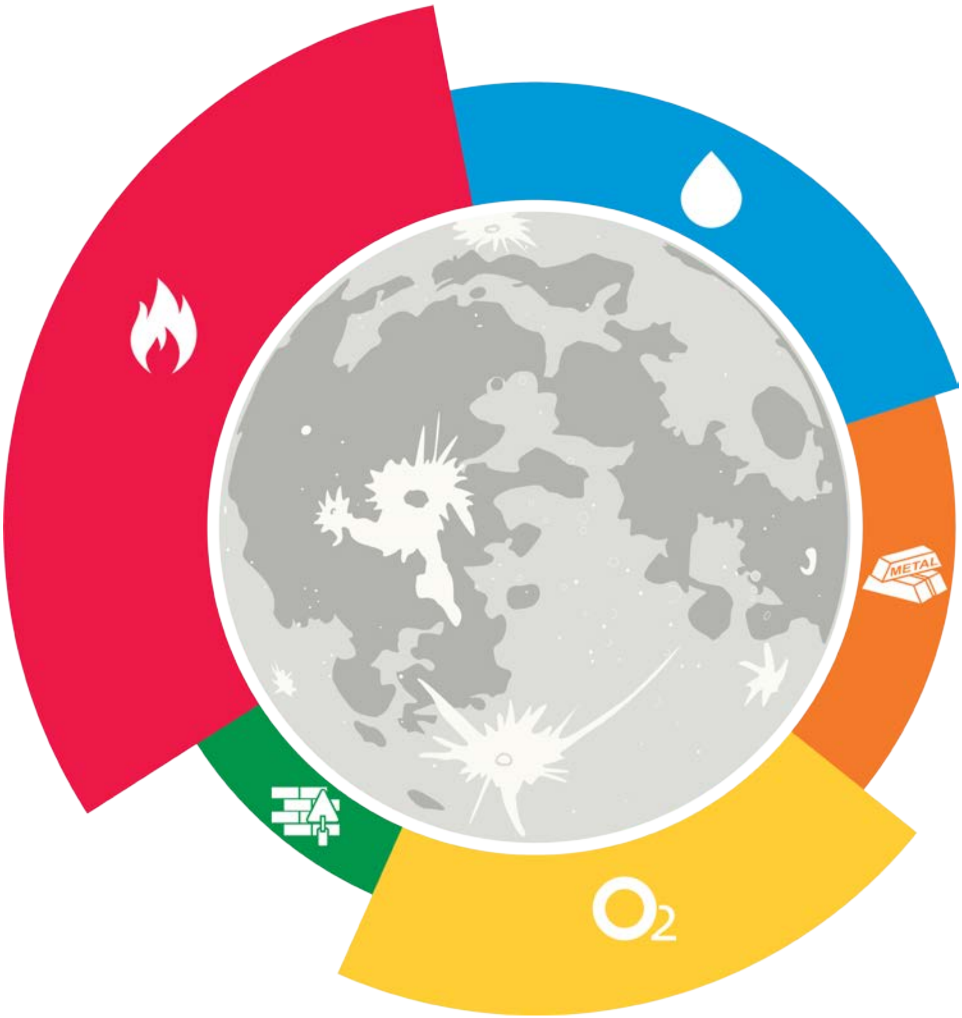
ESA Space Resources Strategy



European Space Agency
Agence spatiale européenne

EXECUTIVE SUMMARY

The resources of space offer a means to enable sustainable exploration of the Moon and Solar System beyond in support of the advancement of ESA's space exploration strategy. The challenge of space resources can also be a means to stimulate innovation on Earth, to find new ways to address global challenges and to generate near to mid-term economic returns for terrestrial industries.

The utilisation of space resources for exploration may be within reach for the first time; made possible by recent advances in our knowledge and understanding of the Moon and asteroids, increased international and private sector engagement in space activities and the emergence of new technologies. Key sectors of interest include mining, metallurgy, materials, energy, robotics and autonomy. The first utilisation of space resources 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.

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

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 utilisation of resources in space, whilst delivering social and economic benefits in the near term here on Earth, in accordance with the international legal framework.

Table of contents:

1 INTRODUCTION

Space resources will be a major topic of activity internationally over the next decade and may become a major motivation for investments in space exploration in the future. Europe has extensive expertise and capabilities to bring to this new field of investigation, from both space and Earth industries. Europe needs to engage now in order to have a role, to influence the way forward and benefit from the endeavour.

We find ourselves at a unique moment in which the resources of space are within reach for the first time. This has been made possible by increased international access to space, advancements in technologies and an increased understanding of the potential resources. A global space exploration scenario is emerging which presents a perspective for the first in situ utilisation of space resources and international activity to access and utilise space resources is growing. This will require a multidisciplinary approach; bringing together space and non-space, science and industry, public and private. The resources of space are vast and their potential enormous. Realising their potential will require innovation and invention, initiative and risk taking, vision and careful planning, but equally a common understanding on the applicable international legal framework. The challenge of space resources can also drive innovation on Earth, challenging technologies and processes used in terrestrial industries towards efficiency, sustainability and optimisation.

A strategy for space resources needs to address some fundamental questions[1]:

How can the resources of space be used to support sustainable space exploration?
What knowledge do we need to gain?
What technologies do we need to develop?
What roles should we play?
What are the benefits and risks for space and for Earth?

This document presents a strategic approach to the space resources opportunity, to enable sustainable human exploration in a way that seeks to optimise the terrestrial benefits, build a community and prepare a way to sustained and cost effective exploration in the future. The strategy reflects the highly interdisciplinary and innovative nature of the domain and the interest that exists internationally, in space and non-space industries, in science and academia and in the public sector. It is certain that the scope and perspective of space resources will advance and change rapidly in the coming years. The strategy exists to establish robust starting conditions for European engagement. It should be reviewed and updated regularly, at no more than three yearly intervals, to ensure its continued relevance.

The decisions we make now will decide Europe’s future in this new domain which, while still very uncertain, offers tremendous potential rewards to those that engage.

[1] The legal, regulatory and policy framework may also be considered as “fundamental”, but it is not ESA to take an active role in these particular aspects, but rather for ESA’s Member States.

2 RATIONALES

Exploration

The costs, complexities and risks of supplying resources from Earth are a limiting factor for space exploration. In-Situ Resource Utilisation (ISRU) offers the potential to locally derive what is needed for living and working in space. The notion of space resource utilisation is already integrated in our space activities through the local production of power from solar radiation. ISRU in exploration is an extension of this enabling approach.

Key products for exploration are propellant, water, oxygen, consumables for life support and materials including metals. Propellants can be manufactured from locally sourced water (e.g. in ice at the lunar poles), hydrogen and oxygen from water and lunar minerals. Building materials can be produced from the dust, soil (regolith) and rocks found on planetary surfaces. Metals and materials can be produced from the metal oxides and silicates found in local rocks.

Economics

A recent study commissioned by the Luxembourg government [RD1] has analysed the potential economic impacts of space resources utilisation through an assessment of the associated future markets and value chains. The various potential products from different destinations are illustrated in Figure 1.

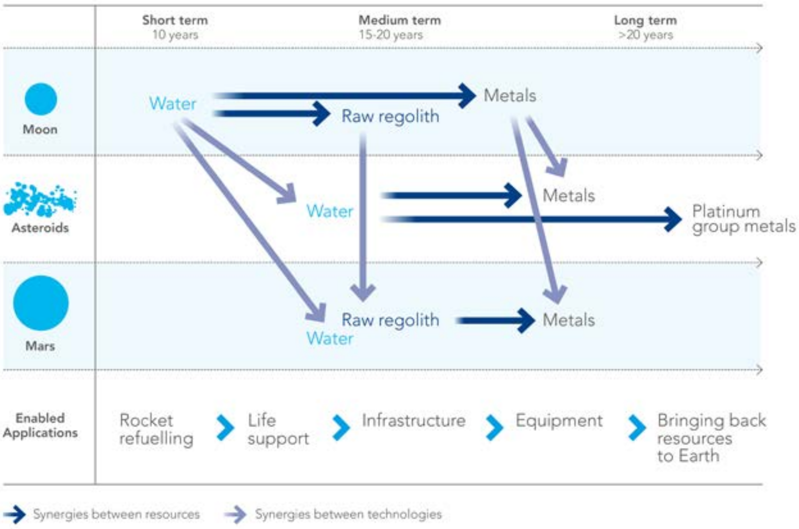


Figure 1 Resources and destinations considered in the socioeconomic assessment of [RD1] (used with permission). Note that the report does not account for oxygen or metal powder as sources of propellant or platinum group metals present on the Moon from asteroid impacts as is the case for deposits on Earth.

The report concludes that market revenues of 73-170B€ 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 54-135B€. 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.

Earth
By searching for and learning to use the resources of space we can create new opportunities for Earth through technology innovation and new approaches to managing the resources of Earth. The mastering of space resource utilisation transcends domains to advance technologies and transfer expertise across sectors. The inspirational quality of the challenge can be a driver of innovation for industry. The challenges and environments of space drive optimised technologies and systems with implications for sustainability and the Sustainable Development Goals[2] and addressing the increasing challenge of resource scarcity[3]. Key sectors where innovation of relevance to Earth is expected include the metallurgy, chemical processing, mining, oil and gas. In the further future the resources of space may even be used on Earth as the cost of access falls and some resources on Earth become increasingly scarce.

3 INTERNATIONAL CONTEXT

The challenges of space resources can only be addressed through a coordinated international effort. Thus the approaches taken by the major international actors in space will be key to advancing space resources and their application. Interest and activity in this area are growing rapidly internationally.

Europe
In Europe, in addition to ESA activities, various national and international initiatives are taking place in diverse areas including technology development, policy and legal aspects, scientific research and commercial activity including a proactive and pioneering approach by Luxembourg[4], who have signed agreements with a number of other European countries regarding cooperation in this area. Other European level activities initiated through the European Commission are being undertaken in particular in regards to technology development, and academic research. Examples include the LUVMI prospecting rover[5] and RegoLight regolith construction[6] project.

USA
In the USA, a renewed emphasis on lunar exploration has reignited interest and activity in the area of lunar resources with both public and private actors investigating. Future investments are expected by NASA, which will build on the extensive activity of the past, performed under previous exploration initiatives. The utilisation of lunar resources is being considered in the context of future human missions to the Moon, for their potential utility in preparing and implementing missions to Mars. US legal instruments have been created to define the rights of US actors who would seek to extract and utilise resources in space.

China
Space resources have featured heavily in communications about the past and future missions of the Chinese Lunar Exploration Programme and provide part of the rationale for those missions. Future Chinese missions are expected to target lunar polar volatiles as potential

---

[2] https://www.un.org/sustainabledevelopment/sustainable-development-goals/
[3] Global trends identified by the World Economic Forum http://reports.weforum.org/global-agenda-survey-2012/trends/scarcity-of-resources/?doing_wp_cron=1547053782.5380969047546386718750
[4] https://spaceresources.public.lu
[5] Lunar Volatiles Mobile Instrumentation (LUVMI) https://www.luvmi.space/
[6] https://regolight.eu/

resources. Reference has also been made to the potential use of lunar resources for future applications on Earth. China's vision of an international lunar research station, to be established initially as a robotic facility for science and research during the late 2020s and early 2030s, may provide an early opportunity for lunar resources to be utilised.

Russia

The future Russian mission Luna-27, which includes ESA's PROSPECT[7] package, targets measurements in the polar region of the Moon, emphasising cold trapped volatiles that may be found there. No specific activities or plans for space resource related activity beyond this mission are known to exist today.

International space exploration plans

The Global Exploration Roadmap (GER) [RD2], prepared by the International Space Exploration Coordination Group (ISECG) describes the current planning for space exploration amongst 15 of the world's space agencies. This roadmap provides an overview of the expected missions that could prospect resources and test technologies and provides a reference timeline for human exploration of the Moon. ISECG provides a forum for international strategic coordination and is the primary instrument for international dialogue in space exploration. This will also be true for space resources, a dialogue which began with discussions on exploring and using lunar polar volatiles[8].

Intergovernmental discussion

The topic of space resources, and their utilisation, exploration and exploitation in particular, has been elevated to the intergovernmental level at the United Nations. Since 2017, the Legal Subcommittee of the UN Committee on the Peaceful Uses of Outer Space (COPUOS) has been discussing, under a specific agenda item, views and opinions on the permissibility and legal framework for resource utilisation and exploitation. Legal and political opinions among the 87 member states of COPUOS (including most ESA Member States, with the Agency taking the role of a permanent observer) diverge, even though there seems to be growing agreement on the benefit of achieving broad international understanding.

Non-governmental initiatives

Multiple international and non-governmental actors are preparing missions to the lunar surface. These include private lunar exploration companies who will begin missions to the lunar surface during 2019. Support for several of these companies is assured through the NASA Commercial Lunar Payload Service (CLPS) programme and has been supported in the past by Lunar CATALYST[9]. Several of these companies, including iSpace, Moon Express and perhaps most notable Blue Origin (owned and financed by billionaire Jeff Bezos), have explicit interest in the resources of the Moon. Private initiatives are also establishing potential commercial applications (e.g. utility of polar ice studied by United Launch Alliance and the Colorado School of Mines Center for Space Resources).

[7] Package for Resource Observation and in Situ Prospecting for Exploration Commercial exploitation and Transportation (PROSPECT) http://exploration.esa.int/moon/59102-about-prospect/
[8] https://lunarvolatiles.nasa.gov/
[9] Lunar Cargo Transportation and Landing by Soft Touchdown (Lunar CATALYST) https://www.nasa.gov/lunarcatalyst

4 STRATEGIC DRIVERS

Destination

In the conceivable future opportunities for space resources utilisation for exploration will be realised using recycled or repurposed equipment in Earth orbit and the resources of the Moon, Mars and asteroids. Of these planetary bodies the Moon offers the nearest term opportunities and should provide a focus for near term activities linked to exploration, where locally sourced resources can be integrated into human mission architectures. Activities linked to recycling in Earth orbit should also be considered but are not described further here.

Lunar surface missions offer the best opportunity to build expertise and capabilities in In situ Resource Utilisation (ISRU) and establish this as a standard part of the way that exploration is performed. ISRU at the Moon prepares for Martian scenarios and utilisation of asteroid derived resources and can create early commercial opportunities. A description of the potential resources of the Moon is provided in [RD5]. The available resources, their likely utility and our knowledge of them drives prioritisation of activities. Activities to prepare ISRU at Mars and asteroids are not foreseen as priority activities before ISRU is established at the Moon. This assumption should be reviewed regularly as global exploration scenario advances.

Application

The applications of space resources drive the prioritisation of selection of technologies, processes and schedules for development. The applications are themselves driven by the exploration plans of the major actors and the timeframes in which different products may be needed. Using the Global Exploration Roadmap as a reference [RD2] human missions to the lunar surface are expected in around 2030 and could be used to demonstrate that lunar resources could be used to enhance missions in advance of full utilisation on later missions in the late 2030s and beyond. Applications of local resources at the Moon could include, in order of the timeliness and likelihood of possible implementation:

- Propellants (e.g. using oxygen from ice or minerals or metal powders from minerals)
- Life support consumables (e.g. oxygen and water as a bi-product of propellant production)
- Metals and materials for in situ manufacturing (e.g. construction materials, Al, Fe, Ti, Si, alloys)
- Products with value on Earth (e.g. platinum group metals from metal rich impact sites)

These applications and their likely proximity drive prioritisation of scientific and technical activities. Oxygen and water have priority as these can be used as propellants, as well as metal powders. Life support consumables are likely to be a secondary product of propellant production as the amounts needed are low and mitigated by high efficiency life support systems. Metal and material use cases require the presence and utilisation of a surface infrastructure. Resource extraction for Earth requires a viable economic case to be established and the key resources of interest to be identified. This is considered a longer term possibility and so not a priority.

5 OBJECTIVES

The objectives of the ESA Space Resources Strategy, focussing 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 advantage of these opportunities should they arise.
- Create benefits in the areas of technology and processes innovation for sustainability in space and on 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.

6 PRIORITIES AND OUTCOMES TO 2030

Based on early assessments of the opportunities for space resources, a set of starting assumptions based on analysis and technical activities (Annex 1) and alignment with the European Space Exploration Strategy the following priority areas and outcomes identified in Table 1 have been identified for the period to 2030, emphasising activities at the Moon while recognising that other destinations (asteroids, Mars) may become relevant for space resources in due course.

Priorities	Outcomes by 2030
Establish the resource potential of volatiles at the poles and regolith and pyroclastic deposits across the lunar surface	Identification and characterisation of at least one non-polar deposit.
	Identification and characterisation of at least one deposit of polar ice.
Mature and demonstrate technologies which are key to the value chain for space resources and have terrestrial benefits	All technologies critical to the production of oxygen, and material bi-products, from lunar regolith or pyroclastic material matured to TRL6 or above including flight demonstration for all technologies that require it.
	New terrestrial technologies and processes derived from space resources activities.
Demonstrate the end to end in situ production of a product from lunar materials on the Moon, with an emphasis on oxygen or water production.	End to end demonstration of the production of water or oxygen at the lunar surface from locally sourced materials.
Establish ISRU as an integrated part of international space exploration architectures and foster demand for locally produced products.	Space resources integration planned for in reference international exploration architecture with early demonstrations defined.

Table 1. Priority areas for space resources activities for ESA and strategic outcomes to be targeted by 2030. These should be achieved through cooperation and coordination with private sector and international partners.

7 INNOVATION

Space resources activities should prepare for the future in space through driving innovation, creating benefits for space and Earth. To ensure that this is achieved a Mission Orientated Innovation and Industrial Strategy framework [RD3], developed in the context of EC programmes, is applied. Such a framework addresses a major Challenge through the realisation of a bold and inspirational purpose or "mission". This triggers imagination and ambition amongst a diverse community of sectors who then create and implement projects. The approach has been developed to foster innovation and maximise the value generated by public sector driven initiatives. "Missions" must engage the public and make clear that through ambitious, bold action at the European level, solutions will be developed that will have an impact on people's daily lives.
The framework is applied here to address a challenge: **Sustained and sustainable human presence in Space.**
This is achieved by realising the "purpose" or "mission": **Human presence at the Moon, sustained by local resources, by 2040.** The purpose should provide an inspirational and challenging yet achievable focal point and guide for activities and efforts for the broad community of stakeholders.
A diversity of *sectors*, examples of which are illustrated in Figure 2, are engaged directly or indirectly to embrace the purpose and collaborate to achieve it. A broad community is then

created which collaborates to identify, define and implement projects. The projects undertaken draw on different ideas, technologies, capabilities and backgrounds in a way that encourages innovation and approaches with different levels of risk.

Projects can be financed by a variety of sources, of which ESA may be one. ESA takes a strategic lead, setting a direction of travel and coordinating and facilitating the community, providing resources to support priority projects that lie within the scope of its programme, but integrating these into the broader ecosystem of community activities. Projects can be diverse in nature from technologies and scientific research to governance frameworks, procurement approaches and tax incentives. Example topic areas for scientific and technology related problems are illustrated in Figure 2.

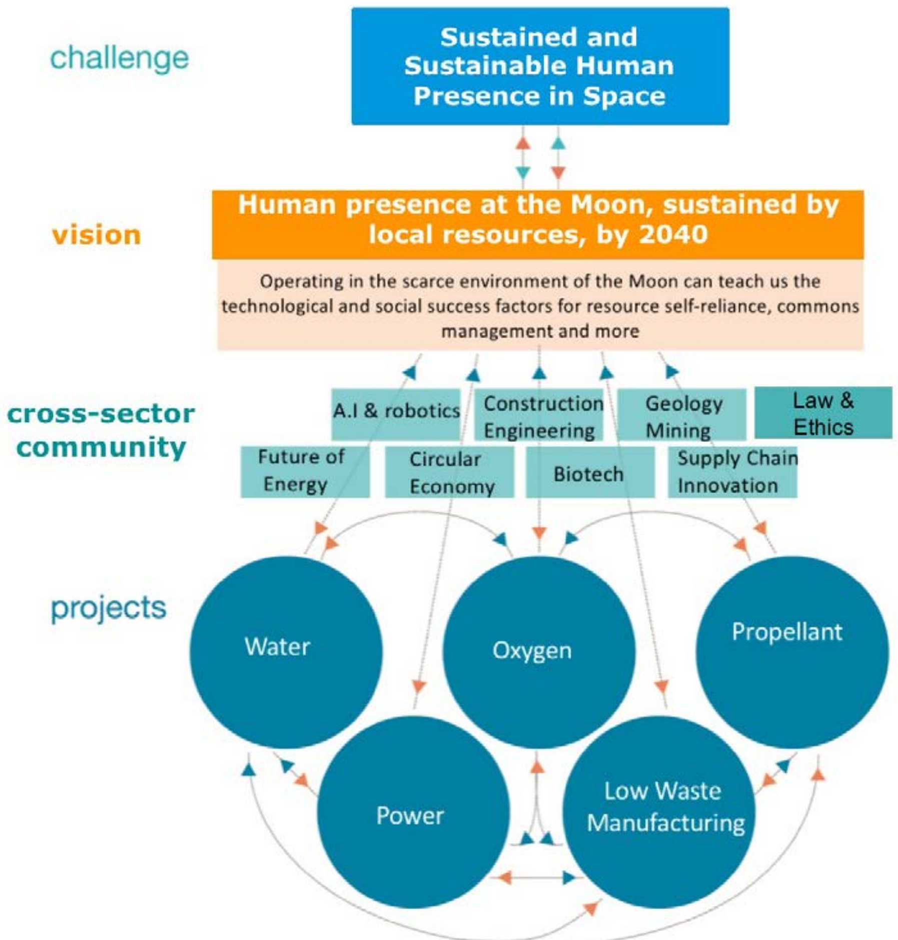


Figure 2: A Mission (purpose)-Oriented Innovation and Industrial Strategy for Space Resources. This framework is adapted from one that is in preparation for future EC programmes following RD3.

8 CROSS-SECTOR COMMUNITY BUILDING AND SUPPORT

Preparing space resource utilisation will only be achieved through the combined efforts and resources of a broad and diverse community of actors. ESA alone cannot and will not prepare this on its own, with its own resources. ESA will play an important and an enabling role as part of this broader community. The community will bring together diverse expertise and capabilities, leveraging expertise and technology from space and non-space actors. It will facilitate cooperation to achieve common goals and encourage competition to drive progress.

It will pool resources from different sources and deliver returns in the future. It will establish a common set of values and a common vision for the future. It will serve the interests of all who engage and deliver value for its members.

ESA's role in this community will evolve over time. Now, at the outset of this movement ESA will provide leadership, gather a core of membership and provide the tools to allow the community to establish and to grow. ESA will show that value can be delivered and show different actors how they can engage and gain value from the engagement. ESA will help the community to establish its vision and values and ensure that these values are consistent with those of the Agency. Most importantly the community looks to ESA to take it to space. ESA will provide access to the Moon and beyond; to explore the resources, to show that they can be used and use them.

To achieve this ESA will need to actively reach out and 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 engagement and integration into the community and to assure effective network building and communications within the community.

9 TECHNOLOGY AND RESEARCH ACTIVITIES ON EARTH

Research and technology development is required on Earth. First activities will focus on establishing a thorough understanding of processes associated with metal oxide and silicate reduction for oxygen production and involved technologies. This should be followed by a systematic process of technology maturation. Key technology areas include:

- Regolith characterisation instrumentation to identify feedstocks and define their grades[10].
- Excavation, hauling and beneficiation to transfer and refine feedstocks prior to chemical processing.
- Electrochemical and thermochemical reduction to produce oxygen and produce metal alloys from lunar materials[11].
- Water and gas purification to remove dust particles, sulphides and other impurities[12].
- Product storage and interfaces for product transfer (including standards) to allow the handover of products to subsequent processing steps and ultimately users.
- At a later stage, technologies for manufacturing objects at various scales with regolith should be developed.

Work will include supporting basic research and development, creating and testing new ideas and then fostering advancement to maturity.

[10] Activities initiated in E3P period 1 through ISRU mission preparation phase and PROSPECT
[11] Activities initiated in E3P period 1 through ISRU terrestrial demonstrator, ISRU mission preparation phase and research partnerships with industry and academia
[12] Activities initiated in E3P period 1 through activity with Air Liquide

One key aspect is to ensure that research facilities required by the community are established and available. This includes dedicated specialist laboratory facilities, appropriate simulants and access to reduced gravity through parabolic flights.
Additional effort is needed to ensure the development of enabling technologies (e.g. for energy generation and storage, robotics and autonomy, dust mitigation).

10 ACTIVITIES IN SPACE: A SPACE RESOURCE UTILISATION PREPARATION CAMPAIGN

Access to the Lunar surface is required. This will be achieved via 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.

Surface activities should address:

- Demonstration of production of oxygen or water in non-polar locations
- Testing of technologies critical to ISRU processes in non-polar locations
- Analysis of potential feedstocks in non-polar locations
- Prospecting for water ice at the lunar poles

Payloads could be considered in the following categories:

- Prospecting and feedstock characterisation payloads consisting of scientific instrumentation to measure important properties of regolith, pyroclastic materials, polar ices or other feedstocks.
- Payloads containing one or more tests of technologies of importance for ISRU.
- End to end demonstration payloads producing oxygen or water from lunar material.

Missions
Two different classifications of missions are envisaged in the future ESA programme; Missions of Opportunity and Directed Missions.

Missions of Opportunity
While PROSPECT is the first example of a Mission of Opportunity, other examples could include:

- An opportunity to provide a complete payload of up to 10kg on a private lunar lander mission to a near side lunar location and to operate that payload for a given period of time, with a given allocation of power and data resources.
- An opportunity to contribute European elements to a payload which is led by an international partner and flown on that partner's mission to a lunar polar landing site. At the surface the payload is operated in line with the international partner's operations plan.

Missions of Opportunity will usually be realised through cooperative agreements between ESA and a partner.

Missions of Opportunity are likely to be characterised by:

- Rapid development and delivery requirements
- Severe resource limitations for power, data, mass and operations
- Increased risk compared with ESA driven mission procurements
- Lower cost to ESA than for Directed Missions
- Limited data return per mission

Directed missions

Directed Missions are missions where ESA has defined a set of mission objectives and derives from these a set of requirements to be implemented on a mission. They are then the basis for the procurement of a mission or flight opportunity which addresses those requirements. Directed Missions may be undertaken independently by ESA or be defined and procured in cooperation with international partners.

Directed Missions for space resources preparation are envisaged as having access to the lunar surface procured from a commercial mission supplier with the express purpose of deploying and operating a specific payload at the lunar surface. ESA defines the mission and science requirements, and leads mission planning and operations working with the mission supplier.

Directed Missions are likely to be characterised by:

- Technology and science driven mission definition, design and operations
- Increased ESA oversight of mission development and procurements within the constraints of the commercial mission capabilities
- Increased cost to ESA compared with Missions of Opportunity
- High scientific quality and high scientific return per mission
- Commercial procurement of mission services (e.g. access, communications operations)

Campaign Phases

Preparation for the utilisation of any given resource in space should follow a sequence of stages of preparation, described in [RD6]. First a resource must be properly understood to assure that a resource exists. Technologies required to excavate and process the resource must be matured and demonstrated to assure confidence in the feasibility of production. Production is then required from a scalable system with the products used by a mission but without dependency. At this point it becomes possible to build dependency on locally generated resources into mission architectures. The role out of this approach is envisaged in three phases through a Space Resource Utilisation Campaign.

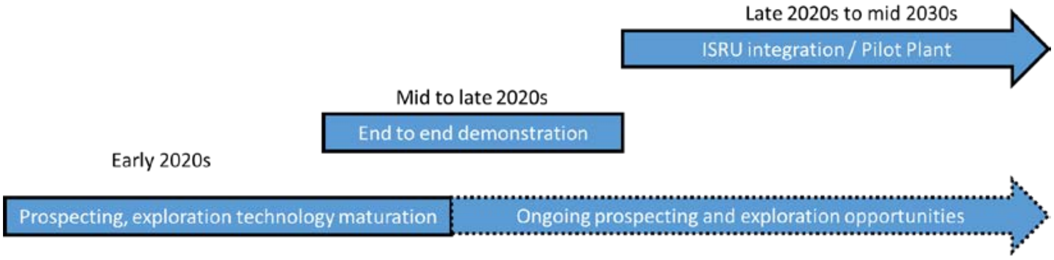


Figure 3 - Phases for the ISRU preparation campaign

Phase 1: prospecting, exploration and technology maturation

Scientific instrumentation will be deployed on Missions of Opportunity[13], and potentially Directed Missions[14] from the mid-2020s, to identify potential resources, to address the present unknowns in their properties as they pertain to utilisation potential and to characterise their properties and establish their grade. Such payloads could include characterisation of volatile content (e.g. mass spectrometers, neutron detectors), elemental composition (e.g. x-ray spectrometers or Laser induced breakdown spectrometers), mineralogical composition (e.g. infrared spectrometers or Raman spectrometers) and mechanical properties (e.g. penetrometry and observation of regolith handling). Mobility is a major benefit. Such instrumentation is also required to accompany technology payloads to provide data on the materials being handled.

Where technology maturation requires access to the lunar environment because suitable environments cannot be identified on Earth, discrete technology demonstrations may be performed. Technologies that are likely to require this are primarily those associated with the handling and processing of regolith in reduced gravity including beneficiation and particle transfer technologies. Other factors that may require testing in situ involve those associated with dust mitigation.

Payloads are presumed to be developed through ESA funding. Alternative funding approaches could be explored on an ad hoc basis where deemed more appropriate (e.g. private sector contributions, funding from national agencies, institutional funding or from other third party sources).

Phase 2: end to end demonstration

An end to end demonstrator payload will demonstrate the production of water or oxygen from lunar regolith source material. The end to end demonstrator should be technologically representative of a scaled production facility where possible but where necessary the scalability may be addressed by other means including ground testing and in situ technology maturation. The approach taken to the end to end process should be one that demonstrates production in the most technically viable way given cost, schedule and risk constraints. Design and development of an end to end demonstrator payload has been initiated during E3P period 1. The end to end demonstration would be followed up in the 2030s by a scaled Pilot Plant, integrated into an exploration mission architecture.

Phase 3: Pilot plant integrating ISRU into an exploration mission architecture

A goal is to prepare a Pilot Plant to be deployed as part of early human mission architectures. The Pilot plant would be used to generate a product that would be used to enhance a human surface mission and thus integrate locally produced resources into a human architecture for the first time. This should mark a transition to allow local resources to be integrated into future missions.

---

[13] Missions of Opportunity are those where an international or commercial partner has presented an opportunity to:

1) Deliver and operate a payload at the Moon,
2) Preferentially access scientific data or returned samples or to participate in scientific planning and operations.

[14] Directed Missions are missions where ESA has defined a set of mission objectives and derives from these a set of requirements to be implemented on a mission.

11 DEMAND STIMULATION

Demand can be stimulated for space derived resources by integrating space resources into future space exploration architectures. An important role of ESA is to stimulate the creation of that demand by working with international partners to integrate space resources into the reference mission architectures of the future and perform whilst increasing confidence in the technical feasibility and benefits of space resource utilisation. This shall be achieved by:

- Studying and deriving architectures for space exploration and space logistics that use local resources
- Working with international and commercial partners to integrate space resources into reference architectures
- Establishing procurement approaches for space resources
- Investing in systems and technologies that can use locally derived resources
- Establishing international interoperability standards to allow the transfer of products between providers and users in space.

An important aspect will be the role of ISECG in aligning the strategies of various agencies. Preparation of a white paper on ISRU by ISECG is planned for 2019.

12 THE BROADER ESA CONTEXT

Advancement of space resources utilisation requires activity across a wide domain of fields beyond those of any single programme in ESA. While this document describes primarily those aspects that are of relevance to the E3P programme activities these should be seen in a broader context of activities across ESA in areas from science and technology to law and governance, ethics, procurement and industrial policy, communications and education. This community of actors within ESA should together be a core part of the broader space resources community providing both leadership[15] and support.

[15] Note that ESA cannot assume leadership in interpreting and further developing the legal and regulatory framework applicable to space resources, as this is beyond the Agency's competences. However, it may offer Member States opportunities for exchange and coordination as is already done, for example, in the frame of the International Relations Committee (IRC).

13 REFERENCE DOCUMENTS

RD1. Opportunities for space utilisation: future markets and value chains, study, (2018), summary[16].

RD2. International Space Exploration Coordination Group (ISECG) (2018), Global Exploration Roadmap[17]

RD3. Resolution on Europe's space exploration strategy (2014), ESA/C-M/CCXLVII/Res. 2 (Final).

RD4. Mazzucato M. (2018), Mission-Orientated Research and Innovation in the EU: a problem-solving approach to fuel innovation led growth, Publication office of the European Union.

RD5. Crawford, I. A. (2015). Lunar resources: A review. Progress in Physical Geography, 39(2), 137-167.

RD6. Carpenter, J., Fisackerly, R., & Houdou, B. (2016). Establishing lunar resource viability. Space Policy, 37, 52-57.

[16] https://space-agency.public.lu/dam-assets/publications/2018/Study-Summary-of-the-Space-Resources-Value-Chain-Study.pdf

[17] https://www.nasa.gov/sites/default/files/atoms/files/ger_2018_small_mobile.pdf

ANNEX 1: UNDERLYING ASSUMPTIONS

Through the work carried out to date in the preparation of the Space Resources Strategy it has been possible to establish a set of assumptions. These assumptions, stated below, provide the basis upon which the approach described in the Strategy has been built. An important aspect of the strategy should be to test these assumptions, to review them regularly and to change them and the strategy where needed.

Assumptions

1. The first use case for locally sourced space resources will be at the lunar surface.
2. The primary source of financing for space resources utilisation activities is the public sector. There is insufficient rationale for comparable or greater investment by the private sector. While this may not always be the case it is likely that the public sector will be the primary source of financing for space resources activities for at least the next decade and probably beyond.
3. The primary use case for space resources in the foreseeable future will be propellant with life support consumables as a secondary use case that alone will not justify the systems or investments needed for space resources. Materials production may follow later if a use case emerges, most likely related to lunar surface infrastructure.
4. Lunar polar ice is important as a potential resource but prospecting and exploration are needed in advance of any technology development or planning for its utilisation.
5. Non-polar materials are generally better understood and are likely to be the first resources to have their utilisation demonstrated despite the high power needs and complexity of utilisation processes.
6. Surface exploration missions are required to locations to prospect and explore in advance of resource utilisation.
7. Research and development are needed in the areas of energy, autonomy, excavation, beneficiation, prospecting and exploration, metal oxide reduction, dust resistance, construction and manufacturing.
8. The expertise to realise space resources utilisation does not exist in the space industry. Partnerships with non-space industry is fundamental to advancing the sector.
9. The primary benefit of space resources activities in the near to mid-term will be an understanding of the feasibility of ISRU and the likely applications and technological way forwards along with the generation of new intellectual property and innovation in terrestrial industrial sectors.
10. Poor availability, quality assurance and consistency of lunar simulants is a limiting factor for technology development. New simulants are therefore required.
11. A barrier to the implementation of space resources utilisation is the absence of demonstration of feasibility. A demonstration of product production and later utilisation in a mission which does not depend on it is required to change this paradigm.
12. There is no international consensus regarding the legality of space resources utilisation and exploitation under international law, nor are there international legal norms on the legal status of space resources or their governance.