Cabeus crater for the LCROSS mission in 2009. This data revealed that many other types of material exist in at least some of the same regions of permanently shadowed crater bottoms where water ice will be likely mined. These other compounds include hydrogen sulfide (H2S), ammonia (NH3), sulfur dioxide (SO2), ethylene (C2H4), and many others in varying abundance. [16, 17]. With this in mind, measures should be taken to utilize, store, or responsibly abandon these other compounds in a sustainable form, as there will certainly be future need for them. During the production of lunar ice, fuel processing, and all other lunar activity, care needs to be taken to protect the Moon environment from unnecessary disruption. Mining and production sites will certainly see disruption, as will routes used for transportation, but where it is feasible the landscape should be protected. This should include using established paths for transportation whenever possible instead of creating new ones, storing waste and unneeded materials in a safe and sustainable manner, and performing tasks in a way that poses a minimal impact on surrounding areas whenever feasible.

3.2 Lunar volatiles for human habitation

There are many ways in which large volumes of water are essential on the Moon. Besides the need for water in lunar propellant production, water is essential for many chemical and biological processes including many essential to human life and agriculture. The need to obtain water for human use on the Moon is huge, especially as both temporary and permanent human habitats are planned. While significant effort will be used, similar to the ISS, to conserve and reuse water, a great amount is needed. Based on estimates from ISS activity, over 350kg of water is needed for a crew member per month when including drinking, hygiene, and respiration. But in addition to this, a significant amount of water is needed for other purposes including the production of food if it is to be done on the Moon. Current water recovery and purification systems on the ISS don't recapture water held in food or fecal waste (nearly 74% moisture), and still recapture just 84.7% of water for reuse in each recovery cycle [18]. These facts demonstrate the need for in-situ produced water for human needs on the Moon, and for better recovery means to reduce waste. When additional needs are examined such as agriculture, science, propellant production, and industrial processes and manufacturing, the needs are made even more clear. Water is also extremely useful for radiation shielding, as it is one of the most effective substances when considered on a per mass basis. Oxygen, a component of water, has many uses, such as it being a vital component of a breathable atmosphere. Hydrogen, another component of water, is also a key component of the Ammonia used in fertilizers used to support plant growth. When human habitation or other needs increase the demand for Moon derived oxygen other sources can be explored like processing lunar regolith. This concept and its related impacts are further explored in section 4.2. Obtaining purified water from the ices mined on the Moon will involve filtering out other materials which should be conserved in a sustainable manner. While whatever is found during this process is essentially a waste product of filtering, it may not be stable if left on the surface of the Moon or released as gas. Because future uses will likely exist for them, sustainable means should be determined and used to store materials currently considered waste.

4. Minerals

Lunar minerals exist in a wide variety and are of extreme importance for the comprehension of its geology and its history, as well as of the Solar System. Numerous types of minerals have been classified and located in specific lunar regions. They are also a vital element for SRU due to numerous reasons, but primarily for their use as building materials and oxygen source. These two applications can be reasonably considered the most important ones beside volatiles extraction for early SRU efforts, and will therefore be taken as reference cases. Future uses of lunar minerals involve metals extraction or other elements such as rare earths.

4.1 Lunar minerals as building materials

Using minerals as building materials is advantageous under many aspects. On one side, building materials usually have the largest masses and volumes, despite considerable savings would be achieved due to the reduced lunar gravity, meaning that their transportation from Earth would be costly and inefficient. On the other side, their in-situ production would require variable degrees of pre-processing of local materials prior to the production phase. In some cases, there could be even no actual production in the strict sense, as relatively simple structures such as berms or dams could be obtained by handling arbitrarily large amounts of bare lunar regolith. For these specific cases, SRUWM should mostly take into account traffic and logistics aspects and the end-of-life of the equipment involved. For the fabrication of other parts, such as beams, pillars, shields, bricks, walls or pads, different technologies are under investigation. These would take regolith as feedstock to produce more compact and less porous components capable of satisfying more stringent mechanical, structural, functional or safety requirements. Two main production processes can be mentioned based on the currently available technologies and concepts for SRU, namely molten regolith casting [19] and additive manufacturing. In particular, the latter is far more likely to be used due to its generally higher energy efficiency, lower mass and greater versatility in producing different shapes. Additive manufacturing (AM) is the process of building three-dimensional parts by gradually adding thin layers of materials. For SRUs purposes, these can be bonded together by sintering regolith particles, or by promoting chemical reactions among regolith and other ingredients. Sintering is the process of fabricating a product starting from powders by promoting the formation of interparticle bonds by means of temperature and pressure [20]. Lunar regolith, mostly in the form of loose dust, is therefore a good input material for sintering. Among the various technologies investigated to sinter regolith, two are generally considered the most promising: irradiation with microwaves [21] or heating of the powders with concentrated sunlight [22]. Considering the residual porosity which is typical of unfinished sintered products or their rough surface finishing and tolerances, it’s reasonable that these technologies will mostly be used, at first, for the realization of pads, dust protection walls or other parts that can easily by substituted and whose mechanical resistance is not a mission critical requirement. In terms of waste generation, little or no waste would be produced during the actual manufacturing step, but some materials could be discarded during a pre-processing step. Indeed, AM and the quality of its products are heavily dependent on numerous feedstock material characteristics such as powder size distribution, particle shape and chemical composition. This implies that some prior beneficiation might be required, either involving chemical or physical methods. The extent of this prior treatment will be linked to the high heterogeneity of regolith sourced in different locations of the Moon, as well as to the developed AM standards [23]. The non-beneficiated regolith could be used for the construction of berms or radiation shields without need for special storage techniques. The sintering machine would be left at the end of service. Regolith can also be used as an ingredient for a geopolymer [24]. A geopolymer is an alternative cementitious mixture that combines a silicon or aluminium rich ceramic material (such as regolith) with an alkaline solution, which in turn triggers a polymerization reaction leading to the obtainment of a compact material. This mixture can in some cases include other compounds capable of increasing the workability of the material upon manufacturing - the so-called plasticizers. All the substances needed to produce an alkaline solution can be sourced on the Moon, and water is one of these. This increases the chances of creating secondary wastes upon water or alkalis sourcing, in addition to a more complex supply chain infrastructure. However, such a material would be more suitable for the construction of habitats or other structural parts requiring superior mechanical compression resistance.

4.2 Lunar minerals as oxygen source

Lunar minerals represent the largest oxygen reservoir of the Moon. Due to their abundance in every lunar region, it is highly probable that SRU missions will process them in order to extract oxygen for life support or propellant production. Every oxygen extraction process involves the reduction of metal oxides, and has as byproducts mostly a mix of reduced metals, metal alloys and partially or non-reduced oxides, depending on the process and on the composition and characteristics of the feedstock material. Also volatiles entrapped in the regolith will be a byproduct. These can all hold economic value and can therefore be stored for future use.

Several oxygen extraction technologies have been considered, such as vapour phase pyrolysis, molten regolith electrolysis, solid regolith electrolysis or ion plasma separation. An excellent review of these processes is offered by Schlüter and Cowley [25]. Among these, the solid regolith electrolysis Cambridge FFC process [26] requires the lowest temperatures and is the best candidate for future Moon SRU. Adapting this process to the lunar environment would require regolith to be sintered into electrodes, which would in turn be immersed into a molten salt at high temperatures (around 900 °C) together with a graphite electrode to complete the electrochemical circuit needed to separate the oxygen contained in the regolith from the other elements. A competing alternative would be the molten regolith electrolysis, where regolith would be directly melted and electrolysed. This would eliminate the need of molten salts and of regolith electrodes sintering, but would come at the cost of a higher processing temperature (around 1600 °C). Without further going into the technical details, this description is intended to suggest that differences in the selection of the process would affect the related supply chain and the required technical capabilities. Also the byproducts, however, would change considerably. These factors have all profound implications in terms of waste management.

First, it shall be considered that these technologies have very low efficiencies in the order of 35% (at small scales) [25], meaning that - ideally - for every tonne of regolith processed, around 650 kg of byproducts would be produced. Efficiency could be increased again by means of a prior - presumably chemical - beneficiation step, that would in turn produce other slugs and wastes. However, that would also allow to obtain a more stable and controllable oxygen extraction process, along with more predictable and tunable byproducts, such as metal alloys with more desirable properties - and thus more economic value. Metals or reduced ores would indeed be fundamental for more advanced manufacturing applications.

Second, the generation of slugs or spent molten salts can be critical. Their impact on the environment might be high due to contamination of - or reaction with - local materials, which could in turn lead to damaging areas of scientific interest or critical resources for human settlements or other activities.

Finally, processing regolith at high temperatures would cause the liberation of the volatiles contained in the minerals, such as hydrogen, helium and carbon dioxide. For every cubic meter of treated regolith, tens or hundreds of grams of volatiles could be liberated. Due to their scarcity, these could hold high economic value on the Moon, but storing them usually involves high pressurization, cooling and storage capabilities. Sustaining the costs of such a waste management effort might not be in the near term profitability objectives of the actors extracting oxygen.

Finally, a plant at its end of life would be left with a considerable amount of spent salt.

The products other than oxygen, derived from processing these oxides, hold additional value and should be captured. While some secondary products may have no near term use, ways should be explored to effectively conserve them by returning them to the local environment or storing them in another sustainable manner to avoid wasting them or contaminating the environment.

Table 1 below offers an overview of the byproducts produced by the technologies mentioned in Section 3 and 4 along with a list of the related storage needs and potential applications.

Table 1: Overview of mining byproducts, storage needs and applications

Byproduct	Storage needs	Applications
Volatiles (NH_3, CO, SO_2...)	Cryogenic/Pressurized storage	Industrial processes, agriculture
Non-beneficiated/dry regolith	None/Far from landing sites	Shielding, berms

Reduced ores, metal alloys	Prevent solid-state reactions	Manufact., beneficiation, building
Spent electrodes	Safe stacking	Regeneration /recycling
Spent salts	Storage in inert tanks	Regeneration /recycling

5. Scalability and Logistics

5.1 Scalability

There are significant but manageable challenges ahead when it comes to bringing SRU technologies to scale. While significant testing can reduce risk, there will be much to learn in early deployments of these new technologies. As access to the Moon becomes easier, challenges will be overcome by iterating design based on direct lunar experience. Because systems must not only function effectively, but do so in a cost-efficient manner, economic considerations will become a primary focus. A lunar economy must support a breadth of customers and suppliers, meaning customers and suppliers at all levels must have reason to participate.

Early SRU technologies on the Moon may be demonstrated in a manner meant to prove out a technology. However these initial demonstrations, similar to the oxygen production demo on the Mars rover Perseverance, likely won't be designed to support customers. To achieve SRU technologies that support initial customers, partnerships between a privately funded effort and that customer are needed. Governments could play a customer role, but private industry may also.

Given these circumstances, the most sensible approach to scale up SRU capabilities is modularity, as this would allow to incrementally add extra capacity without having to replace entire facilities, while also leveraging economies of scale and implementing improvements at each iteration. It shall be therefore considered how waste production would consequently scale, especially at the systems of systems level. Plus, in case a single module needs to be replaced, appropriate disposal procedures shall be implemented to ensure this does not cause disruption to the environment or to SRU activities.

The first area in which to consider is the scale of enterprise is the production of propellants on the moon. Producing both LOX/LH2 and other propellants mixed from Earth materials and lunar LOX will allow the lunar economy to escalate the manufacturing of propellant to a much larger scale than would otherwise be possible. While traditional mining would be incredibly impractical for lunar purposes, given their heavy weight that would have to be brought from Earth, other techniques such as the abovementioned thermal mining would minimize the scaling costs to the ability of humans to move the mined volatiles to processing facilities. In this case, particular attention shall be given to the equipment designed to permanently operate inside lunar craters, as disposing such assets there at end of service might hinder other SRU or scientific activities. Furthermore, storing the volatiles that usually accompany water might become increasingly harder with scale.

With regards to minerals, scaling AM techniques may be relatively simpler and less energy intensive than oxygen extraction processes. Automation and robotics have large margins for improvement and optimization of AM machinery operations. Such assets would also be very flexible and could be repurposed or reprogrammed frequently and be designed to last for a very long time. Also, there would be almost no need to simultaneously scale byproducts storage facilities due to the fact that manufacturing is indeed additive rather than subtractive (i.e. does not eliminate excess material from a starting part), so very little waste is generated from the process with little or no need for storage or movement. AM lunar platforms are currently conceived to be mobile, which might further facilitate end-of-life repurposing. Moreover, designing multipurpose AM machines would further reduce the need to import additional equipment.

Finally, scaling oxygen extraction techniques can be hard. At the beginning, chemical processes could benefit from larger, optimized plants. However, they would also need larger power supply facilities, which usually implies lower efficiencies, as well as more resupplies from Earth due to complex - and often expendable - parts required. Also in this case, additional problems with scale are related to storing large quantities of volatiles. Regolith processing plants could ultimately be designed to be dismantled or reconfigured at end-of-service, facilitating the re-use or recycling of their components.

5.2 Logistics

Scaling to systems that support mass quantities of SRU however requires building a large supply chain of lunar miners, refiners, manufacturers, and end customers. This supply chain likely grows from a small group initially, each of which take on multiple roles. This initial group may be formed and expanded through a combination of private and government investment.

The development of SRU technologies for the lunar economy will likely accelerate as more participants join the initially small group involved. This will likely occur due to market competition as new entrants attempt to do a better job or offer a lower price, or through increasing involvement of governments who desire to support a new capability. As SRU derived products become available, including lower cost propellants, these products will also support lower cost space activities. Reducing costs for space activities, supported by SRU products, will then enable new business cases to close due to newly lower operational costs. These new businesses and activities will then drive increased demand for SRU materials and products, supporting further investment in SRU technology development and gradual expansion of lunar operations. This cycle then continues until demand stabilizes or further demand drives exploration of SRU opportunities beyond the Moon.

All this will translate into more complex logistics, including the logistics of the waste created by these processes. This includes handling, transporting, storing and disposing byproducts as well as broken or spent parts and components.

During oxygen or water extraction, volatiles that are produced may undergo fractional distillation, which would maximize the economic value for re-use but which would come with technical challenges and costs that would discourage organizations from pursuing this path.

In this case, storage might be easier in permanently or quasi-permanently shadowed areas to take advantage of the low temperatures, but access to these areas might require dedicated transportation capabilities.

Byproducts from the reduction processes may also be stored as inert powders in separate containers. Lastly, molten salt spillovers, exhausted electrodes, and other plant waste would also be created and would need to be either disposed or stored for future use.

However, the logistics issues and trade offs will depend on waste classification based on the relative usefulness, perishability and hazard.

As the number of actors increases, different paradigms for SRUWM logistics might be required. For instance, multiple disposal areas in the proximity of each actor’s operating areas might become less desirable compared to a lower number of common areas. This would indeed optimize the usage of space, but might be sub-optimal for the actors based on their relative position from the disposal site. Furthermore, the future need to regularly send humans, propellant, and materials away from the lunar surface, into lunar orbit or beyond, means that waste products from those journeys must also be considered. Export from the Moon to cis-lunar space and beyond will be a popular choice when possible as transport from the Moon requires a lower change in velocity versus the launching it from Earth’s surface. Once water, propellant, and other goods are available on the Moon this will make it a popular source to obtain these goods for many purposes beyond the Moon. Various means to leave the surface of the Moon are possible, using water, produced propellants, or future systems like electromagnetic rail guns. Among these, serious thought should be taken to conserve Moon resources and prevent release of excessive products of combustion. Likely near term Moon activity won’t reach the level of atmospheric gas injection that could result in long term changes to the Moon. However, long term activity if allowed to reach a consistent injection rate of around 60kg/s (or 132 pounds per second) could lead to an atmospheric change in the Moon, from photoionization loss dominated to thermal escape dominated. With such a change, pollutant gases would take hundreds of years to dissipate, verus a matter of days with the Moon’s current form of near-vacuum atmosphere [27].

6. Recommendations and Best Practices

There are many opportunities in space resources and there are numerous paths that could be taken in their acquisition and use. What most processes for extraction, processing, and utilization have in common are waste products. As has been discussed, these come in many varying forms which require different methods of storage or disposal. When considering the best approach, the goals of the overall space economy and environment must be taken into account instead of simply technical possibility. The technical reality, scalability, affordability, schedule efficiency, and space environment should be balanced to find the best solutions.

Table 2: The technological readiness level (TRL) and environmental waste management impact for upcoming technologies.

Impact	**TRL**		
	High	**Mid**	**Low**
High	Traditional mining		Molten regolith casting
Medium		Lunar concrete, Molten regolith electrolysis	Aquafactorem, Ion plasma separation
Low	Concentrated Sunlight AM	Microwave AM, Thermal mining, FCC Cambridge	Vapour phase pyrolysis

6.1 Investing in Highly Scalable Technologies

Because there are very few SRU technologies operating on a tiny scale, and most concepts have yet to be demonstrated, it is important to remember that scalability is essential. While small demonstrations of technology may give positive results, it is important to prioritize development of technologies which operate efficiently and affordably at much larger scales. All developments can contribute to technical knowledge, but it is those which are scalable that will enable steady progress by allowing increased scale with each iteration. This is vital to enabling steady capability growth for an emerging space resources economy.

There are numerous technologies that can be considered scalable and which deserve attention. To be ideal these technologies must also be utilized to build systems that are cost efficient to build and operate. Some basic examples of scalability worth investment to develop cost efficient solutions are storage technologies, space nuclear power, in-situ manufactured solar power systems, thermal mining, multiple-use and repurposable tech, repair/refurbishment using in-situ resources, electrolysis processes, multi-stage manufacturing using in-situ resources, movable/modular facilities, standards for power distribution and management, closed loop habitats, fully Earth-independent capabilities, recycling facilities, and more efficient rockets.

6.2 Creating and Promoting SRUWM Practices

It remains to be seen how to incentivize public and private buy-in on SRUWM. However, in terms of technical incentivization, it is important to select and invest in methods and models that allow for waste management with minimum energy consumption as a cost, in order to make the process more economically attractive.

Table 3: Examples of best available practices for key lunar economic activities.

Task	**Best SRUWM Practices**
Creating Propellant	Use of LOX/LH2 propellant instead of methalox products which waste hydrogen byproducts
Mining Water	Thermal mining/beneficiation avoids energy waste for traditional mining techniques
Treating Materials	Complete treatments near mining site, minimize transportation
Storing Waste	Select binding techniques for volatiles/unsafe materials that do not require active supervision
Using Materials for Building	Additive manufacturing provides higher efficiency and lower material quantity requirements

Oxygen Extraction	Solid regolith electrolysis requires the lowest temperatures/least energy investment to complete
Machinery Design	Design for recycling/repurposing

It will be important to develop many effective SRUWM practices to support SRU activities. As each example in Table 3 demonstrates, there are considerations that should be assessed when developing ways to reduce and manage lunar waste as processes scale in size with a growing space economy. The table shows just a few examples, but there are a great number of other factors which should be studied and considered to produce the best set of guiding factors for initial SRU operations and SRUWM. As knowledge of the lunar environment increases in the future, other points of interest and base locations will be found. This will have a large effect on the distribution of stored waste and how waste management might be designed to interface with lunar operations. It will also be important to reassess and add new SRUWM practices as SRU activities scale up and new capabilities are pursued.

As SRUWM practices are developed it will be vitally important to maintain a healthy focus on both waste management goals and economic viability. The space environment must be protected as operations grow in scale, but if restrictions impose too great a cost they will prevent SRU activity. SRU activity must have SRUWM practices that allow private SRU growth and which don't reduce the financial rewards that can justify taking the significant risks involved in space activities.

6.3 Classifying Lunar Waste

In terrestrial applications, the value of leftover waste is connected to its lunar waste classification (LWC). Given the lack of an economy on the Moon, it will be necessary to gauge toxicity of each new potential process, the associated moving and storage costs, and the raw quantity of leftover waste in order to begin to classify the waste future governments or companies may intend to produce in their ventures. Three axes ought to be explored: 1) perishability, 2) hazards, and 3) usefulness, in terms of economic, scientific, or cultural. With these defined, it will become simpler to designate requirements for waste treatment and storage.

6.4 Legal Recommendations

The rules governing the exploration and use of space are laid down in international space law, a multi-level regulatory system centered around a core group of multilateral agreements collectively known as *Corpus Iuris Spatialis.* For decades, it was uncertain whether space resources activities were permitted under international space law, and eventually under which conditions. After some States declared their position through the enactment of favorable national legislation, in 2018 the United Nations Committee on the Peaceful Uses of Outer Space (UNCOPUOS) finally adopted an agenda item dedicated to the subject. During the first year of debate, the Committee registered statements both in favor and against the legality of space resources activities under current international space law. One year later, no State objected anymore to the legality of SRU and the debate has moved to what governing mechanisms should be developed to ensure their peaceful and sustainable conductment. Currently, the Committee is divided among those who consider mandatory the development of an ad-hoc multilateral agreement, and those who believe instead that the early stages of SRU would be better regulated at the national level. For the purpose of this paper, it is assumed that the latter position will prevail and thus that each State will be responsible for ensuring compliance of SRU activities with international space law. At the same time, for this approach to succeed it will be fundamental to develop appropriate coordination mechanisms at the international level, in order to reduce the possibility for conflicts and harmful interference. To such end, this section will propose three basic recommendations aiming at ensuring the peaceful and sustainable conductment of SRU activities.

The first recommendation is the prompt, detailed and transparent registration of both planned and existing lunar activities, within a dedicated Lunar register. In the early stages of lunar activities, this recommendation is addressed to those States whose nationals will actually be involved in lunar surface operations. To compensate for the lack of a centralized international registration procedure, it is of the utmost importance that each national Lunar Register will include a mutual recognition clause. The aim of this clause is to minimize the risk of competing activities over the same area on the Moon, through the reciprocal recognition of foreign lunar activities. Accordingly, before registering a planned lunar activity, every State will make sure that the involved area has not been already registered in another jurisdiction for activities that would be incompatible with the one in question. The downside of this mechanism is that time becomes the decisive criterion for legal protection, thus triggering a potential race to spurious registrations aimed at "booking" an interesting area on the Moon before anybody else does it. To mitigate this risk, States should only register realistic activities, through a considerate evaluation of their feasibility. As part of this latter evaluation, States should only register activities presenting reasonable territorial and temporal extensions. For instance, any application to mine the entire south pole of the Moon for 100 years should always be rejected, first as evidently unfeasible and second as contrary to the spirit of international cooperation which shall animate the utilization of the Moon. While this first recommendation is non-specific to either space resources or waste management endeavours, having a system of coordinated lunar registers is a fundamental precondition for the development of sustainable and effective SRUWM practices.

The second recommendation is the establishment of a classification system for lunar resources, including a standardized definition of waste, to be used in the licensing process for lunar resources activities. From a legal viewpoint, the limited amount of resources available on the Moon, coupled with their non-renewability and the risk of perishability, all call for a very limited definition of lunar waste. As discussed in the above technical sections, all the by-products of lunar extraction activities could be used for other purposes and many of them risk, if not properly stocked, to be permanently lost. Accordingly, to comply with the principle of due regard under Article IX OST and truly achieve the sustainability goal, we must maximize our efforts to minimize the loss of lunar resources. The development of a classification system for lunar resources, coupled with guidelines for the adoption of appropriate mitigation strategies, may offer a good starting point in this respect. This classification system should be based on relevant best practices, to be ideally developed in dedicated international multi-stakeholder fora, and used in the licensing process for lunar resources activities, as laid down in the following recommendation.

The third and final recommendation is the development, at the national level, of dedicated licensing procedures for lunar resources activities. This is because the territorial element implied in these endeavours requires special adjustments to the procedures ordinarily used for satellites or launching operations. Accordingly, every licensing procedure for lunar resources activities should involve at least three stages. First, the interested area should be available for use without the risk of causing harmful interference. This assessment, as suggested in the first recommendation, should be done through the use of a dedicated Lunar Register in coordination with the international community. Second, the proposed activity must be presented as feasible, i.e. realistically achievable with the means available to the licensee. Again, as mentioned in the first recommendation, this element is important to avoid misuses of the registration process. Third, the licensing authority should make sure that the activity can take place in a safe and sustainable manner. Such evaluation should rely upon the presentation of an appropriate Lunar Impact Assessment Plan (LIAP), accounting for how the proposed activity will impact on the existing lunar environment and how these impacts will be addressed. This LIAP should then be tested against the classification system suggested in the previous recommendation, to make sure that it complies with the relevant mitigation strategies established therein.

These three recommendations are of course just a portion of a more comprehensive approach towards the regulation of lunar resources activities. However, if properly implemented they may already offer a sufficient starting point for ensuring that the early stages of lunar resources activities will be conducted in compliance with the main requirements of international space law.

7. Conclusion

Space Resources Utilization will unlock a whole new era of exploring, using and living space.

The old history of humanity on Earth demonstrates how the expansion of new civilizations and their development and maturation are all profoundly linked to the external environment, and how repeated negative actions against it can turn against a peaceful growth. Part of the success of a civilization therefore lies in its ability to establish constructive interactions with the surrounding world, and to recognize it as a critical and essential condition for its survival.

The near term evolutions of SRU for lunar development have been outlined with the goal of identifying technologies, solutions and strategies holding the greatest potential so far to reduce the amount of wastes produced on the Moon and to improve their management, so to be ultimately integrated into a circular economy framework, also taking into account the foreseeable logistical and scalability aspects that will characterize the future development of the first SRU activities.

In particular, attention has been given to lunar volatiles and minerals as sources of water, chemical propellant, building materials and oxygen, which are indeed regarded as the most important resources required to establish a robust and sustained presence on the Moon.

Based on this analysis, byproducts can be classified based on their perishability, hazard and usefulness. This allows to formulate recommendations on best practices to be adopted to ensure safe and effective lunar waste management. It has been demonstrated how such findings and guidelines can be successfully integrated into the developing legal frameworks established to regulate lunar activities.

These recommendations are not focused solely on the technical implementation of the scenarios examined, but also include legal considerations and technology development roadmaps. Moreover, given the economic value of most byproducts, it is here worth highlighting the role of a circular economy as a market-enabling paradigm rather than as an actual source of further restrictions on commercial ventures. This shall not be limited to resources but extend to end-of-service machinery as well. Ultimately, this opportunity to condense the learned-the-hard-way environmental wisdom will not only ensure long term lunar development, but will also bring useful practices or technologies back to Earth and will prepare humanity for the next delicate and pristine world: Mars.

The SGAC Space Exploration Project Group embraces this vision with enthusiasm and proactively works towards the advancement of lunar resources research. The work presented in this paper has been foundational in these regards and has encouraged the establishment, within the Project Group, of the Technical Unit Research for a Thriving Lunar Ecosystem (TURTLE), which will broaden the scope of these analyses to encompass other relevant aspects of Moon development, thus promoting a holistic and systemic approach to research.

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