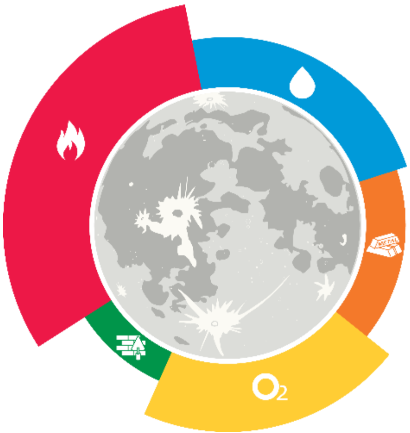
TOWARDS THE USE OF LUNAR RESOURCES

European Space Agency, European Space Research and Technology Centre, Noordwijk, The Netherlands

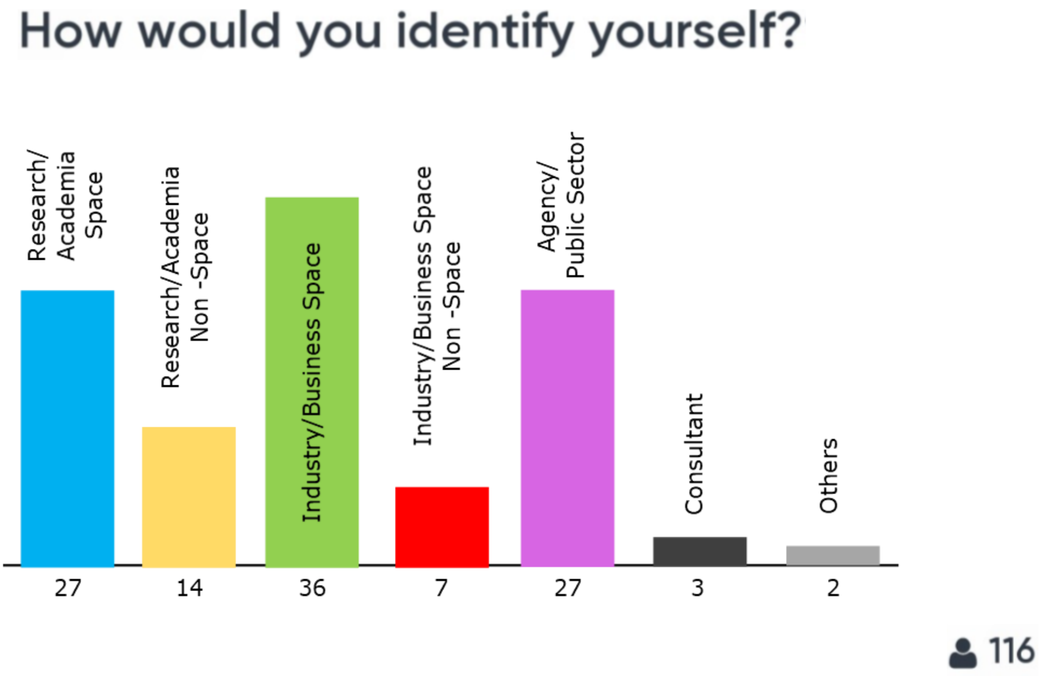
July 3rd – 5th 2018



Summary

"It's not about doing ISRU, it's about achieving the benefits of ISRU for a reasonable cost, mass and risk."

Between the 3rd and 5th of July 2018 more than 250 people came together at ESA's European Space Research and Technology Centre in the Netherlands, to explore the opportunities presented by the use of lunar resources. Participants were present from industry and academia, from space and terrestrial sectors and from agencies and public sector organisations. The three-day workshop included around 100 presentations and discussions. Areas discussed included rationales, science, technology, legal aspects and economics.



The major findings of the meeting are summarised below:

- The primary end user of space resources in the near to mid-term will be space agencies, although it is possible that private sector users may also emerge during this period. The primary product of interest in these initial stages of resource utilisation will be propellant produced at the lunar surface. Applications of locally produced materials may come later. Life support may benefit from local resources but will not be a driver.
- The resource with the highest potential utility is polar water. Prospecting missions are required to improve knowledge of polar water resources and are a high priority. For other locations knowledge is sufficient to allow the initiation of technology demonstration but significant unknowns remain and prospecting and feedstock characterisation should be an element of missions to any unexplored locations.
- Fundamental research into lunar materials and the underlying science of resource utilisation is needed in addition to technology development. In addition fundamental scientific research at the Moon 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.
- 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.
- An urgent need exists for high fidelity, quality assured analogies and simulants for technology development and testing.

- Ongoing support and engagement is required by all stakeholders in the ongoing international discussions on the legality and governance of space resources.
- While a long term economic case for lunar and space resources may exist, in the near to mid-term the economic rationales are primarily linked to the potential for space resources to be a driver of innovation and the development of new intellectual property with potential space and terrestrial applications in areas including resources and material production industries.
- Missions are needed which prospect the lunar poles in-situ, demonstrate the feasibility of resource production on the Moon, characterise new lunar materials and establish enabling capabilities and infrastructure on the Moon regarding power supply, communications and navigation.
- International and public-private partnerships and coordination are fundamentally important if this new sector is to emerge.
- A diverse and dynamic space resources community now exists in Europe. There is an opportunity to leverage present activities and momentum to advance this sector. This requires that ESA provides strategic leadership, facilitates the growth and development of this community and provides flight opportunities to the Moon.

Content

Architectures and Use Cases

"ISRU does not exist on its own, it needs to provide a service"

The introduction of In Situ Resource Utilisation (ISRU) into exploration scenarios should be based on the benefits it introduces. Potential benefits include:

- Reducing the cost of lunar surface missions through local production of propellant for reusable landers and ascenders.
- Enabling a reduction in cost for satellite transportation to high Earth orbits (e.g. Geosynchronous Earth Orbit) from LEO through propellant delivery to Earth orbit from the Moon (as studied by United Launch Alliance) .
- Fuelling of spacecraft in lunar vicinity or LEO in advance of missions to Mars and beyond.

The primary product of importance for propellant production is oxygen. This can be extracted from polar water ice, which can also be a source of hydrogen. Alternatively oxygen can be extracted directly from minerals in the lunar regolith. Various technologies have been identified that could achieve this. Valuable and enabling infrastructure elements would be fuel depots at both the lunar surface and in cis-lunar space.

Metals and materials production is expected later as infrastructures on the lunar surface are required to support increased human and robotic surface activity. Life support may also benefit from ISRU but the small quantities of consumables required and improvements in closed loop life support technologies mean that life support needs will not be drivers.

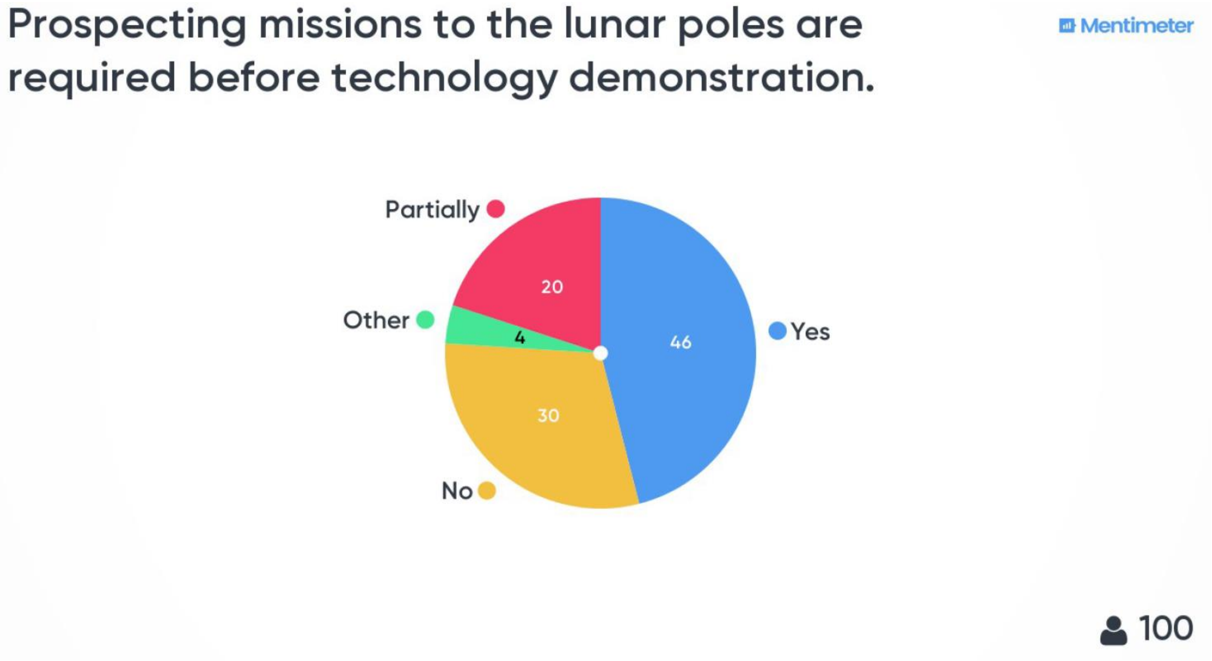
The primary users of lunar resources for the foreseeable future are expected to be space agencies and government programmes. Private sector users are likely to emerge but in order for this to happen public sector actors must invest in the early stages of prospecting, technology development and infrastructure development. If this occurs then private sector users and investors are likely to emerge. At the present time the risks and uncertainties associated with space resources are unlikely to be consistent with private sector investment models.


In one word: why are YOU interested in lunar resources?

Prospecting

" We have tons of remote data, we need a new prospecting approach to calibrate and add value to the existing datasets "

Prospecting is an essential first step for the utilisation of potential resources and an essential step to be carried out in advance of investment by the private sector. Prospecting missions to the polar regions are a high priority as polar water was identified as the resource of highest potential interest, but for which many uncertainties remain. Current data from missions in lunar orbit and the L-CROSS impactor do not provide sufficient information on the water abundance and distribution. Surface measurements are required to understand the nature of polar water to a sufficient degree to allow its utility to be determined and de-risk technology demonstration activities at the poles.



Prospecting missions to the lunar poles are required before technology demonstration.

Prospecting of other areas should still be envisaged as significant unknowns remain. In particular, information on pyroclastic deposits is incomplete and their high resource potential as a feedstock, due to their expected volatile and metal oxide content, is not fully understood. Properties of regolith outside of Apollo landing regions are also poorly constrained, particularly in polar regions.

In the polar regions the most complete prospecting approach would be through missions including mobility to provide measurements across a region and in different environments. Rovers and hoppers provide means to achieve mobility, but the challenging thermal environment at the poles might complicate their design and limit their operational lifetime. Missions of this type can be complemented by simple, low cost surface measurements in diverse locations using penetrators and impactors. Static landers can also support prospecting, noting the limitations and risks for interpretation of data imposed by fixed landing sites and a lack of mobility. In such cases comprehensive instrumentation is required to maximise the information returned from single sites and provide the maximum possible context.

Any technology demonstration missions should include instrumentation for the characterisation of feedstocks.

Basic Fundamental and Applied Research

“A distinction should be made between minerals as a resource and minerals as reserve of lunar history”.

Knowledge of the resources at the lunar surface is currently limited and requires fundamental research to improve this knowledge. This is true across the lunar surface but is particularly true in the polar regions. Through supporting fundamental science on the Moon improved understanding of potential resources will be established. This will include an understanding of the resources we are aware of now as well as the identification of potential resources that we are not aware of yet.

Fundamental research is also required in areas related to the chemistry and physics underlying many of the technologies required for resource extraction. The complexity of the chemical engineering associated with resource extraction and its deviation from what has been learned on Earth must be explored. The end to end process of working with granular material with unique properties in the lunar electrostatic and low gravity environment presents multiple unknowns which must be addressed through a process of scientific applied research.

Technology

"How can we connect technologies which are not usually connected together?"

ISRU will require the development of new technologies and the extension of existing technologies applied in terrestrial resource industry and other sectors. It is important to note that the present uncertainties and diversity of technology options available mean that it is not possible to conclude at the present time which technologies are the most likely to be the most successful if applied. There is therefore a need to enable the development of multiple technology options and to encourage new innovations, such that the most favourable technologies are able to emerge as the sector matures.

An important aspect of the development of technology for ISRU will be the creation of new Intellectual Property (IP) with potential applications for space and Earth. The role of ISRU as a driver of innovation is expected to be the primary motivation for private investment and public private partnership in the near to medium term.

Findings in the specific technology areas are presented in the following sections.

1) Polar volatiles

“We need a sample from the polar regions"

Polar volatiles, in particular water ice, were highlighted as the highest priority as potential resources however the primary objectives in this case are to prospect and understand their formation, abundance and distribution. Other elements of interest may also be present in polar cold traps (e.g. nitrogen in ammonia, hydrogen sulphide, cadmium, mercury and gold) although these elements are more likely to be considered as contaminants than resources. Technology priorities are driven by the needs of prospecting missions. The instrumentation technologies of primary interest for surface prospecting include:

- Mass spectrometers to actively measure evolved gases and isotopic compositions
- Neutron spectrometers to evaluate bulk hydrogen abundance
- Ground penetrating radars, which could also benefit from being operated from orbit.
- Near infrared spectrometers for analysing samples and surface materials for water ice
- Seismometers at a later stage to evaluate specific ice deposits.

Major gaps exist in knowledge of abundance, lateral and depth distribution and composition of volatile deposits which can be addressed with these instruments.

Technology gaps exist related to enabling access and operation of these instruments in relevant locations. Key areas are power availability and low-temperature components to enable survivability and operations in dark and cold regions and the mobility needed within these regions to map the distribution in different locations and environments.

Approaches to the extraction and purification of water ice need to be addressed, a major contaminant being sulphur. Other areas of importance for future work will include the storage and transportation of oxygen and hydrogen for propellant. Studies into this and other aspects of the application of the knowledge gained to future polar ISRU systems, and the identification of major technology issues for these systems also needs to be addressed but as a lower priority.

One area that was highlighted was the need to develop the systems that will use and distribute propellant.

Activities on the surface of the Moon should include prospecting missions, which should include elements of technology demonstration at small scale, with larger scale technology demonstration being initiated once the prospecting phase is well underway. Some technologies in this area are applicable to different applications (e.g. cryocooling) and should be considered.

Surface missions to be considered include penetrators and impactors to provide point measurements at diverse sites at low cost, mobility on scales of km to map specific deposits and observe local distributions. Missions to diverse locations are needed. Access to cold traps and survivability are key capabilities.

2) Oxygen and water production from regolith

"Good research is going on with respect to lunar volatiles; but for refuelling I'd go for the oxygen in the regolith."

Technologies for extracting oxygen from lunar regolith have been investigated at different levels for several decades and in particular in the context of the former NASA Constellation Programme. Technology demonstrators have been prepared in the past which used hydrogen or methane to reduce regolith simulants and Apollo samples. Experimental campaigns were carried out in analogue field campaigns in Hawaii. Some research was performed at lower Technology Readiness Level (TRL) with molten electrolysis or pyrolysis of lunar regolith simulant using concentrated sunlight.

At the workshop, participants identified six potential technologies that are of interest for producing oxygen and/or water from lunar regolith:

- Hydrogen reduction
- Carbothermal reduction
- (Metalysis-)FFC(-Cambridge) process
- Molten electrolysis
- Ionic liquids electrolysis
- Vacuum pyrolysis

Each of these technologies has strengths and weaknesses for space applications and associated technology and knowledge gaps. In all cases technology development activities are required to establish the viability and implications for integration into lunar exploration scenarios.

For technologies using reducing agents or salts, recycling of these materials has to be proven to demonstrate the extent of dependence on resupply. For all technologies the lifetimes of components need to be optimised. Materials used, the complexity of the processes and the challenges of adaptation to a space environment are all major aspects to be addressed. The different processes need to be robust to various regolith compositions and filtering or cleaning steps need to be insured to obtain pure water/oxygen as an end-product. Heat and energy consumptions should be considered at a later stage of the technology development for each of these identified processes.

The drivers for technology selection are likely to be energy needs, mass, consumables needed, reliability, oxygen extraction yield and purification steps required for the outputs of the processes.

3) Materials and construction technologies

"We should go back to the stone age on the Moon and adapt our way of thinking to the harsh space environment."

Materials and construction technologies could be applied in successive phases of human exploration missions. Robotic missions could be used to prepare the ground for astronauts landing on the Moon. Preparations could include landing-pads, terrain levelling, and construction elements for shelters to protect equipment and crew from radiation, dust, micrometeoroids and temperature variations. The complexity of such robotic missions was however noted as being beyond the scope of what is currently conceivable and so applications and operations in this regard are considered a long-term possibility requiring significant investment in particular in operational capabilities, robotics and automation as well as the core technologies of materials production.

Solar cells and energy storage facilities could also be considered as part of future energy production systems to sustain robotic manufacturing operations. Although raw regolith can be utilised in some applications, the extraction of pure metals from the lunar regolith could eventually be contemplated to support construction activities or for producing machinery compounds.

The needs for sustaining human presence on the lunar surface were quite clear to the community but consensus does not yet exist for the order in which the different steps should be carried out. One option could be to first use robots to prepare infrastructure and associated energy systems. A focus for technology developments should be on versatile components and parts which offer multiple uses (e.g. electrical engines, vacuum components). Taking advantages of the natural lunar environment features such as lava tubes could bring a benefit for habitat construction but also extra technical challenges.

After the arrival of a crew, additional tasks would have to be taken into account. A structure providing sufficient level of air tightness (“affordable leak”) would have to be built, together with life support systems. Storage solutions would have to be found for consumables (water, oxygen, nitrogen) extracted from the regolith or brought from Earth. Food production and living area items which bring comfort to the crew should also be planned as part of long duration missions.

Construction technologies on the lunar surface are different from terrestrial ones. Several technologies were identified by the community:

- 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.

Gaps and challenges were also brought up:

- Proofs that the technologies would work when exposed to abrasive, electrostatically charged dust, in low gravity and under vacuum are still missing.
- Habitats with windows to have an open view to the outside environment would bring up new design challenges regarding radiation protection and thermal control.
- The poor thermal conductivity of regolith could be critical for thermal management of a habitat
- The state of the soil (density, compaction) could affect the excavating capability and habitat construction operations.
- There is a lack of knowledge about available materials in polar and highlands regions.
- Qualification of processes, validation of performance in lunar environment is to be determined.

4) Regolith handling and processing

"We should not repeat the same mistakes we did on Earth, we should learn from the mining industry"

From the prospecting to the storage of the extracted oxygen, the lunar regolith has to be handled through a series of steps. Understanding these steps is needed to close the loop and have in mind the big picture and end-to-end processing of the regolith.

For a community involving people from both the mining industry and the space sector, it was recognised that having a common language and an agreed definition was needed. The following were proposed:

- Prospecting: the task to find areas of ore/feedstock in order to optimise a particular process
- Mapping: the task to accurately define the geographical/depth location of the ore/feedstock
- Sensing: in-depth sensors, spectrometers, and sampling/drilling equipment to confirm presence of the ore/feedstock
- Extraction: the task to take away the ore/feedstock from the rest of the material in the mining field
- Separation: which may require stripping surface material, drilling, blasting, excavating, sieving, and transportation of the ore/feedstock from the mining field to the processing facility
- Beneficiation: the task of improving the value of the ore/feedstock by removing from it undesirable elements (e.g. gangue materials) or properties (e.g. uneven size)
- Sorting: this process sorts the ore/feedstock from tailings based on the sensing of the chemical/optical characteristics
- Concentration: this process separates the tailings by the physical characteristics of the ore
- Transformation: this process is the extraction of the desired product from the concentrated ore/feedstock
- Waste: Amounts of gangue and tailings which otherwise would clog the processing plant.

Identification, excavation and processing techniques are different according to the targeted feedstock:

- Polar volatiles can be acquired by sublimation, heating the regolith. A cold collector would then condense or solidify the volatiles.
- Rocks for the construction of shelters can be found on the surface.
- For regolith, depending on the feedstock needed, the complexity of excavation and beneficiation processes can vary significantly. Extraction of the first ~10 cm of regolith presents obstacles mostly related to the unknown clumping and flow properties of the regolith. Extraction of deeper regolith presents unknown obstacles due to the unknown hardness of the material under compaction (especially when encountering icy regolith).

The actual technology to perform the extraction of the identified feedstock cannot yet be identified and the applicability of terrestrial technologies needs further investigation. Most terrestrial mining operations deal with materials which are rich in clay and with relatively high water content, while lunar regolith is very dry and a composition very different from clay. Properties and effects of regolith when handled in mining processes on the Moon are not known in sufficient detail to establish whether known techniques can be used effectively. In particular the following gaps in knowledge need to be resolved:

- Electrostatic properties of fines
- Mechanical properties of all types of regolith
- Tendency to attrition
- Scale of operations

These gaps could be filled by carrying out in-situ experiments on the Moon. Although large scale ISRU appears very far in the future, the value of ISRU in space exploration could be demonstrated effectively in a relatively small mission of high scientific return, only possible with ISRU. Such mission could target the production of rocket fuel/oxidiser from polar volatiles, to propel a rocket for returning samples to Earth.

5) Energy

"We have unlimited energy on Earth, we can go quite crazy, we waste a lot. On the Moon, we need to think differently."

Energy requirements for processing the lunar regolith were discussed by the community. Although the energy demand is unknown, it was agreed that the survival of a lunar night and in permanently shadowed regions (PSRs) should be the main goals, thus driving the choice of technology. These technologies were identified as suitable for a lunar application:

- Stirling engine + radio-isotope systems
- Regenerative fuel cells
- Next generation batteries
- Nuclear fission

The development for ISRU processes of these technologies is however disparate and can be difficult: for instance in the EU, nuclear fission is facing the general public distaste.

Lunar regolith, raw and processed, could play a role in energy storage as heat reservoir. The discussions highlighted the next points:

- Sintered regolith as thermal storage displays an improved thermal conductivity
- Existing synergy with the construction ISRU aspect – blocks can also be a heat storage element.
- There is a potential use of heat from oxygen extraction processes and molten salts as storage to support lunar night operations.
- A dual use system is hence envisioned, for both oxygen extraction and as a thermal energy reservoir.

The lack of information regarding the material and thermal properties of processed regolith prevents however the current assessment of its potential role and impact for energy saving in the overall ISRU scheme.

The community highlighted also several gaps remaining in the existing energy systems and that would need to be addressed:

- The material efficiency and temperature ranges where the thermoelectric materials can operate within remain constrained.
- Understanding the quantity and quality of the water deposits is crucial in order to use the supply of water for fuel cells or for cooling ISRU systems.

- The viability of mirrors for application such as solar sintering has to be further studied.
- Degradation and maintenance of the systems, for both human operators and robotic operators, are too little considered for ISRU systems.

Finally, new potential sources of energy were considered. Harvesting the Thorium, the lunar plasma environment or the radiations from the shielding materials could be interesting leads that would need to be further investigated before taking part in the energy plan of an ISRU mission.

What needs to be done on the Moon?

"We know well-enough the soil for ISRU demonstrations and for local prospecting."

After prospecting missions, technology demonstration missions are required. The objectives of technology demonstration can be to raise the technology readiness of key technologies, to test and rate off technology concepts and to demonstrate the end-to-end production of products from lunar materials.

In order to prepare these missions knowledge gaps and technologies that have to be tested in the actual lunar environment must be identified. During the workshop the following features of the lunar environment were identified as design drivers of the oxygen/water extraction technology that required in situ testing:

- Reduced gravity. The low gravity (1.6 m/s^2) could affect the design and the scalability of fluidised beds and other processing devices. Parabolic flights might not reproduce this gravity for sufficient timescales for testing.
- High vacuum. The low pressure, about 10^{-10} mbar, is hard to recreate in an artificial environment with analogue materials (e.g. "Dirty" vacuum chambers in France and Korea).
- Fine particles. The process applicability in an abrasive, electrostatically charged dust environment cannot be easily demonstrated on Earth.
- Cold temperatures. Survivability in harsh conditions would have to be validated on-site, especially if the cold traps are targeted.

ESA mission plans for ISRU technology demonstration were identified as offering an important opportunity to raise the TRLs and test scalable technologies. From the payload perspective, some scientific instrumentations should be advanced to characterise the feedstocks and perform prospecting activities. Camera systems are required to support operations and to engage the public. Opportunities should be made available wherever possible for scientific investigations.

Analogues and simulants

"The quantity of Apollo samples used for ISRU demonstration was too small to be relevant."

A major need was identified for agencies to assure access to sufficient quantities of lunar regolith simulants of assured quality.

At present access to lunar materials from Apollo is possible for ISRU testing but only under rare conditions and at scales of a few grams. For most research and technology testing activities large quantities of lunar analogue materials are needed. Analogues and simulants are widely used at present to perform experiments with a granular media mimicking the chemical and physical properties of the lunar regolith. Unfortunately, the choice of a simulant is too often driven by its availability and not by its intrinsic features. Quality can also vary according to the mode of production and supplier, thus making comparisons between research studies and technology demonstrations difficult. In addition, some research/engineering centres develop their own simulants, usually not available to others.

Simulant standardisation, quality assurance and availability are essential if the field is to advance. It is considered that agencies are the appropriate organisations to lead in this area.

Legality and governance

"*Mankind will ask, 'are you allowed to do stuff on the Moon?'.*"

There is an ongoing discussion on the legal and governance aspects of lunar resources at international level. Currently, laws for ISRU on the Moon fall within the Outer Space Treaty (OST). The main articles which rule the use of lunar resources are the following:

- Article I: "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 [...], and there shall be free access to all areas of celestial bodies"
- Article II: "Outer space, including the Moon and other celestial bodies, is not subject to national appropriation by claim of sovereignty, by means of use or occupation, or by any other means.
- Article IX: "[...] States Parties to the Treaty shall pursue studies of outer space, including the Moon and other celestial bodies, and conduct exploration of them so as to avoid their harmful contamination [...]"

The Moon Agreement (MA) follows the same direction and reaffirms many of the provisions of the OST.

The community highlighted gaps in the international framework regarding the use of the extracted lunar resources. The gaps could then be filled by a state legislation and be different from a country to another. Stakeholders need to work on blocks for the development of an international framework on space resource activities, "enabling an environment activities that takes into account all interests and benefits of all countries and humankind".

It is important that potential stakeholders in space resources are engaged in the ongoing discussion about legal and governance aspects.

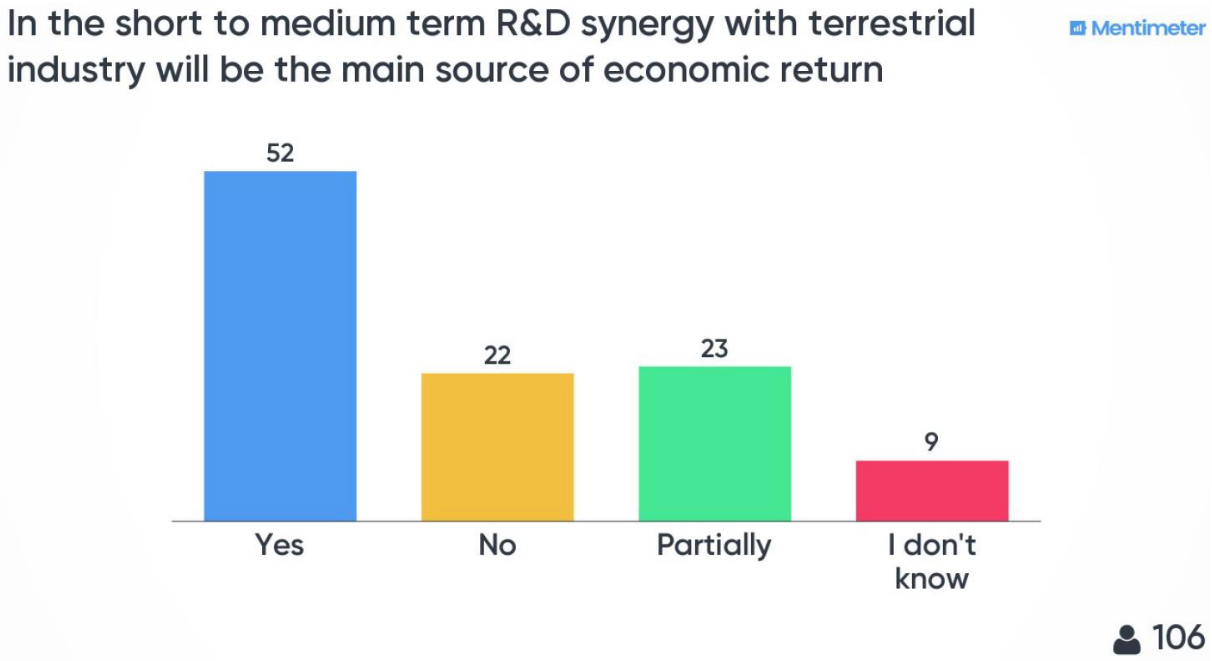
Economics

"ISRU is not about science and tech - It is also about creating a completely new space economy"

The primary economic rationales in the near to mid-term are expected to be linked to technology development which creates new IP and can act as a showcase for terrestrial industry. Most of the community agreed that in the short term, there is no viable self-standing business case from lunar resources. "Spin along" and "spin out" activities with terrestrial industries could exist and provide economic benefits to terrestrial industry and spin in capabilities into the space sector. In some cases, the technology could serve another purpose in another space activity (e.g. electronics working at cryogenic-temperatures for satellites).

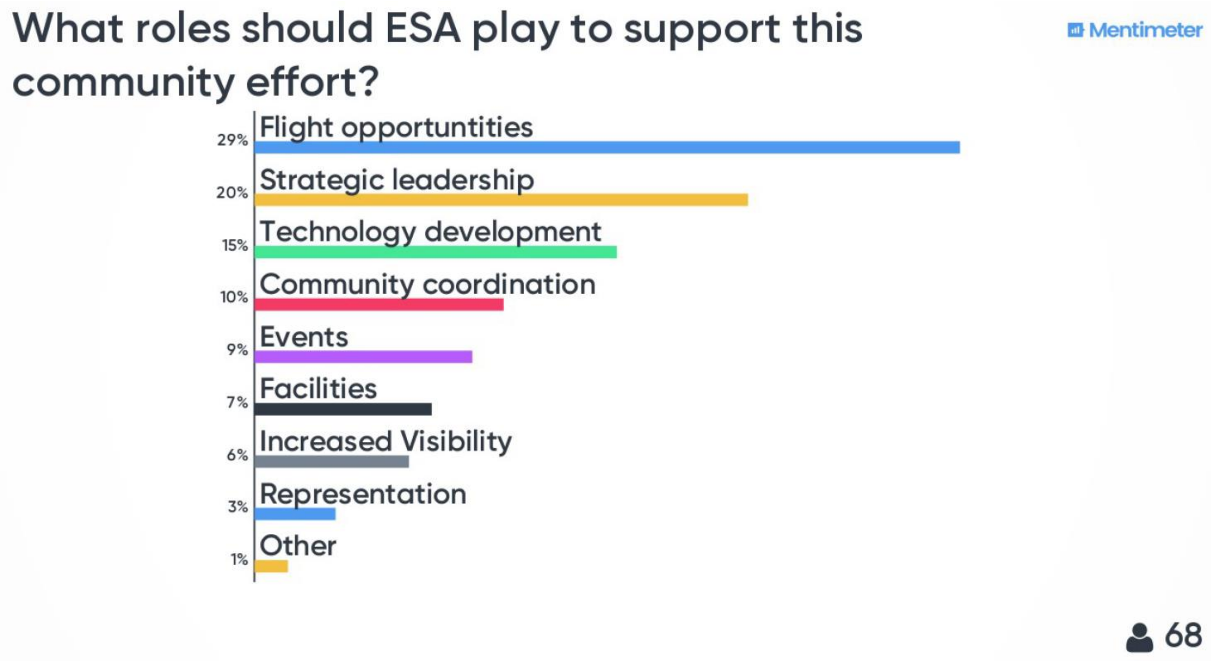
Eventually propellant production and supply could enable self-standing business cases. With a fuel depot in cis-lunar orbit, satellites in LEO or GEO could be fuelled with propellant from the lunar surface. Along this journey, international and commercial partnerships should be prepared, which assure mutual benefits. The realisation of these longer-term business models is contingent upon nearer term public sector investments and market creation. In addition, there is a near term need to identify and address limiting factors for agency engagement with SMEs and non-space stakeholders (e.g. decision making time, procurement approaches, IP issues).

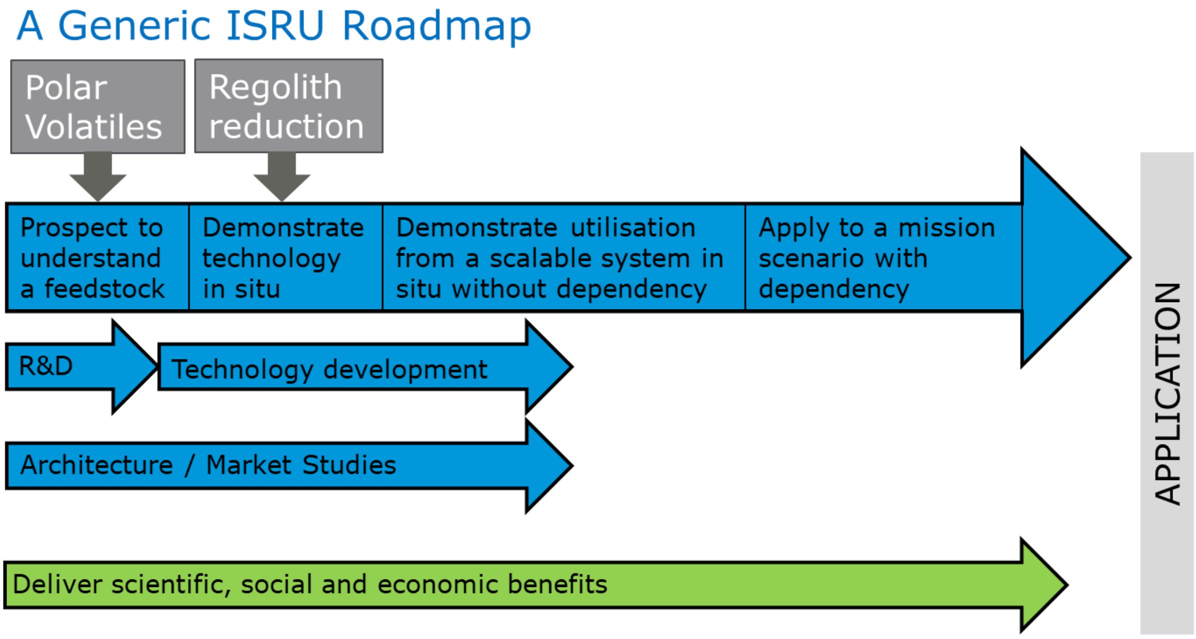
Propellant in cis-lunar space could act as an enabler and trigger a momentum towards the use of lunar resources. In the long term, the lunar surface could have its own market with companies trading fuel, metals and data. The ISRU technology and the experience developed for the lunar surface could be reused on Mars or on asteroids.



Role of ESA

At the end of the workshop, the role of ESA in fostering ISRU activities was discussed. The expectations of the community were that ESA should create flight opportunities and provide strategic leadership; providing a long-term vision to the community.


What roles should ESA play to support this community effort?


A Generic ISRU Roadmap

Polar Volatiles

Regolith reduction

Prospect to understand a feedstock

Demonstrate technology in situ

Demonstrate utilisation from a scalable system in situ without dependency

Apply to a mission scenario with dependency

R&D

Technology development

Architecture / Market Studies

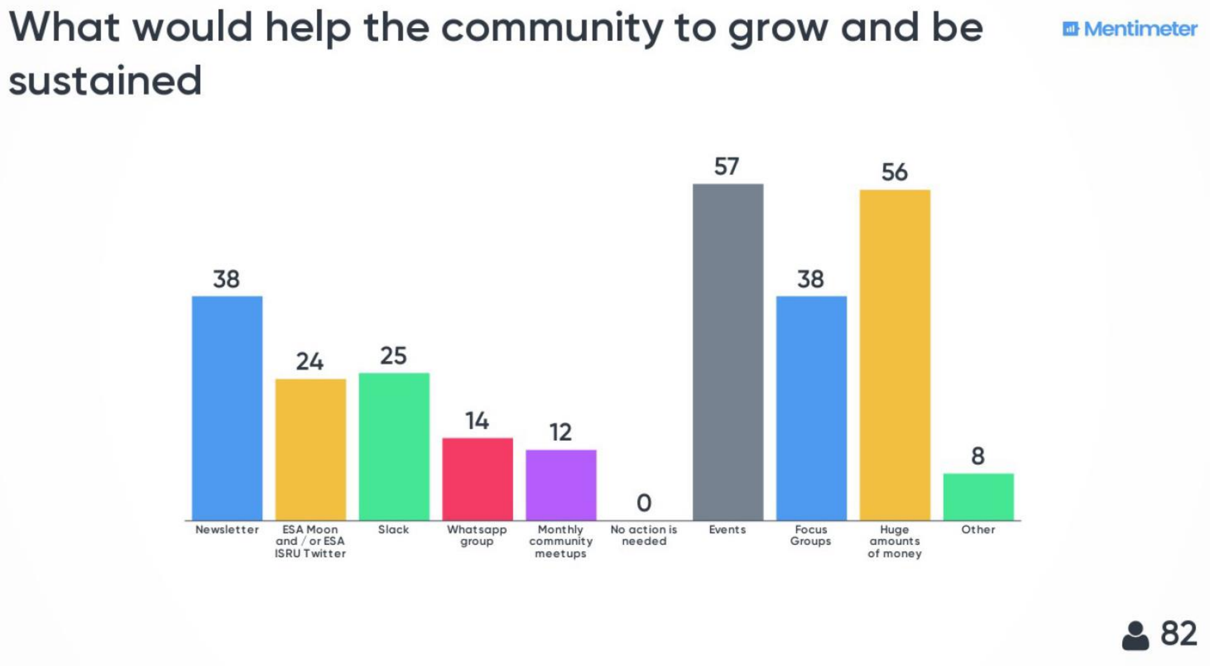
Deliver scientific, social and economic benefits

APPLICATION

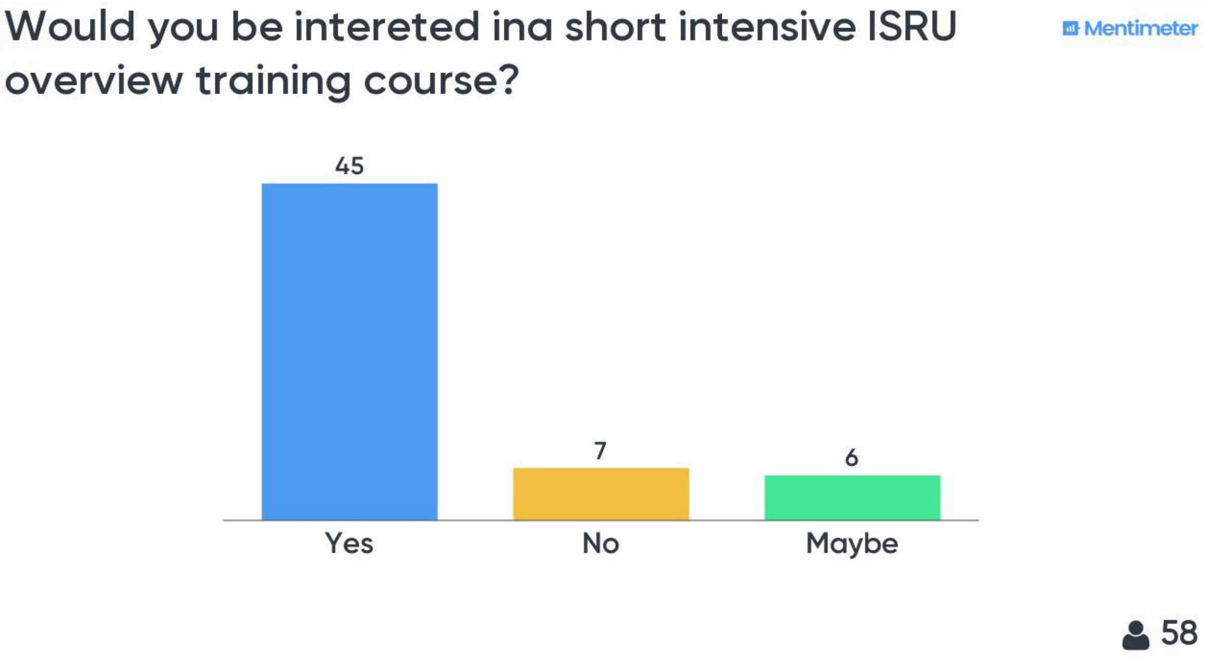
What next ?

The community agreed that the momentum created by the workshop should be built on with some urgency. ISRU related events and funding opportunities were identified as the mandatory elements to keep the community together and attract more stakeholders.

More information can be found on the ESA webpage (http://exploration.esa.int/moon/) and a slack channel is also already in place: https://isru-moon.slack.com.



A significant fraction of the community also expressed interest in participating in a space resources training course in order to have an overview and basic knowledge of the different ISRU aspects, processes and technologies.



Authors

This document was prepared following the "ISRU Workshop: TOWARDS THE USE OF LUNAR RESOURCES" by the organising committee and leads of the splinter sessions. They are listed below in alphabetical order:

Mahesh Anand, Open University, UK
Yael Asher, ESA, Netherlands
Robert Buchwald, Airbus Defence and Space, Germany
Ian Carnelli, ESA, France
James Carpenter, ESA The Netherlands
Melchiorre Conti, Metalysis, UK
Aidan Cowley, ESA, Germany
Luca Del Monte, ESA, France
Thorsten Denk, PSA, Spain
Annalisa Donati. ESA, France
Richard Fisackerly, ESA, The Netherlands
Jessica Flahaut, CNRS, France
Moritz Fontaine, ESA, France
Andres Galvez, ESA, France
Kathryn Hadler, Imperial College London, UK
Katherine Joy, University of Manchester, UK
Angeliki Kapoglou, University College London, UK
Julien Lamamy, iSpace, Luxembourg
Maucus Landgraf, ESA, The Netherlands
Veronica La Regina, ESA, The Netherlands
Michelle Lavagna, Politechnico di Milano, Italy
Robert Linder, ESA, The Netherlands
Advenit Makaya, ESA, The Netherlands
Piero Messina, ESA, France
Alexandre Meurisse, ESA, The Netherlands
Andrew Morse, Open University, UK
Pierre Rebeyre, ESA, The Netherlands
Philipp Reiss, Technical University of Munich, Germany
Elliot Sefton-Nash, ESA, The Netherlands
Karol Seweryn, Polish Accademy of Science, Poland
Matthias Sperl, DLR, Germany
Romain Tartese, University of Manchester, UK
Floriano Venditti, OHB, Italy
Gianfranco Visentin, ESA, The Netherlands
Diego Urbina, SAS, Belgium

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