CHALLENGE 1

# IN-SITU RESOURCES UTILIZATION

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## 1. INTRODUCTION

In-situ resource utilization (ISRU) is the practice to generate own products with local material, thinking in humans or robots working or staying on other solar-system bodies, like asteroids, the Moon or Mars.

The development of ISRU methods for the deep exploration of space and in particular for the exploration of Mars will become increasingly important in the following decades. As it is impossible to transport from Earth the required amount of some critical commodities, raw products need to be collected and transformed, in-situ, through new processes that are yet to be defined and tested.

Some of the most important products that need to be produced include oxygen, water, and methane as well as construction and radiation shielding materials. Among the new technologies that are being considered, additive manufacturing (or 3D printing) of lunar and Martian regolith is a possibility. The regolith is the layer of loose, heterogeneous surface deposits covering the solid rock. It includes dust, soil, broken rock and other related material present in all the planetary surfaces. Other efforts focus on extracting volatiles from the regolith, and this requires, in turn, new processing technologies and an extensive effort on mapping where the most critical resources (water, regolith with useful volatiles, metals, salts) may be concentrated and at reach.

The ISRU will require processes such as drilling, collection, storage, sorting, and chemical processing of lunar/asteroid/martian regolith to synthesize oxygen, water, and metals. Those extracted resources can be used as fuels for propelling rockets, life support consumables and building materials for a lunar/martian base. Concentration rates of those resources in the regolith are affected by the particle size. Regolith on the Moon, Phobos, Deimos (both are natural satellites of Mars) and Mars or asteroids is also of high interest. In particular, the lack of wind and water on Moon for example, allows regolith dust grains to maintain sharp and jagged edges, which increases its abrasiveness compared to powders we are familiar with.

Promising locations on the Moon, for example, for ISRU are those with ice: water can be used for life support and fuel, and ice is very easily separated from rock. The first lunar ISRU missions are focused near the Moon's south pole. A widespread presence of water ice has been detected in the permanently shadowed areas of the Polar Regions in the Moon. These deposits could be a valuable resource of hydrogen and oxygen for life support and fuel[1]. They aim to solve operational problems in the extreme cold of permanent shadow and determine the distribution of volatiles, including non-ice volatiles like hydrogen or carbon dioxide.

Mining proposals are focused on purely robotic flights. Space mining will likely start with extraction of water from the Moon and accessible near-Earth asteroids (NEAs). It's estimated that the Moon contains amounts of water contained in ice sheets found in 'permanently shaded craters'. Within about 40 of these craters, there are 600 million metric tons of water ice[2] this amount would be enough to launch one space shuttle per day for 2.200 years. Hydrogen can be extracted from water to be used as jet fuel, or to be used to drink and produce food, as well as to provide radiation protection.

In addition, the lunar soil is that 40% of it is made up of oxygen. This makes the Moon a very attractive option to host a space refuelling station, and in fact, there are multiple proposals to this effect. While companies are looking at extracting water from regolith, the exploration community is also interested in its insulating properties and how well it can provide protection from cosmic rays.

However, ISRU is not limited to water. Metals mined from extra-terrestrial bodies can be used to 3D print spaceship components. In fact, 3D manufacturing in space started in 2014, when the International Space Station's (ISS) 3D printer produced its first product. The primary goal of the project was to verify that a 3D

1 https://www.esa.int/About_Us/Business_with_ESA/Business_Opportunities/Water_and_oxygen_made_on_the_Moon
2 NASA Radar Finds Ice Deposits at Moon's North Pole' (NASA) www.nasa.gov/mission_pages/Mini-RF/multimedia/feature_ice_like_deposits.html

printer could function in a microgravity environment and developing materials strong enough to withstand space's vacuum, not achieved up to now. It remains to be seen whether metals extracted from space will be suitable for 3D printing. This kind of printing offers a potential means of facilitating lunar settlement with reduced logistics from Earth. As an example, the lunar material must be mixed with magnesium oxide. This turns it into 'paper' to print with. Then for the structural 'ink' a binding salt is applied to convert material to a stone-like solid. The current printer builds at a rate of around 2 m per hour, while a next-generation design should attain 3.5 m per hour, completing an entire building in a week[3].

On the other side, microgravity environments allow precise control of liquid and gas convection. The space vacuum also allows the creation of very pure materials, minimizing their defects. In addition, extreme temperatures in space, often necessary in the manufacturing process, are available.

ISRU philosophy to use the material on an extra-terrestrial body (i.e. for construction, isolation, fuel provision) can be divided in various actions: Prospection, Preparation or Exploration, Extraction, Construction and finally, Protection of the environment. In this chapter we want to present the state of the art on the ISRU, and discuss how CSIC as a national research institution can get involved on in a short, medium and long terms.

## 2. IMPACT IN BASIC SCIENCE PANORAMA AND POTENTIAL APPLICATIONS

The Exploration Roadmap of ESA and NASA to fulfil Human and Robotic exploration of Mars have been defined, and the first steps are now being implemented. However, the requirements on propellant mass do not allow for large landed missions. The future Mars Ascent Vehicle for humans will require about 7.0 mega tons of methane ($CH_4$) and 22.7 mega tons of oxygen to lift-off from Mars, back to Earth, with four crewmembers. This represents about 80% of the weight of the spacecraft, and this is to date one of the most critical problems that inhibit the human exploration of Mars. In addition to propellants, such as $CH_4$, water is another critical product, both for life-support systems and its possible transformation into hydrogen ($H_2$) and oxygen ($O_2$) for propulsion or again for life-support systems. ISRU is thus a new research activity which is being supported both by NASA and ESA.

3 http://www.esa.int/Enabling_Support/Space_Engineering_Technology/Building_a_lunar_base_with_3D_printing

CSIC scientist should participate in this kind of missions in the future. Nowadays, they are participating in building hardware and producing software of some instruments presents in mission to Mars, Mercury, Jupiter, asteroids and comets. This participation also needs getting involved in the interpretation of the data acquired by those instruments. From the scientific point of view, CSIC scientist should get involved in more missions to data acquisition on the Moon, Mars and asteroids/comets with the final idea to have first access to the data on where the key material abundances are present in the surface or sub-surface of those bodies.

## 2.1. Economic Impact

Space resources will play a critical role in future in-space economies. Incorporation of space resources into exploration missions will reduce costs and improve their economic viability. Space resources technology has multi-sector, near-term commercial value in existing terrestrial markets.

Using space resources is expected to create socio-economic benefits in three major areas. The first refers to the space resources utilization industry itself. The second area includes development of knowledge and technology in technical domains, such as materials science, manufacturing, additive manufacturing, robotics, and data analysis, which are expected to provide indirect benefits of the order of 2.5 B€ over 50 years. Third area refers to expected contribution to wider effects with a strong contribution to social and strategic benefits by enabling space exploration and development, and with some contributions to environmental benefits by lessening dependence on Earth's finite resources. Finally, a broader contribution to social and environmental benefits is expected by decreasing dependence on Earth's finite resources.

Exploitation of resources in situ, such as water, regolith or metals present on the Moon, Mars or nearby asteroids and comets, requires the establishment of new supply chains for effective activation. Although the first operational applications are expected to be ready in the next decade, preparatory steps are being taken today to develop enabled technologies and obtain prospective information on future exploitable space resources.

Companies, space agencies and other organizations must detect opportunities and anticipate future needs to create value chains in the use of space resources for their successful development. Although the use of in-situ space resources still has uncertainties, analysis of the different value chains reveals promising important aspects for the future of the industrial sector.

A recent study commissioned by the Luxembourg government[4, 5] has analyzed the potential economic impact of space resources utilization through an assessment of the associated future markets and value chains. The report concludes that market revenues of 73-170 B€ are expected from space resources from 2018-2045 supporting 845 thousand to 1.8 million full time employee years. Potential exploration cost savings (or equivalent cost of activities that would otherwise not have been undertaken) to end-users are estimated to be 54-135 B€. Technology and knowledge spill overs are estimated to be of the order 2.5 B€ over 50 years, which might be considered conservative based on recent interactions with terrestrial industry. Additional benefits are predicted based on industrial clustering, development of new standards with contributions to social, strategic benefits, environmental benefits.

Preparing space resource utilization will only be achieved through the combined efforts and resources of a broad and diverse community of actors. Cross-sector community will be involved in ISRU, including robotics, construction, engineering industries, geology mining or biotech companies.

ESA will have to actively engage with actors from different sectors and different scales, from Start Ups to large multinationals; from universities to public sector agencies, from industry on Earth to industry in Space. ESA will facilitate their participation and integration in the community and will ensure the effective construction of networks and communications within the community.

On the other hand, Spain, as an active member of ESA, should also get involved in it. It is of particular interest for the CSIC to actively participate in this development process, generating knowledge and new technological developments for its transfer to the space industry and also scientific participation on instruments/mission to the mentioned bodies.

Meanwhile, research and technology development are required on Earth. In parallel, flight opportunities across several missions in an ISRU preparation campaign. This is likely to be driven by the availability of flight opportunities, the capabilities of international and commercial missions and the timeliness of payload development and readiness for flight.

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4 Opportunities for space utilisation: future markets and value chains, study, (2018).
5 https://space-agency.public.lu/dam-assets/publications/2018/Study-Summary-of-the-Space-Resources-Value-Chain-Study.pdf

# 3. KEY CHALLENGING POINTS

## 3.1. Prospection

Space resources will be a major international topic in the next decade. ESA's position as a leader and an enabler for European science and industry would ensure that Europe has a role to play in the medium to long term utilization of resources in space, whilst delivering social and economic benefits in the near term here on Earth, in accordance with the international legal framework.

In that context, which are the most probable candidates for doing ISRU?

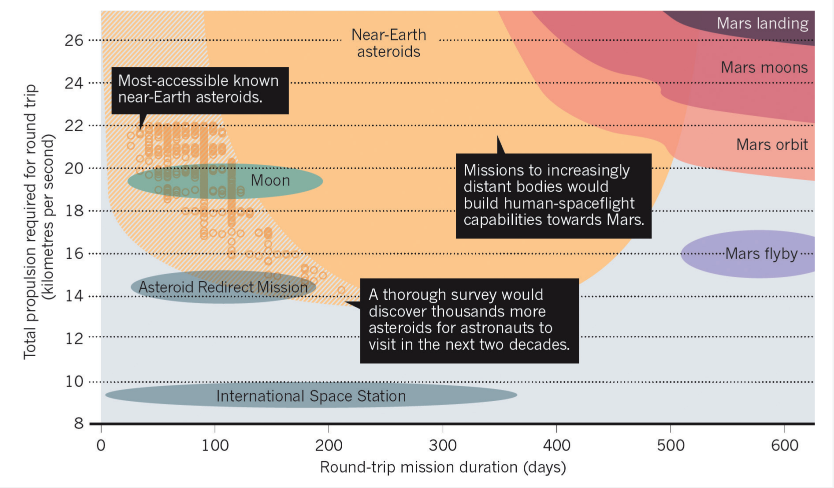
The most immediate candidates to be colonized are the Moon, some near Earth asteroid and Mars. Figure 1 presents the viability to reach each target. It is represented the total propulsion required for a round trip to the target versus the duration in days. The total propulsion is directly related to the cost of the mission.

As can be seen, the most accessible place in space is the International Space Station (ISS). Astronauts aboard the ISS today receive regular cargo shipments from Earth with food, air, water, rocket fuel, and spare parts. Then, there are a few, for the moment, NEAs that can be reached. Also, investing in asteroid discovering surveys can identify more small NEAs to be reached in short missions. The next, large body, with mineral resources, which can be used, is our Moon and in a long-term vision, Mars is the preferred target.

NEAs are easy to reach, in some cases, but still difficult to stay on target and extract materials. Once we are on the surface of the NEAs, the main problem is to anchor the ship to an object of one to several kilometres in size and install the mining machinery. Mars has the opposite problem, it is easy to install the mining machinery but it is still difficult or expensive to reach and stay there.

In this sense, the first utilization of space resources contemplated by the European Space Agency (ESA) will be on the Moon; a source of water, oxygen, metals and other materials. The strategy covers the period up to 2030, by which time the potential of lunar resources will have been established through measurements at the Moon, key technologies will have been developed and demonstrated and a plan for their introduction into international mission architectures will have been defined. Priorities for investments will be based on the available materials at the Moon, their applications in exploration and the demonstrated interest from terrestrial industries to partner and co-invest.

**FIGURE 1–**Adapted from Binzel (2014).




The resources of Mars and asteroids are also important considerations and activities at the Moon should prepare the way for future utilization at these locations.

In particular, the specific objectives of the ESA Space Resources Strategy, focusing on the Moon, for the period 2020-2030 are:

- Confirm whether space resources can enable sustainable space exploration and which resources are of primary interest for this purpose.
- Identify and create new scientific and economic opportunities for European industry and academia in the area of space resources and position European science and industry to take de advantage of these opportunities should they arise.
- Create benefits in the areas of technology and processes innovation for sustainability in Space and Earth
- Engage new industrial actors in the space endeavour
- Establish ESA's role as part of a broader community of international, public and private actors and create new international and commercial partnerships.

***The Targets***

What kind of material can be found in Mars, the Moon or the asteroids?

Mars and the Moon are basaltic differentiated bodies, composed by a metallic nucleus, an olivine mantle and a basaltic surface. Asteroids are shattered remnants of planetesimals, bodies that never grew up to became planets or fragments of larger bodies that suffered catastrophic collisions. Those, asteroids can be perfect testers of the interior of larger bodies, a unique opportunity to be in contact of a planetary nucleus or mantle. On Mars and the Moon, we will only have access to the surface or sub-surface of the bodies, the first kilometre from the surface, meanwhile, the surface of asteroids can be samples of any part of a shattered body or a pristine rock from the beginning of the solar system formation.

There are metallic asteroids that sampled the iron nucleus of a differentiated body like Mars or the Earth. This is an excellent opportunity to obtain minerals formed at high pressure and temperature like into the nucleus of a planetary body. Also, asteroids could be part of the hydrated mantle of a body like Ceres, where the interior models indicate the presence of a liquid ocean in the interior.

The extraction of material from the surfaces of Mars or the Moon are limited to those related to basaltic formation or deposited into the surface along millions of years. On the sub-surface of Mars, we are expecting to find hydrated materials formed when Mars has a liquid ocean on the surface. Also, the water and carbon mono(dio) oxide can be extracted from the polar regions.

In summary, in the near future investment on discovering new and easily reached NEAs is mandatory to have more targets in the list. At the same time, and as is currently doing by different space agencies is the detailed research on the characterization of the surface of the Moon. And finally, in the long term, the surface and sub-surface characterization of Mars need to be studied in detail, where a manned mission is planned in the next 20 years.

### 3.2. Preparation and Exploration

For the preparation of the site to be explored, we have our own reference that is our own Earth. The knowledge on the internal (shallow and deep) structure of the Earth as well the exploration of Earth's resources relies on a multitude of different geophysical and geological measurements and subsurface imaging approaches. Data acquisition, processing, structural imaging and interpretation techniques are essential and constantly improving. They provide us with new constraints, such as needed for fundamental understandings on geodynamic processes, geo-risks, and exploration of resources.

Similar strategies can be applied on any extra-terrestrial body. After decades of observation and study of the planets and bodies from the distance either from the Earth or from orbiting instruments the main challenge in the next decades will be the exploration of the sub-surface, difficult to assess from the distance. The best way to study in detail the surface and more important the sub-surface of a body is to put appropriate instruments on the surface of the targets. Radar technology and radio frequencies instruments installed on in-orbit satellites can also be used to characterize the sub-surface in remote mode.

Right now, in 2020, the sub-surface structure of the NASA mission's InSight landing site on Mars is being studied using different direct, in situ geophysical investigations. For instance, the magnetic field at the landing site is ten times stronger than was predicted from satellite data (Banerdt et al. 2020). Its interaction with solar winds affects surface environments and is being used to study the magnetic weather, crustal magnetization, and dynamo, among others. Further, with InSight for the first time a seismometer has been placed on the surface of another planet. The first seismic measurements reveal many small magnitude Marsquakes that together with the seismic response from dust devils are now being used to constrain the very shallow and crustal structure of Mars (Lognonne et al 2020). Seismic wave speeds and attenuation of energy permit to constrain the seismic structure and to compare it to Moon and Earth. Different structural discontinuities are being revealed and mapped owing to the identification of reflected waves. Seismicity is low compared to Earth. In the first 10 months, about 460 events (quakes, landslides, etc.) have been detected of which 174 have been studied more into depth.

At present, revealing the interior structure and dynamics relays on robust single-station approaches. The problems to tackle are non-unique, and data might be limited due to unfavourable deployment and environmental conditions. For instance, at the InSight landing site temperatures vary during a martian day over 70 $^{o}$C and winds are shaking the lander and instruments. Thermal stresses and lander modes are being recorded and can mask smaller signals in the acquired data. New capable methods for the exploration of extra-terrestrial bodies need to be developed and extensively tested to image and monitor the subsurface with less ambiguity and higher resolution to efficiently guide any further exploration or resources.

### *Exploring the subsurface*

First direct information on the rocks and composition of the Moon, asteroids, and Mars came from surface samples collected in the frame of the first landed missions. Those surface samples are part of the so-called regolith, the uppermost layer covering the surface. But regolith samples mainly represent the altered and unconsolidated surficial horizon that is not necessarily representative of the composition of the rocks in the sub-surface. Therefore, the exploration of the sub-surface is necessary to learn on the actual structure and composition of the planets and bodies under investigation. Also, we should be ready to face many open questions on the present-day activity and active geodynamic processes (active faults, plate tectonics, volcanic activity) and the evolution in each case, as we already known this can be different for the different bodies. Most of these should be proven during the exploration of the internal structure and dynamics.

As of today, we can envisage the sub-surface exploration will progress by applying geophysical methods based on our experience in exploration of the Earth's sub-surface but considering the specific constraints and particular and specific environmental conditions on different planets and exploration objectives. Specific conditions like temperature, gravity, magnetic field and presence (or absence) of fluids in the sub-surface will be a major constrain for the applicability of some of the standard geophysical exploration methods and existing instrumentation. Therefore, it will be necessary to implement innovative instrumentation to achieve these challenges.

The common approach and steps using available methodologies for Earth exploring would be to start obtaining a big picture of the sub-surface and then go to the detail, using large coverage methods first (remote sensing and satellite info), then geophysical surveys from close to the surface (e.g. drone surveys), from the surfaces with instruments deployed on the ground and finally achieving direct measurements by drilling, borehole logging and sampling and borehole monitoring.

We can envisage following these steps and the specific techniques that could be applied, from the use of remote sensing exploration methods (e.g. satellite based) as first step a second and next step would be the direct exploration from the proximity of the surface (i.e. low-frequency geo-radars, spectrometers) and finally directly from the surface: all three steps are complementary and provide us with different types of data:

- Surface geophysical measurements and monitoring applying seismic, magnetic, electromagnetic, gravity and temperature geophysical methods, where applicable. Both airborne (when possible) and also using equipment and instrumentation deployed on the surface of the planet or body investigated would provide us with indirect measurements of the sub-surface and with a first picture on the structures and layers underlying the regolith. These methods of exploration are used always in the first phases of the sub-surface exploration on Earth because large areas and volumes of rocks are investigated and help to identify anomalies in the sub-surface and possible targets and objectives for drilling, the next step. This is the general approach when the exploration targets are sub-surface resources (e.g. hydrocarbons and mineral resources).
- Drilling and borehole/down-hole sampling, geophysical logging down-hole logging and imaging and down-hole monitoring are direct types of tools and measurements for investigation of the subsurface applied on the Earth. It is expected that first planetary drillings will cover the first meters of the sub-surface but future drilling should reach hundreds to thousands of meters, following the evolution of planetary drilling technologies. As it has been stated in recent attempts to drill in Mars, the drilling techniques should be improved and refined in the next year in order to achieve successful sub-surface drilling and sampling. At the same time new borehole logging and monitoring tools will be developed and adapted for the exploration of planetary sub-surfaces. These tools would be used inside the boreholes for continuous measurements, profiling and imaging (with optical and hyperspectral cameras) to map mineral content, textures and composition of the rocks at depth and also on possible fluids and gases. And specific instrumentation would be dedicated to monitoring.

Borehole instrumentation is somehow protected from surface extreme conditions and this would be an advantage for the quality and reliability of the measurements performed, usually less noise and more stable conditions during extreme environmental changes experienced during day and night and in case of storms.

It is convenient to highlight at this point that, even in case of successful drilling and logging, we would be able to reach only the first meters or kilometres as drilling capabilities are nowadays in the range of 12 km (vertical or horizontal) on the Earth. To investigate and learn more on the structure and composition of deeper levels we would need to apply again indirect geophysical methods to investigate the deep structure and composition using methods like seismic monitoring.

*Scale and scope*

Using the tools and methods presented, the exploration would offer the first big pictures of the sub-surface and an outline of large structures (plates, sutures, major faults and faults systems, large volcanoes and major boundaries between layers of different composition). Also, the possibility to detect large ore bodies rich in mineral resources, based on geophysical anomalies characterized and interpreted by experts. This would be the large-scale scope of the exploration. Then by drilling and logging in boreholes we would obtain direct and detailed mineral composition, gases and fluids as well as rock textures, structures and geo-mechanical properties can be defined in detail, and also confirm or refine the geophysical interpretations and models obtained from geophysical methods.

Sub-surface planetary exploration has already started and we know about first results obtained from the sub-surface. Seismic sensors were deployed on Mars (InSight mission) detected possible on-going seismic activity (Banerdt et al., 2020) that could be related to active geologic processes in the subsurface. Also, recently subsurface imaging was achieved using geo-radar instrumentation deployed by the Chinese rover Yutu-2, mission operating for months on the Moon's far side (Chunlai Li et al 2020). These recently published results were obtained using a 500 MHz LPR (Lunar Penetrating Radar) and revealed the layered structure of the first 40 m section of the lunar sub-surface. These results indicate the presence of granular and porous rocks and outline a layered structure of rock bodies underlying the 12m thick regolith, homogenous and mostly composed by fine materials. Also, the internal textural properties consisting of heterometric boulders embedded in finer grain granular material. This can be considered one of the first and successful exploration achievements and first results of exploration using conventional techniques developed and used on the Earth as "ground penetrating radar". Chang-4 successfully landed on the eastern floor of Von Karman crater within the South Pole Aitken Basin. The Lunar Penetrating Radar (LPR) was on-board the Yutu-2 rover. The radar is a dual frequency GPR system, operating at 60 Mhz (low frequency) and 500 Mhz (high frequency), with a frequency band of 40 to 80 Mhz and 250 to 750 Mhz, respectively (Chunlai Li et al, 2020).

### 3.3. Extraction

The possible sources of extraction of resources are the regolith present on the surfaces (i.e. Moon, asteroids, Mars), dust and gases from the atmospheres if present. After the prospection of the place to understand the resources and determine how abundant is, and the distribution of the resources also with the hetero/homogeneity we need to determine the energy required to evolve or separate the resource. Martian and Lunar regolith contain valuable elements for many applications. Some examples are iron (Fe) and magnesium (Mg) for aerospace applications, silicon (Si) for solar cells, sodium (Na) or Mg for the preparation of binders' form cement like materials, oxygen (O) for the life support or propellant. Terrestrial mining technology to recover metals from metal oxides is very mature. But processes generally use large volumes of chemicals that are often caustic or corrosive or thermal methods that require high-energy inputs.

How can we extract all these materials from the regolith? In 2018 the European Space Agency organized a workshop called "Towards the use of Lunar Resources" where participants identified potential technologies that are of interest for producing oxygen and/or water from lunar regolith:

- **Hydrogen reduction:** The hydrogen reduction process has some appeal in ISRU because hydrogen is available as a gaseous reagent on the Moon and at other destinations that also harbour water. In its first stage of development, the process aims at reducing available minerals such as Ilmenite ($FeTiO_3$) found on the Moon to produce oxygen. Extract oxygen from regolith by high-temperature reaction of iron oxides in the regolith followed by water electrolysis. The reaction is limited to iron oxides, which forces the selection of a soil where these oxides are abundant and/or the use of techniques to beneficiate the regolith to obtain a soil with a larger portion of iron oxides. The simplicity and the relatively low operating temperatures of this technology make it a good candidate for early demonstrations of oxygen extraction on a limited scale during robotic space missions.
- **Carbothermal reduction**: This is a mature terrestrial technology using carbon to reduce metal oxides (ores) to produce metals such as iron in blast furnaces and metallurgical grade silicon. The same process can be used to reduce minerals containing various metallic oxides in the lunar and other asteroidal or planetary regolith to produce oxygen.
- **The FFC Cambridge process:** This process is an electrochemical method in which solid metal compounds, like oxides, are cathodically reduced to the respective metals or alloys in molten salts.

- **Molten electrolysis:** This is the process used to extract aluminium from bauxite, an ore, which also contains impurities such us iron oxide and silicon dioxide. Until now, only laboratory studies with lunar regolith simulants have been published (Ellery et al. 2017) among others. They formulated a concept to link the molten salt electrolysis with additive manufacturing of the metals produced. Molten salt electrolysis is used industrially for the production of aluminium, lithium, magnesium and other metals such as rare earth metals.
- **Ionic liquid (IL) electrolysis:** organic salts are molten at or near room temperature. Being entirely composed of ions, ILs have a number of properties that makes them attractive for in-space use, including electrochemical and thermal stability, low vapour pressures, and high ionic conductivity.
- **Vacuum pyrolysis:** this method is the decomposition of materials at elevated temperatures in an inert atmosphere. The focus of these pyrolyses related techniques is the production of oxygen from the regolith. Just to mention a few of them are the solar concentration, solar heating of regolith, resistive heating of regolith, sintering, regolith boiling, and more. Vapour phase pyrolysis, in principle, only requires regolith and concentrated sunlight, but faces difficulties in the separation of metals, metal oxides and oxygen in the gas stream.

Novel approaches to oxygen production are still being proposed (e.g. ionic liquids processing of regolith. It is likely, with the increased focus on lunar exploration, that new processes will be identified and the performance of the existing processes improved, taking inspiration and knowledge from other industrial and research sectors (e.g. metallurgy research for terrestrial smelting, semiconductor processing methods). There is a technological challenge in realising such processes in-situ (Schluter and Cowley, 2020).

***Extraction of elements***

In practice water ice in the inner solar system space is scarce, with exception of high latitude hidden regions in Lunar and Martian craters.

Water ice is now widely considered to be present on the lunar surface in specific locations. Using near infrared spectroscopic data from the Moon Mineralogy Mapper instrument on board the Chandrayaan-1 spacecraft, Li et al. (2018) claim to have found direct evidence for water ice at the surface of lunar polar, permanently shadowed regions. They state that the ice content dispersed in the regolith could be up to 30 wt%. These water deposits, if accurate and accessible, represent a tantalising resource that could enable many ISRU processes.

Hurley et al. (2016) estimated the total amount of hydrogen in the lunar polar volatiles to be $10^{11}$ kg. However, they also state that the radar data does indicate that the hydrogen is present either in ice grains <10 cm, or found as "hydrated minerals, adsorbed molecules, pore-filling ice, and small ice grains mixed with regolith", which would complicate the mining and processing in terms of immediate accessibility.

Water can also be extracted from phyllosilicates. Clay minerals are composed of sheets of FeO/OH, MgO/OH, or AlO/OH in octahedral configurations forming sheets with connected $SiO_4$ tetrahedral. These are common in carbonaceous chondritic asteroids, Mars and probably some Moon regions. For example, in Mars a clay common mineral is smectite. It has a layer of $H_2O$ molecules bound to Na or Ca sandwiched in between the metal-bearing sheets and adsorbed $H_2O$ on all surfaces. Such adsorbed water is released at temperatures ~100-150 °C and the bound water can be harvested by heating to ~300 °C. Once released the water or hydroxyl is easy to get oxygen by electrolysis.

In carbonaceous asteroids it was identified different types of phylo-silicates that might be source of water. The meteorite specimens of the most hydrated CI, CM and CR chondrite groups contain up to a 12% of water in mass, but that is an (probably biased) upper limit. In general, the abundance is 1-4% in mass (Trigo-Rodríguez et al., 2019 and references therein). Volcanic glasses in the Moon and Mars also contain water, so their well-localized deposits could be an additional source of water.

Oxygen can be obtained by $H_2$ reduction of ilmenite (Fe,Ti oxide), producing Fe, $TiO_2$ and water (again by electrolysis we can get $H_2$ and $O_2$). Oxygen also can be obtained from some phylo-silicates and oxides present in the regolith. In basalt-rich Lunar and Martian terrains the water is available as the (hydroxyl)-bearing phase: apatite - $Ca_5[PO_4]_3(OH,F,Cl)$.

Another source of oxygen is the lunar regolith itself, as it contains approximately 45% of oxygen per weight. As regolith is ubiquitous to the lunar surface, oxygen can be extracted from it essentially everywhere, although the composition varies considerably. The most abundant oxide is $SiO_2$, ranging from 40.7 to 47.1 wt%.

To extract oxygen from the minerals in the lunar regolith, the metal oxides present therein have to be reduced to the corresponding metals. The iron content in the lunar regolith is notably location-specific. In mare basalts, the iron content can be in the range of 14–17 wt%. Xia et al. (2019) used the Interference Imaging Spectrometer on the Chang'e_1 orbiter to determine a detailed map of the six major oxides ($SiO_2$, $Al_2O_3$, CaO, FeO, MgO and $TiO_2$) and Mg# with a resolution of 200 m/pixel. It needs to be mentioned that lunar regolith melts incongruently. Its solidus temperature, below which all of it is solid, varies between 1050 ºC and 1150 ºC and its liquids temperature, above which all of it is molten, range from 1150ºC to 1400ºC.

Water can be extracted also from apatite, but this mineral is also a useful raw material for the production of phosphorus (P) and phosphoric acid. This is because the apatite can be pyro-metallurgically treated using carbon (C) to extract P without fluxing at temperatures exceeding 1800 °C. In addition, the resulting slag phases allow the extraction of REEs.

Specific minerals are an opportunity. Rare Earths Elements (REEs) are also common in some undifferentiated bodies. On the Moon, for example, the KREEP-rich region underlies the Oceanus Procellarum and Imbrium Basin region contain the "KREEP" material: impact breccia and basaltic rocks enriched in Potassium (K), Rare-earth elements, and Phosphorus (P). The majority of lunar samples (Apollo, Luna, or meteoritic samples) contain REE-bearing minerals as trace phases, e.g., apatite and/or merrillite. Some carbonaceous chondritic asteroids contain significant amounts of REEs.

Helium-3 ($^3$He), and Helium-4 ($^4$He), plus other light chemical elements transported by the solar wind which have been implanted in the lunar regolith, so they could be also extracted, preferentially from the fine-grained component.

Organic compounds with significant amount of C are common in carbonaceous chondrites, and localized regolith-rich regions in Mars and the Moon. In C-rich asteroids is not only forming organic compounds generated by aqueous alteration-driven catalysis because metamorphosed materials have significant amorphous carbon. This is because of being heated and de-hydrated as consequence of impacts. Sometimes C-rich projectile collisions produce extremely rich clasts.

### *Conclusion*

Water can be used for life support and fuel. Oxygen can be obtained from regolith and using sunlight as power source. Hydrogen and oxygen from water will provide habitable conditions for the astronauts to breathe "quasi-atmospheres". Other minerals like phosphorous, carbon, and REE also can be obtained using different techniques.

Development of new strategies based on the use of ISRU for protection from cosmic rays (analyses of electromagnetic properties of regolith to study its feasibility as protection from cosmic rays) is recommended.

Finally, the analysis and optimization of fertility of lunar and other regoliths to achieve more self-sustaining agriculture systems at future bases need to be considered.

As an example, Alex Ignatiev (Lunar Resources, Inc., Houston, Texas) and colleagues presented the latest ideas for how to make solar cells directly on the lunar surface. A rover with a wheelbase on the order of 1–2 meter and weighing about 200 kilograms could be equipped to produce a glassy substrate a few millimetres thick on which silicon and aluminium vapours are deposited to make thin film solar cells.

Both autonomous and tele-operated robots will have a key role as far as materials extraction is concerned. Whether in combination with manned bases or as autonomous robot colonies, ISRU sites will likely have a mine and an automated mineral processing facility. Space mining robotics (and, more in general automation in process control technologies) will benefit from spinning-in/spinning-out effects from terrestrial mining technology. Specific challenges are detailed in section 4. In particular, mining and robotics technologies are mentioned in the "ESA Space Resources Strategy"[6] as enabling technologies that need research activities on Earth.

**Attention is claimed to all techniques related to extract purified minerals from a component like lunar, asteroid and martian regoliths, given priority for the lunar case in the next twenty upcoming years.**

Construction advancements in additive manufacturing or 3-D printing, may make it possible to use regolith harvested on the Moon, Mars and its moons,

6 https://sci.esa.int/documents/34161/35992/1567260390250-ESA_Space_Resources_Strategy.pdf

and asteroids to construct habitation elements on extra-terrestrial surfaces, such as living quarters and storage facilities.

Gravitational force on the Moon is 1/6 of that on Earth. In addition, the sieve system requires periodic cleaning of accumulated particles on the sieve to prevent clogging, and so the system requires a mechanical cleaning system which will make the system more complex and increase the failure risk because small regolith particles easily enter gaps in the mechanical system. Therefore, a new type of the size sorting system that reliably works in the Moon environment is necessary.

One important issue to face is a size sorting system required to increase fluidization of particle motions and increase the surface area of particles and reaction rate for the improvement of the ISRU performance (Sander and Larson, 2013). An electrostatic size sorting system has been developed (Kawamoto and Adachi, 2014). This system utilizes an electrostatic traveling wave that transports regolith particles by utilizing the Coulomb force and a dielectro-phoresis force. The travelling wave was mainly used for the cleaning of regolith particles deposited on surfaces of solar panels and optical lenses (Calle et al. 2011). While the particles were transported using the travelling wave, size sorting of the regolith was conducted by using a balance between the electrostatic and gravitational forces acting on particles, which depends on the particle diameter. In a previous study (Kawamoto and Adachi, 2014), a demonstration of particle size sorting using the electrostatic systems were experimentally conducted in a low vacuum environment (=10 [Pa]). Although the system could sort small particles less than 20 μm in diameter from the bulk of the regolith in the vacuum environment, the analysis of the particle dynamics in the electrostatic field was not enough. In particular, the effect of the particle charges, which largely affects the particle motion, was not investigated. Later, in 2016, the researchers measured the charge of each particle, and the effect of those charges on particle movements was investigated by conducting a model experiment and a numerical calculation based on the distinct element method. In addition, it was experimentally demonstrated that particles less than 20 μm in diameter were sorted from the bulk of a lunar regolith simulant under moderate vacuum conditions (~1.5×10-2 [Pa]). Masato et al (2016) developed a particle-size sorting system of lunar regolith using an electrostatic force for ISRU on the Moon to extract indispensable resources from the regolith and realize long-term explorations. The system utilizes only the electrostatic force, and it does not need gas, liquid, or even mechanical moving parts.

***Particle handling on Mars***

Dust particles on Mars have an effective radius of 1.0 μm over much of the atmospheric column below 40 km throughout the Martian year. This includes the detached tropical dust layers detected in previous studies. Effective radii range from > 3 μm below 20 km to near 1.0 μm at 40 km altitude.

The martian atmosphere typically contains 10-400 billion metric tons of dust particles ranging in diameter from <1 to >10 μm, but it is too dispersed to be acquired by rover sampling systems. Most of the particles on Mars are ferrous, susceptible to a magnetic trapping effect. The Curiosity rover includes a tool, known as the Collection and Handling for Interior Martian Rock Analysis (CHIMRA) to collect and sort samples from the Martian surface. This tool, has a system of chambers and labyrinths used to sort, sift, and portion samples. Curiosity sorts samples by flexing the wrist joint on its arm to position the turret, while using a vibration device to move material through the chambers, passages, and sieves. The vibration device also creates the right portion size for dropping material into the inlet ports on the rover deck for rock-analysing instruments (SAM and CheMin) inside the rover's body. However, it is uncontrolled manipulation of the particles, which demand new devices based on the vibration concept.

***Robotics and Artificial Intelligence technologies***

There is an increasing interest for ISRU (but also Resource exploitation for Earth) in the space community. This would allow longer and sustainable missions. In fact, to date, all that is needed (oxygen, water and other consumables for life support, propellant and materials for construction and manufacturing) needs to be transported from Earth to space. This will be especially critical for long-termed human missions.

Working in space, however, is a critical issue. Extremely harsh environmental conditions, exposition to radiations and other hazards will impose to human's minimal exposition to the external environment. Therefore, robots (both autonomous and tele-operated) will be key tools for resources discovery, extraction and transportation, as well as for (semi) automated constructions of structures such as human shelters and docking stations.

Key technologies and research topics related to these scenarios are listed below.

*Tasks*

- **Autonomous exploration/mapping** for assessment before human settlements. Prior to the landing of humans, detailed maps (including geological and meteorological features) are needed. Teams of robots can perform this task for the preparation of human arrival, but also during their stay (e.g. in search for resources, see above).
- **Automated and/or tele-operated building/assembly** of structures. Some infrastructure may already be in place before arrival of humans, assembled by autonomous robots. Additionally, tele-operated robots may be of great help in order to perform operations supervised by in-situ operators, with the purpose of reducing risks (exposition to radiations etc.). The use of locally available resources shall be considered, which connects this topic with ISRU.
- **Autonomous and/or tele-operated vehicles for logistic** (transportation of materials). Same as above.

*Technologies*

- **Autonomy**. The lack of high bandwidth and real-time communications with human operators makes autonomy and intelligence a key feature of the systems. This includes the capability of understanding their surroundings, self-localization, situational awareness, motion planning, as well as high level task/mission planning and self-awareness.
- **Multi-robot coordination.** Also related to autonomy is robot coordination. Many tasks will carry out in a more efficient ways by teams of robots that shall coordinate their activities.
- **Modularity** and (self-?) **re-configurability** for improved resilience.
- **Locomotion** in harsh environments. Legged locomotion as an alternative to wheels, especially for mining robots. Need to consider low gravity.
- **Tele-operation**. In-situ human operators to remotely operate mobile robots and/or other manipulation stations on the planet for logistics (loading/downloading/local transportation), but also for exploration/production (such as foraging or mining).
- **Energy**. (Re-)charging for underground operations or in absence of direct sunlight (e.g., the dark side of the moon).
- Geo-physical sensors for ore detection.

Construction technologies on the lunar surface are different from terrestrial ones. The community identified several technologies:

Sintering or melting of regolith: solar, microwave, laser, resistive heating. Solid structures can be built out of sintered lunar regolith and molten regolith can provide additional air tightness to the edifice.

- Regolith consolidation using binders: chemical, polymer, bio-based binders (e.g. enzymes). Most of the binders would have to be brought from Earth and space environment conditions can adversely affect binders (outgassing, radiation-induced degradation), but can also be used at their advantage (e.g. binder curing with radiation).
- Additive manufacturing (3D-printing) with extracted metals or lunar regolith was found promising as a versatile technology for construction or metallic hardware manufacturing.
- 3D-printed materials, inflatable or foldable structures could all take part in the architecture and design of the habitats.
- Basic technologies: Digging and compaction of dust to produce blocks could also be considered.

It is worth noting that the above-mentioned enabling technologies are common to other ISRU applications, like planetary exploration and mining robots.

***Health issues to be addressed***

The current noise control and vibration technologies should be adapted to undertake new challenges concerning aerospace exploration and maintain safety of structures and staff in space mission.

Any on-orbit laboratory or space mission with a long-term person occupation presents a significant acoustic challenge considering the equipment that may create a noisy environment. It is important to maintain reasonable noise levels not only for hearing loss of the technical staff, but also for acoustic comfort and habitability, and for avoiding risks associated to reduced speech intelligibility between staff and the ground or between the crew members. The main goal would be to explore the sustainable integration of acoustic materials designed to be both absorbing and insulating in order to reduce interior noise annoyance for vehicles in missions or for permanent settings of personal staff.

Also, lightening of structures is one of the fundamental strategies for improvement of performance in the aerospace industry. They can be found in various applications such as fuselages, arrays of solar panels or antennas for satellite.

The mass density reduction leads to increase the transmitted vibrations that may result in vibroacoustic fatigue up to the limit of fracture. It constitutes then a danger for the integrity of the components or equipment's to be transported. The use of vibro-acoustic materials will mitigate the transmission and also contribute to reduce vibrations of the instruments for space observations.

The Lunar regolith offers diverse relevant products, but the effects of dust particles (size < 200 μm) should be addressed before any human activity.

These particles have potential for coatings, on seals, gaskets, optical lens, suits, windows, electrical components, etc. However, they are harmful, causing physiological effects on humans, especially with respect to the lungs, the lymph system, and potentially the cardiovascular system, in the case of extremely fine particles.

### 3.3. Protection

***Legal Framework***

International law applicable to outer space activities lags behind rapid technological advances. There is currently no clear answer to the legal questions posed by space mining. There remains significant legal uncertainty about how to proceed in mining on the Moon and asteroids under existing international and national law. International agreements state that no government can claim outer space or celestial bodies as their own. Private companies interested in investing in space see these uncertainties as a major impediment to the future commercial development of space. These companies argue that the absence of property rights is an impediment to obtaining external financing, hinders the protection of their investments in space and the guarantee of adequate income on their investments.

The Treaty on the Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Organs, "Outer Space Treaty", is the founding text of international space law.[7] It entered into force in 1967 and has been signed and ratified by more than 100 nations.

Article I provides: " *the exploration and use of outer space, including the Moon and other celestial bodies, shall be carried out for the benefit and in the interests of all countries...Outer space, including the Moon and other celestial bodies, shall be free for exploration and use by all States without discrimination of any kind,*

7 Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies, 27 January 1967, 18 UST 2410, 610 UNTS 205.

*on a basis of equality and in accordance with international law, and there shall be free access to all areas of celestial bodies."* The Treaty does not clearly address whether the extraction of space resources is lawful.

The Treaty present a problem, there is not a single definition of celestial bodies, if this category includes asteroids (see Article II and Art VI of the Treaty). If they are not defined as celestial bodies, then the prohibition of the Outer Space Treaty on national appropriation of the Moon and other celestial bodies would not apply to them.

The International Institute of Space Law considers that, while the Outer Space Treaty does not create an express right to extract space resources, it also does not prohibit such action.[8] In particular, Article I provides for the free exploration and use of celestial bodies in outer space without discrimination. However, the Treaty does not clarify the free use of non-renewable natural space resources.

The Outer Space Treaty is the 'constitution' of international space law; other treaties also bear on commercial space mining ventures:

Moon Treaty: addresses resource extraction from the Moon, and likely also applies to asteroids. It declares that the Moon and other celestial bodies in the solar system, as well as their natural resources, are the 'province of all mankind', the 'common heritage of all mankind' (Marboe 2016 and Roth 2015). The Moon Treaty has been signed by fewer than 20 countries and was not signed by the United States or other space-faring nations. Some regard the Moon Treaty is obsolete and it could present a significant barrier to private space mining.

The Liability Convention: on International Liability for Damage Caused by Space Objects[9] includes the Agreement on the Rescue and return of Astronauts and Objects Launched into Outer Space (***'Rescue Agreement'***)[10] and the Convention on Registration of Objects Launched into Outer Space (***'Registration Agreement'***)[11]. The Liability Convention creates a liability framework for damage cause by spacecraft and establishes a strict liability standard for accidents on the Earth's surface and a negligence standard for accidents elsewhere. Where disputes arise, they are resolved through the Claims Commission. However, because Claims Commission decisions are only binding with

8 Position Paper on Space Resource Mining' (International Institute of Space Law, 20 December 2015) www.iislweb.org/docs/SpaceResourceMining.pdf
9 Convention on International Liability for Damage Caused by Space Objects, 29 March 1972, 24 UST 2389, 961 UNTS 187.
10 Agreement on the Rescue of Astronauts, the Return of Astronauts and the Return of Objects Launched into Outer Space, 22 April 1968, 19 UST 7570, 672 UNTS 119.
11 Convention on Registration of Objects Launched into Outer Space,14 January 1975, 28UST695,1023 UNTS 15.

the consent of the parties. Any space-mining mission would have to meet the requirements of these international agreements.

Article III of the Outer Space Treaty states that States Parties shall conduct activities in outer space 'in accordance with international law'. At present, the relationship between traditional international law and space law remains unsettled. There is some uncertainty about how activities should be carried out in space "in accordance with international law". Some government and industry representative's advocate requesting an amendment to the Outer Space Treaty to provide private companies with legal clarity (Foust 2017). Specifically, they point out that the Treaty was drafted at a time when commercial space mining was unthinkable. However, the opening of the Treaty for the amendment and attempt to reach broad international consensus would be risky and difficult. Others are opposed to seeking amendments to the Treaty.

The Hague International Space Resources Governance Working Group ('Working Group') seeks to address this uncertainty for resources development in outer space. The goal of the Working Group is to 'assess, on a global scale, the need for a regulatory framework for space resource activities and to prepare the basis for such regulatory framework'. The Working Group prepared draft set of 'building blocks' for a regulatory framework for the development of resources in space in 17 September 2017 to "create an environment conducive to space resource activities that takes into account all the interests and benefits of all countries and humanity". To this end, the Working Group supports the pillars of international law, including the idea that the development of space resources should be solely for peaceful purposes, and for the benefit and interest of all countries and humanity independently of its degree of economic and scientific development. The Working Group believes that implementation of the international framework should be monitored on the basis of reports of states and intergovernmental organisations. It recommends that States and intergovernmental organizations take responsibility for the development of resources in outer space by creating laws to authorize and regulate these activities, as well as products generated by these activities; the legal framework created by the State or intergovernmental organization must be consistent with international legal principles.

As was mentioned before, the United Nations developed the Moon Agreement in 1979. Only 16 countries have entered into the Moon Agreement – and the parties do not include key industrialised countries like China, Russia or the United States. The Moon Agreement describes the Moon as 'the common heritage of mankind'. However, the Outer Space Treaty refers to outer space as 'the province of all mankind', but not as its 'common heritage'. Thus, the countries who are parties to the Outer Space Treaty, but not the Moon Agreement, have not adopted the view that outer space should be treated in a manner analogous to the deep seabed.

***Planetary protection***

The COSPAR (Committee on Space Research) Planetary Protection (PP) Panel defines a policy that is a scientific guidance framework for space exploration. This Policy is defined and upgraded by agreement between the scientific community and space agencies in compliance with the United Nations Outer Space Treaty. The different space exploration planetary protection categories (I-V) reflect the level of interest and concern that biological contamination can compromise future investigations or, for sample return missions, the safety of the Earth. The categories and associated requirements depend on the target body and mission type combinations. This categorisation is revisited when new scientific results challenge the current perception and indicate the necessity for updates or when challenges appear from new players in the space field or new requests. It is foreseen that the PP policy will have to be reviewed periodically in the following decades. The COSPAR Planetary Protection policy places lander missions to Mars under Category IV, which requires stringent bioburden control and reduction mechanisms. Furthermore, any mission dedicated to the search of present or past life on Mars is assigned Category IVb which requires that the entire landed system is restricted to a surface bioburden level of ≤ 30 spores per $m^2$ or levels of bioburden reduction driven by the nature and sensitivity of the particular life-detection experiments. Any subsystem of the lander system that is involved in such a mission must also be subjected to a bioburden control of ≤ 30 spores per $m^2$. The challenge is now the preparation for the human exploration and sample return missions and the potential intersection with activities devoted to finding signatures of life of Mars, which may be compromised by the aerial dispersal/spreading of bioburden from landed robotic platforms and then, in the future, from human-crewed missions. Also, new detection protocols for clean rooms need to be defined, as nowadays, only cultivable organisms are detected by swab-sampling and agar growth. However, most of the microorganisms cannot be detected this way, and the resistance of them to the sterilisation procedures that are now in place is also unknown.

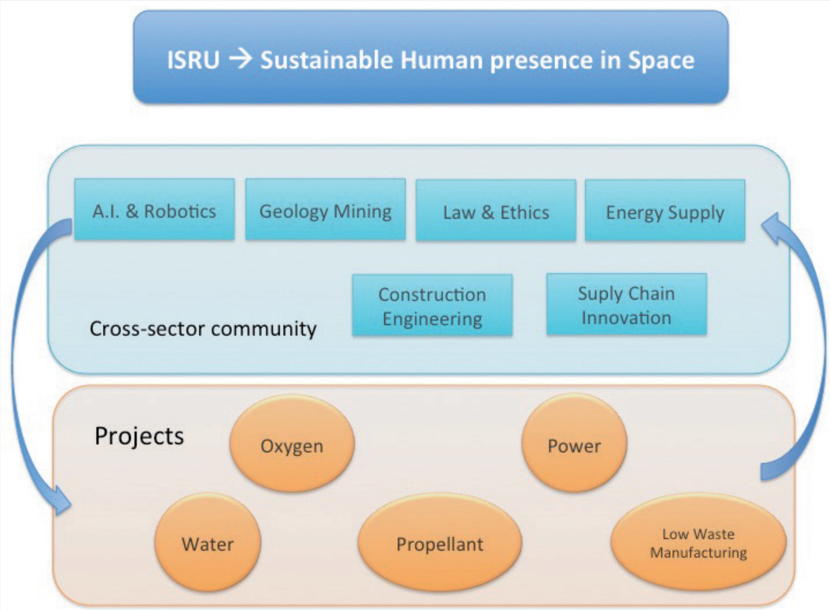
## 3.4. Conclusions

The exploitation of Moon resources is an important and immediate point. Kornuta et al. (2019) and Jones et al. (2019) have examined whether materials from the Moon can be manufactured into propellant for spacecraft and whether a commercial business case can be made. In many cases, ISRU missions propose finding water ice or hydrated minerals and extracting the water to be electrolyzed into its constituent components of hydrogen and oxygen, or reducing the oxides in the regolith for oxygen. These components are then cooled, liquefied, stored, and utilized as propellant for rockets in cislunar space. Fundamental research into lunar materials and the underlying science of resource utilization is needed in addition to technology development. **Fundamental scientific research at the Moon, asteroids and Mars is important to better understand the resources we are aware of and to identify opportunities we are not aware of yet whilst delivering near term benefits for science.**

The NASA 2020 Mars Rover mission that has landed at Jezero Crater, Mars, will collect and cache geological samples for their future return to Earth. The transportation to Earth will require a sample-retrieval mission and an Earth return mission. ESA is now developing both of them. An international team of 77 researchers (International MSR Objectives and Samples Team, iMOST) has prepared a white paper describing the potential goals of the Mars Sample Return (MSR) mission. This team has reviewed the state of the art of the latest scientific and engineering discoveries about Mars and its exploration plans, to define the scientific objectives, the samples of interest, their amount, the requirements on sampling, and the analytical methods that would be applied to the Martian samples once on Earth. These suggestions were adapted to the realities of the NASA 2020 Mars Rover sampling system. The objectives of the sample studies required to improve our understanding of the Martian history, present state and future exploration risks and potentials of Mars are classified as 1) Geological environments; 2) life; 3) Geochronology; 4) Volatiles; 5) Planetary-scale geology; 6) Environmental Hazards and 7) In-Situ Resource Utilization (ISRU).

Independently of the technological challenges associated with this mission architecture, the future scientific challenges related to Mars Sample Return will mostly concern the development of high accuracy instrumentation, and protocols to maximise the analysis of these samples with the regard to the 7 goals detailed above. This includes the development of life-detection protocols that need to be applied as a pre-screening before the samples are released to laboratories that do not have the highest standards of bio-security. Also, it is unclear yet which organisations will receive the samples, for curation and then for storage. International cooperation and participation within European initiatives are desired.

**FIGURE 2–**Sustainable human presence in space. All the activities included in the cross-sector community are related with all the projects connected on the extraction of materials using ISRU.




On the other hand, it is important to recommend studying, developing and improving the technology to extract any of the mentioned minerals from the regolith on different bodies. Recommendations are needed also to solve problems with those technologies: power supplies, communications, hardware problems.

Technology development is needed in areas related to energy production and storage; resource extraction; material production and metallurgy; manufacturing and construction; regolith excavation, handling and processing; accessing and operating in extreme environments. In figure 2 it is represented the relation between all the material productions like water, oxygen and power and the cross-sector community that may be interested in ISRU.

The European Space Agency is seeking innovative ideas for exploring lunar caves, though an ESA's Open Space Innovation Platform (OSIP), which provides individuals and businesses with the opportunity to collaborate with ESA experts and contribute to the future of space research. It is run through

Discovery & Preparation, which lays the groundwork for ESA's short- to medium- term future activities.

In parallel, the NASA's Space Technology Mission Directorate has established a Lunar Surface Innovation Initiative. It is a technology development portfolio to enable human and robotic exploration on the Moon and future operations on Mars. The activities will be implemented through a combination of unique NASA work and public-private partnerships.

High on the list are technologies for in-situ resource utilization to generate products using local materials, such as technologies for converting lunar ice into drinkable water and other important resources.

Technology development and demonstrations will mature the following capabilities:

- Utilizing the Moon's resources;
- Establishing sustainable power during lunar day/night cycles;
- Building machinery and electronics that work in extreme environments, like super-chilly permanently shadowed craters;
- Mitigating lunar dust;
- Carrying out surface excavation, manufacturing and construction duties;
- Extreme access which includes navigating and exploring the surface/ subsurface

An urgent need exists for high fidelity, quality assured analogies and simulants for technology development and testing. (ESA outcome Workshop ISRU, 2018).

Last, but no least, legal framework on the outer space is still not defined and a lot of discussion and work to define all the points necessary for mining on the Moon, asteroids or Mars. In short, companies and governments are working to develop technologies that allow the extraction of space resources under conditions other than Earth. While there is some legal uncertainty around the ground, consensus appears to be growing among nations affecting the area that the extraction of trade resources is compatible with international law. International law provides a framework for resource development in outer space, and existing treaties and proposed regulations and laws borrow heavily from the principles of international law. Still, outer space is not the sea, and an asteroid is not an island or a distant land. Over time, the law of space will evolve in its own direction.

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