

UK ISRU Technology Review



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Cover Image: **PROSPECT Drill (ProSEED) and Mini Lab (ProSPA)**

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This independent review, led by Frazer-Nash Consultancy Ltd., was commissioned by the UK Space Agency in 2025 to explore the capabilities of the UK space sector in the In-Situ Resource Utilisation (ISRU) technology field.

This report sets out the findings from the review. It provides conclusions regarding UK capabilities, international ambitions, and opportunities for the sector.

The review was supported by ISRU-UK as a consultee, the association group for active organisations in this technology area, and by individual responses from representatives of UK organisations already involved in research and development of such technologies.

The judgments and views expressed in this report are those of Frazer-Nash Consultancy, or the perception of those engaged and consulted during the formation of the report. The UK Space Agency provided Frazer-Nash Consultancy with editorial guidance, this body of work is for information purposes only and does not represent national policy.



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Glossary

Beneficiation	Separation or concentration of valuable components from excavated materials.
Enabling Technologies	Technology which is required for/ supports ISRU activities e.g. power, communications, thermal management.
Excavation	Physical removal of material from the surface or subsurface.
Icy Regolith	Regolith that also contains frozen volatiles such as water ice.
Processing	Conversion of materials into usable forms / resources.
Products & Purification	End results of ISRU operations, useable products and any necessary post-processing to achieve this.
Prospecting	Resource identification and characterisation.
Regolith	A blanket of unconsolidated, loose, heterogeneous superficial deposits covering solid rock including dust, broken rocks and is present on terrestrial planets, asteroids and moons
Volatile	A substance easily evaporated at normal temperatures. In this report, this includes solar wind implanted gases (hydrogen, helium, carbon, nitrogen, etc.) and polar ice in the lunar context.

List of Abbreviations

CSIRO	Commonwealth Scientific and Industrial Research Organisation
ESA	European Space Agency
ESRIC	European Space Resources Innovation Centre
EUR	Euro
HMG	His Majesty's Government
ISECG	International Space Exploration Coordination Group
ISRO	Indian Space Research Organisation
ISRU	In-situ Resource Utilisation
JAXA	Japan Aerospace Exploration Agency
LIST	Luxembourg Institute of Science and Technology
LSA	Luxembourg Space Agency
LSII	Lunar Surface Innovation Initiative
NASA	National Aeronautics and Space Administration
NSS	National Space Strategy
OST	Outer Space Treaty
PSR	Permanently Shadowed Regions
PwC	PricewaterhouseCoopers
SMD	Science Mission Directorate
STFC	Science and Technology Facilities Council
STMD	Space Technology Mission Directorate
TRL	Technology Readiness Level
UKSA	UK Space Agency
(UN)COPUOS	(United Nations) Committee on the Peaceful Uses of Outer Space
USD	US Dollar

1 Introduction

The UK Space Agency commissioned this Technology Review to provide a comprehensive assessment of the United Kingdom's capabilities, opportunities, and strategic positioning in the field of In-Situ Resource Utilisation (ISRU) for space exploration. This report supports the Agency's ambition to inform future research, development, and investment decisions so that the UK can position effectively in an appropriate niche, adding value to the international community's efforts without duplicating existing functionality.

The report examines current developments across the UK and internationally, identifying the UK's potential contributions within this global context. It draws on consultation with industry, academia and key stakeholders integrating these findings with publicly available international research. In addition to presenting the current state of ISRU technology and strategic ambition of key international players, this report identifies UK based facilities and capabilities which could be leveraged to support international collaboration.

The report presents a series of road mapping tools which can be used to piece together a technology roadmap for a particular ISRU application, covering the key functionality required, the technologies which are being developed to achieve these functions, and an overview of how these technologies could be integrated to achieve an overall capability.

"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". – ESA Space Resources Strategy [26]

1.1 Scope

To produce a report with appropriate level of detail and focus, the following limitations were applied across this study:

- ▶ This report does not intend to provide a comprehensive list of relevant technologies against each ISRU function. To set appropriate boundaries, this report only considers technologies that line up with the UKSA roadmap criteria. To do this, we provide an overall analysis areas of opportunity within the context of existing UKSA/ESA/NASA ambitions.
- ▶ To be considered in the roadmap, UK technologies must meet the UK strengths and opportunities identified in the National Space Strategy (NSS) [1] – Growing existing strengths; leadership in high growth areas; leadership in emerging sectors – and must also align with the one of the Mission scenarios, i.e. Lunar Vicinity, Lunar Surface, Mars or ESA Mission. For creation of the roadmapping tools and evaluation of technologies, this study considered the key stages (e.g. prospecting, excavation, etc.) of carrying out ISRU missions and assessed technologies against the key functions (e.g. remote mapping, surface mapping etc.) required to carry out ISRU missions. The following elements were considered for each technology included in the study:
 - The ISRU use cases that the technology supports, e.g. propellant, life support or construction
 - Which agencies, academic institutions and private companies are developing the technologies
 - The Technology Readiness Level (TRL) of each technology with respect to the ESA TRL rating system [2] (see Table A 3 for definitions). When considering TRL definitions, scale was not factored in. A technology proven at TRL 9 is not necessarily ready to support ISRU at a scale relevant to NASA/ESA ambitions, although it may have been used on a mission on a much smaller scale.
- ▶ We recommend that following this report, in cases with UK and international technology options, a further determination should be made in the future by UKSA as to whether the UK can be considered 'a leader in this field' in accordance with the UK Space Exploration Technology Roadmap criteria.

- ▶ This report does not aim to be an exhaustive gap analysis, as conducted in the ISECG In-Situ Resource Utilisation Gap Assessment Report [3]. The primary focus on ESA and NASA missions is in alignment with the NSS [1], which states the intention to maintain our partnership with ESA to lead cutting edge missions and develop and access ESA facilities, skills and expertise. Another key aim in the NSS is to grow the UK as a science and technology superpower, with focus on collaboration on the NASA-led Artemis programme to return humans to the Moon. This focus on ESA and NASA is not intended to prohibit further international engagement, but to bound the review scope appropriately.



Figure 1: Artist impression of a Moon Base concept using lunar regolith as habitat shielding. Photo Credit: ESA - P. Carril [4]

2 ISRU Overview

In-Situ Resource Utilisation (ISRU) is the use of local resources at mission destinations, as opposed to bringing all supplies from Earth. More broadly, Space Resources refers to all materials sourced beyond Earth. Local supply of critical consumables can support mission life extension, enhance crew safety and enable missions not possible without ISRU [3]. ISRU is anticipated to enable longer-term lunar habitation and onwards travel to Mars and potentially become a core enabler of an in-space economy.

2.1.1 ISRU for lunar applications

As the lunar environment is a key focus of international objectives, the Moon is expected to be an ISRU test bed. Lunar resources can be broadly divided into two categories: regolith-based and water/volatile-based [3]. Large water-ice reserves are speculated to exist in Permanently Shadowed Regions (PSRs) and regolith can contain solar wind implanted volatiles including hydrogen, helium, carbon, nitrogen, fluorine, and chlorine. Regolith-based resources include bulk regolith which can be used for construction e.g. additive manufacturing of habitats or landing pads, extracted metals for producing satellites, conducting maintenance, building extraction tools, silicon for solar arrays, and specific constituents of interest such as KREEP (potassium, rare earth elements, phosphorus) deposits. Crucially, lunar regolith is composed of more than 40wt% oxygen, which is essential for life-support and a key constituent of propellant mix when appropriately processed. PwC's *Lunar Market Assessment* [5] envisions water and volatiles dominating development efforts in the near term, with infrastructure and equipment developing medium term (>10 years) [5].

2.1.2 ISRU for Mars based applications

Mars benefits from a CO₂ atmosphere and has had the sole successful ISRU demonstration mission to date: MOXIE (Mars Oxygen In-Situ Resource Utilization Experiment). NASA's MOXIE payload aboard the Perseverance Rover produced oxygen from the Mars atmosphere utilising solid oxide electrolysis in 2022 and 2023. Key Mars' resources include the CO₂ atmosphere and ice and hydrated minerals embedded in regolith. Life support and propellant are the primary use cases, with secondary requirements for regolith usage in building and radiation shielding. Due to the cost of bringing resources to Mars, ISRU is key to a sustained human presence.

2.1.3 ISRU for other space bodies

ISRU is also applicable on other Space bodies, although this is a longer-term aspiration compared to lunar and Martian applications. Martian moons benefit from lower escape velocities, which mean less propellant is needed to return resources to LEO when compared to that needed to do so from the lunar surface. Near-Earth Asteroids could be sources of ISRU material such as water-rich minerals for refuelling satellites and potentially rare earth elements that could be returned for use on Earth. ISRU can also be an enabler for deep space missions, for example extracting water from Enceladus or Europa to support extended human presence or robotic missions [6]

2.1.4 Cost drivers for ISRU

The key driver for ISRU demand is launch costs. The propellant required to deliver one mass unit (1 u) of payload from Earth LEO to the lunar surface is about 2.5 u, and to Mars' surface is about 8–10 u [7]. Using lunar-sourced propellant has been estimated to reduce the cost of a human Mars mission by 2-3 times [8], noting that transporting propellant from Earth to the lunar surface costs approximately 36,000 USD/kg, with this cost increasing the further one moves into space [9]. A lunar ascent requires approximately 6 tonnes of LO₂/LH₂ propellant to transport 1 tonne of payload to LEO. If ascent propellant can be produced in-situ, this minimises the launch mass, enabling more payloads to be transported in less missions.

“The most significant impact ISRU has on missions and architectures is the ability to reduce launch mass, thereby reducing the size and/or number of the launch vehicles needed, or use the mass savings to allow other science and exploration hardware to be flown on the same launch vehicle. The next significant impact is the ability to extend the life of assets or reuse assets multiple times.” – International Space Exploration Coordination Group (In-Situ Resource Utilisation Gap Assessment Report, 2021) [3]

2.2 The ISRU Value Chain

ISRU comprises a broad field of technologies, with many use cases. While a singular value chain may not be definitively agreed across the sector, the following 5 elements have been taken as bounding scope for this Technology Review and as a basis for the presented technology roadmaps:

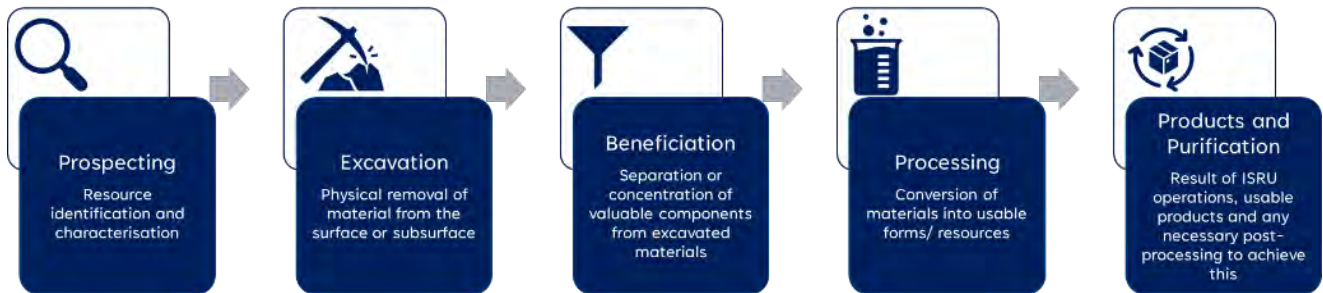


Figure 2: The ISRU Value Chain

This value chain has been used to characterise technologies and enable clear links from initial resource identification and characterisation (prospecting) through to end products. The end products have been selected to align to this report's near-term demonstration objectives and use cases: propellant, life support and construction. This is inclusive of oxygen, water and materials extracted from regolith. Placing technologies in this value chain is essential in ensuring that technologies have both a defined use case, and identification of gaps in producing high priority products.

Technologies can frequently be used for multiple applications (e.g. a technology which can extract oxygen from regolith, can likely extract metals) but that technologies are not simply plug and play across the whole value chain and are typically designed for a specific application. Similarly, not all environments are applicable to an ISRU technology (e.g. methane production is viable on Mars but not the Moon) and there are likely variations within environments as well. Environmental specifics are therefore not outlined for this reason and to help the report focus on the core capability of a technology.

There are also enabling technologies across this value chain which have been considered as essential to ISRU. Such technology areas include power, communications, navigation, thermals, autonomy, and regolith handling. As these areas have broader applications than ISRU alone, they are not considered within the scope of this report and roadmap.

2.3 Potential Benefits from UK ISRU Investment

2.3.1 Economic Growth

The UK's investments in ESA have positively impacted the UK's growth, employment, productivity and private research and development (R&D) investment with a direct economic return of £7.49 from every £1 contributed to ESA [10].

The ISRU commercial market is expected to be largely driven by propellant demand, stimulated by future missions to the Moon and Mars. Studies have calculated the global 2040 ISRU propellant market at up to USD 49.6 billion [5], noting that this has high dependencies on the volume of missions and a sustained human presence in Space. Developing UK technologies strategically to support the propellant value chain could unlock areas of this market.

2.3.2 Global Partnerships

The Space Regulatory Review 2024, highlights ISRU as a key area of focus, noting that lunar exploration is driving international conversations and stating the UK should set out domestic and international policy to provide UK industry with the certainty to invest in the developing lunar economy [11]. Furthermore, the Space Industrial Plan [12] highlights the need for industry and government partnerships and new ways of working in this disruptive era of space technology and exploration in an ever-diversifying international landscape.

The UK engages with the global discussion on space resource utilisation as a member of UNCOPUOS, and through its active engagement in the Space Resources Working Group [13] and the Action Team on Lunar Activities Consultation (ATLAC) [14]. The UK's key goal is to enable responsible ISRU in line with the principles of the Outer Space Treaty (OST). Internationally the United Kingdom has taken the view that international discussions should focus on principles for in situ resource use and extraction first, with more future focused space resource issues, such as commercial return to earth of space resources for sale, discussed in the future closer to their fruition when mission architectures and the regulatory policy needs can be better understood.

The UK Space Agency has supported and strengthened transparency measures, including information-sharing on planned ISRU activities in line with Article XI. These steps help ensure openness, prevent harmful interference and promote equitable participation by all States – regardless of capability – supporting fair, responsible and sustainable access to space resources.

The UK Space Agency and HMG advocate a practical, inclusive approach that prioritises in-situ use of extractable resource to support safe and well-coordinated lunar and deep-space operations. As a signatory to the Artemis Accords [15], HMG continues to contribute internationally to the development of norms on interoperability, responsible conduct and deconfliction.

Accordingly, the UK Space Agency and HMG expect forthcoming international discussions to deliver tangible progress on ISRU principles, confirming their use under the OST, enhancing transparency measures, and further strengthening coherent, cooperative practices through both COPUOS and the Artemis Accords.

2.3.3 Terrestrial Technology Development

ISRU development can drive terrestrial advancements in resource efficiency, sustainability and cost reduction:

- ▶ **Resource Efficiency:** ISRU involves maximising the use of local resources - applying these principles on Earth can help industries optimise material usage and reduce waste, supporting a more circular economy.

An example of how ISRU principles can be used on Earth is the treatment of mining wastewater, as demonstrated in Australia. A cost-effective technology known as virtual curtain was used at a Queensland mine to remove metal contaminants from wastewater, discharging the equivalent of 20 Olympic swimming pools of rainwater-quality water (see photograph in Figure 3) [16].



Figure 3: Virtual curtain treatment of contaminated wastewater in pit [Image Credit: CSIRO] [16].

- ▶ **Environmental Sustainability:** By minimising energy and consumables required for production of useable materials, ISRU principles can help reduce the carbon footprint associated with extraction, processing, and transport of materials on Earth. This aligns with global environmental conservation and sustainability goals.

Steel production currently accounts for 7-8% of global greenhouse gas emissions [17]. Many technologies related to oxygen and metal extraction from regolith are directly applicable to terrestrial metal production. ESA is currently funding ISRU company Maana Electric to investigate the possibility of a European prototype system able to use material with relatively low iron content (low-grade) and electricity to produce carbon-neutral steel [18]. The high-level function chain and associated benefits of Maana Electric's ISRU green-steel production system are illustrated in Figure 4.

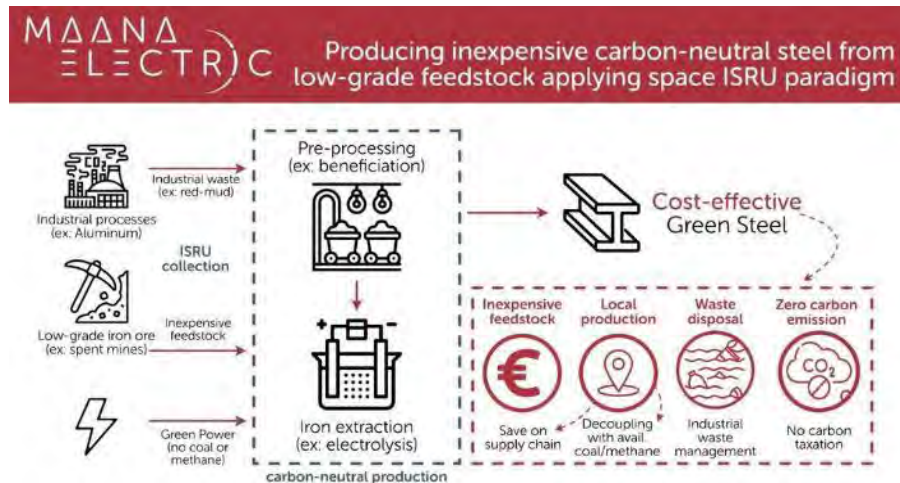


Figure 4: High-level function chain and associated benefits of Maana Electric's ISRU green steel production system [Image Credit: Maana Electric] [18].

- ▶ **Cost Reduction, Technological Innovation and Spin-offs:** Research in ISRU fosters breakthroughs in a wide range of fields, including advanced robotics, 3D printing with local materials, solid oxide electrolysis, and autonomous systems. These technologies have direct applications in Earth-based industries, such as:
 - **Energy and Chemical Processing:** Advancements in solid oxide electrolysis for oxygen production can be leveraged for more efficient energy generation and storage systems on Earth.
 - **Materials Science:** The necessity of minimising payload mass for space missions has driven the development of highly efficient, lightweight technologies. The development of lightweight, corrosive-resistant alloys and components for use in extreme environments has applications in chemical processing plants, desalination, and even medical implants.
 - **Construction:** Using novel building materials and innovative construction techniques with on-site resources (e.g., creating "lunar concrete" concepts applicable to Earth). It has been identified that off-Earth construction could catalyse change on Earth to develop structures that are lightweight, strong, environmentally efficient and reliable [19].

3 Global ISRU Landscape Review

This section presents an overview of global ISRU strategies, planned missions and technology demonstrations of major space agencies from across the globe. This supports identification of where the UK can be a key partner, providing enabling technologies and support to planned missions. When combined with the technology overview in Section 5, the global landscape review allows for the identification of critical gaps in international strategies and current technologies which present an opportunity for UK support or leadership.

3.1 Agency Visions & Strategic Goals

The lunar market is substantial, with over 450 lunar missions planned to launch between 2023 and 2033, generating USD 151 billion in revenue [20]. Notably, the government sector is predicted to account for most of this demand, generating 75% of the lunar market's total revenue during this period [21], hence commercial developments will largely be tied to agency vision & strategic goals. As 48% of lunar missions by 2032 are expected from North America (largely due to NASA's Artemis Programme) [22] alignment to these objectives has been identified as a key opportunity. Alignment to ESA objectives is also crucial, as 70-75% of UKSA's annual budget (68% 2025-26 [23]) is typically committed to ESA as a member state, while ESA's collective funding model enables pooling of resources to deliver ambitious projects which would not be possible for a single nation [10].

As stated in ISECG's Global Exploration Roadmap, "[Space Exploration] enhances international collaboration and diplomacy on a global scale, uniting nations in pursuit of common goals and fostering mutual respect and understanding" [24]. As a party to the Outer Space Treaty (OST), the UK is committed to carrying out activities on the moon in line with that commitment as a responsible supervising state (article VI) for the activities of UK based operators [25]. Additionally, as a signatory of the Artemis Accords, the UK is committed to a shared safe and responsible vision to enable human activity on the Moon and Mars [1]. Technologies and use cases examined in the subsequent technology review are aligned to these international objectives with an objective to demonstrate UK opportunities within the global landscape.

3.1.1 ESA and Europe

In the wake of growing international and commercial interest in the resource potential of space, ESA set out its ISRU ambitions within its 2019 Space Resources Strategy [26]. This strategy is aligned with the overall objectives of NASA's Artemis programme to establish human presence on the moon by 2040, with a primary focus on the identification and extraction of lunar polar volatiles, and the development of technologies that would demonstrate water and oxygen production on the lunar surface.

ESA provided their renewed space exploration roadmap, *Terrae Novae 2030+*, in 2022 which built on the Space Resources Strategy and set out how this would provide the foundation of an expanded vision for European exploration of the solar system to 2040+ with a horizon goal of European presence on Mars, of which ISRU would be a critical enabling technology. The renewed strategy emphasised the need for greater operational independence for Europe's space capabilities and supports efforts to establish end-to-end European capability for resource utilisation. This strategic need for independence was echoed in 2023 by ESA's High Level Advisory Group in their 'Revolution Space' report. An example of the European response to this growing interest area is the formation of the European Space Resources Innovation Centre (ESRIC). To catalyse private investment and cement itself as an international centre for space resources information and technology, ESRIC was created by the Luxembourg Space Agency (LSA) and the Luxembourg Institute of Science and Technology (LIST) in 2020, and is supported by ESA. ESRIC and ESA launched the Space Resources Challenge to "[drive] innovation [and] ... kickstart new commercial endeavours" [27] which continues to release funding calls for projects in this interest area.

In response to ESA's *Terrae Novae* Exploration Strategy, members of the European space resources commercial landscape created the *Euro2Moon* association that will "support ESA's vision by creating a strong industrial ecosystem

and developing an ambitious and sustainable ISRU implementation plan” [28]. At the Council of Ministers meeting in November 2025, member states committed EUR 22.3 billion to continue the work of the Agency, of which nearly EUR 3 billion was designated for the Exploration Programme, where much of ISRU technology developments and associated missions are managed. For its part, the UK subscribed an additional EUR 152 million to the Exploration programme on top of existing commitments [29].

3.1.1.1 Planned Missions and Mission Strategy

In its first phase ESA is seeking to deploy robotic scientific payloads on “Missions of Opportunity”, either by providing small payloads on private lunar landers or contributing scientific elements to a partner organisation’s mission. Towards the latter end of this phase (mid-2020s and onwards) ESA will increasingly consider “Directed Missions” – missions directed, procured, and overseen by ESA. Subsequent phases will build on these endeavours to provide an end-to-end demonstration of a European capability to produce breathable oxygen or drinkable water on the lunar surface by the late 2020s. This will then be used as the basis for the development of a pilot plant that would support future human exploration.

Other exploration missions will significantly contribute towards enabling activities that will support lunar mapping, access, operations, and broader ISRU opportunities such as *Lunar Pathfinder*, *Moonlight*, and *Argonaut*. While not necessarily directly tied to said missions, European ISRU capabilities are already integrated into the wider aspirations and projects of ESA to encourage compatibility. Several European ISRU payloads are in development and scheduled for mission deployment in the near to medium term. Notable examples are presented in Table A 1 in Annex A.

3.1.2 NASA

The Moon to Mars Architecture is the cornerstone of NASA’s strategy for crewed exploration of deep space, with an objectives-based approach to human exploration [30]. NASA views ISRU as essential for achieving sustained human exploration beyond Earth. Lunar Infrastructure has been identified as a key area for achieving Moon to Mars, with the following overarching goal:

“Create an interoperable global lunar utilization infrastructure where U.S. industry and international partners can maintain continuous robotic and human presence on the lunar surface for a robust lunar economy without NASA as the sole user, while accomplishing science objectives and testing for Mars.” [30]

Starting with the Moon under the Artemis program as a proving ground for Mars, NASA aims to harness resources such as lunar regolith and polar ice deposits to produce oxygen, water, propellant, and construction materials directly at the point of use.

Central to this strategy is the Lunar Surface Innovation Initiative (LSII), which develops foundational ISRU systems and supporting technologies that Artemis missions will rely on. LSII encompasses six capability areas: In-Situ Resource Utilisation, Surface Power, Excavation and Construction, Extreme Environment Operations, Dust Mitigation, and Extreme Access. Complementary NASA programs, include the Science Mission Directorate (SMD) instrument selections and Space Technology Mission Directorate (STMD) technology demonstrations, which support these capabilities by advancing sensors, drills, and processing systems critical to ISRU.

NASA is advancing a diverse set of ISRU efforts across recent, ongoing, and planned missions. The examples listed in Table A 2 in Annex A reflect activity across several parts of the ISRU landscape: some focus on prospecting and characterising local resources, others explore excavation and material-handling approaches, with one mission having already demonstrated oxygen production from the Martian atmosphere. Together, they offer a snapshot of ISRU-related work across past, present, and future mission efforts.

3.1.3 Australian Space Agency and CSIRO

The Australian landscape provides a range of lunar and Martian surface analogues for testing, and Australia’s heritage in remote and autonomous operations in mining is largely applicable to ISRU [24]. This experience has fed into

development of the In-Situ Resource Utilisation Facility – a large lunar testbed for realistic testing of rovers and related equipment [31]. While relatively early in developing their space ecosystem, Australia is clearly identified as a UK Strategic partner, evidenced by the UK-Australia Space Bridge signed in 2021 [1], therefore providing additional opportunities for collaboration.

3.1.4 Canadian Space Agency

Canada has been involved in ISRU related technology development for many years, including the creation of a Lunar Surface Exploration Initiative in 2021 which aimed to “advance technologies focused on five fundamental fields for lunar exploration”. One of these areas was “Mining and In-Situ Resource Utilisation” [32]. The Canadian Space Agency in partnership with Impact Canada also sponsored a track of the *Aqualunar Challenge* (UKSA Sponsored the UK track), which was an international challenge prize to “to drive the creation of innovative technologies to make human habitation in space possible by finding ways to purify water buried beneath the Moon’s surface” [33]. Canada’s heritage of capability and special status within ESA demonstrate its strategic value as a partner for Europe.

3.1.5 Japan Aerospace Exploration Agency (JAXA)

JAXA has a long heritage of space missions and sovereign capability with potential for ISRU applications, for example, Japan was the first nation to successfully return samples from an asteroid to Earth with the *Hayabusa* mission. JAXA has already initiated. JAXA has initiated a study (in collaboration with *JGC Holdings Corporation*) to develop a concept of a lunar ISRU plant to produce propellants (hydrogen and oxygen) for supply near and on the lunar surface with an objective of achieving sustainable exploration activities on the lunar surface from the 2040s [34]. Japan is also a participant in the Artemis program, is developing technologies essential for lunar operations such as communication and navigation technologies to enable long-term exploration [24] and in partnership with the Indian Space Research Organisation (ISRO) is developing the Lunar Polar Exploration Mission (LUPEX) which will search for water in the lunar south pole region [35].

4 Survey results

4.1 Overview of survey methodology

Following the global landscape review and characterising the benefits of ISRU to the UK, it was necessary to characterise the existing UK ISRU landscape.

This was done through a survey, which was accessible to all organisations currently active in the UK. Questions were developed in line with UK Space Agency requirements, and the survey was distributed through the Frazer-Nash Consultancy website, shared via UK Space Agency LinkedIn and the *ISRU-UK* mailing list. The questions asked in the survey are detailed in Annex B.

While this survey provides useful insights, several limitations should be acknowledged. Participation was voluntary, which may introduce self-selection bias and limit the representativeness of the sample. Responses reflect participants' self-reported perceptions and may therefore be subject to bias. The survey was administered online, which may exclude individuals with limited digital access. Finally, the survey captures opinions at a single point in time, and results may not reflect changes in attitudes or behaviours that occur subsequently.

4.2 UK ISRU Technology Survey Results

4.2.1 Who were the Respondents?

An overview of the organisations represented in the survey are given in the pie charts in Figure 5 below:

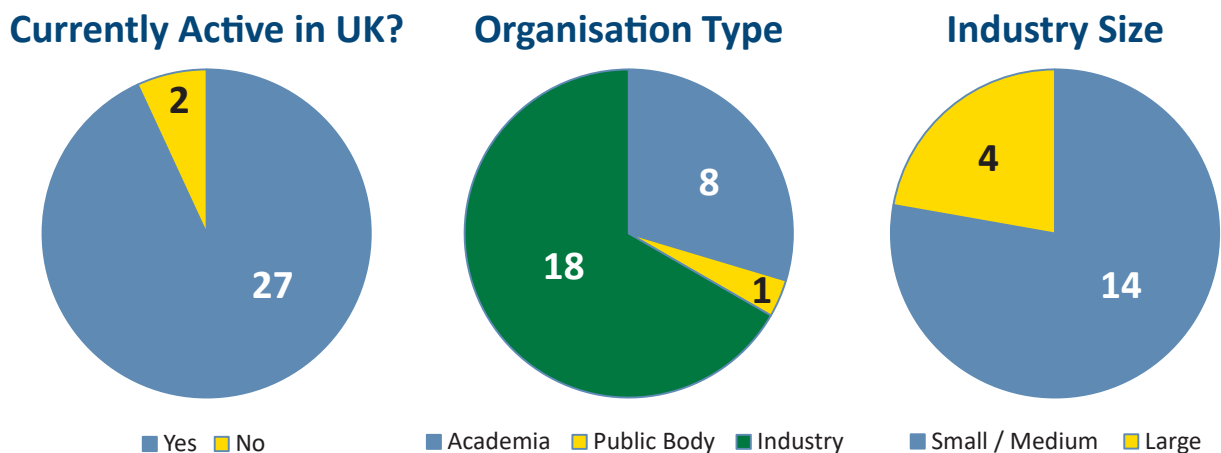


Figure 5: Overview of organisations represented in the survey, where the numbers on the pie chart slices represent the frequency of responses.

We received a total of 29 responses – 2 of which were from international organisations and hence were discounted. 67% of the responses were from industry, 30% were from academia, and 3% (1 response) was from a non-departmental public body. Out of the 18 industrial respondents represented in the survey, most responses were from small-to-medium-sized organisations (78%).

The locations of the organisations that were most frequently cited are represented in the word cloud in Figure 6 below. Four locations – London, Harwell, Bristol, Yorkshire – were tied as the most frequently cited, each representing 11% of all responses.



Figure 6: Word cloud illustrating locations of survey respondents. Larger text indicates higher frequency of mention.

4.2.2 Technology Information

Respondents were asked to provide a categorisation of the environments their technology was envisioned for, and where in the value chain they sit:

- ▶ 85% are applicable to the Moon.
- ▶ 44% are applicable to Mars.
- ▶ 15% are applicable to Asteroids.
- ▶ 7% are applicable to other environments.
- ▶ 11% not specified.

The responses given to survey question “Where in the ISRU Value Chain does your technology sit?” are represented in the pie chart in Figure 7, and the technologies described by survey respondents after selecting an ISRU value chain option are given in Table 1. Note that some technologies perform more than one function and therefore were counted in multiple categories, meaning that the pie chart reflects functional overlap rather than a one-to-one classification. Capabilities were also excluded from this pie chart but are listed in Table 3 – see Section 4.4 for further details.

Where in the ISRU Value Chain does your technology sit?

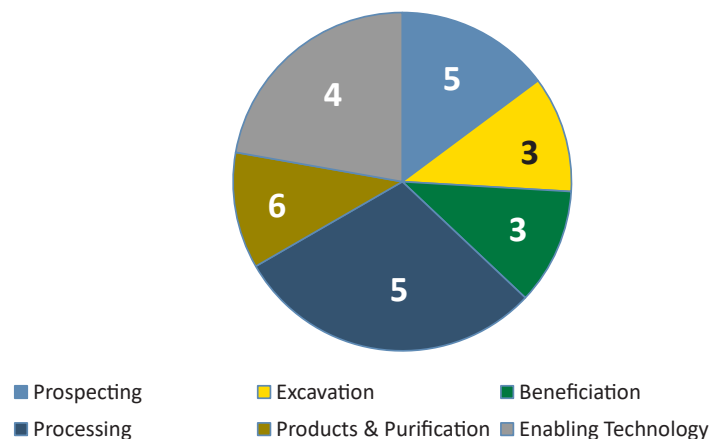


Figure 7: Overview of responses where the numbers on the pie chart slices represent the frequency of functions reported (including cases where technologies were classified as more than one function).

Table 1: The technologies described by survey respondents.

ISRU Value Chain Function	Survey Response Frequency	Technologies / Capabilities Described by Survey Respondents
Prospecting	15%	- Chemical analysis of drilled lunar samples to identify ice and volatile species - Remote sensing and in-situ instrumentation for resource prospecting
Excavation	11%	- Robotic excavation - Automated material handling
Beneficiation	11%	- Regolith size classification and separation - Mineral Enrichment
Processing	30%	- Water extraction / purification from icy regolith - Microwave heating regolith - Volatile extraction from regolith - Densification of lunar regolith for construction materials - Oxygen and metal extraction from regolith
Products & Purification	11%	- Water extraction / purification from icy regolith - Microwave heating regolith - Volatile extraction from regolith - Densification of lunar regolith for construction materials - Oxygen and metal extraction from regolith - Metal processing for electric propulsion
Enabling Technology	22%	- Electromagnetic radiation-shielding technology - Solar energy collection and wireless power transfer - Sub-surface sounding and tomography - In-situ dust removal technology - Transfer of liquids and gases produced by ISRU

The results for survey question “What is the current TRL of your technology?” are represented in the bar chart in Figure 8. This revealed that the majority of ISRU technologies being developed in the UK are low-TRL (i.e. TRL 5 and below). However, two survey respondents reported mature technologies at TRL 7-9 which were as follows:

- ▶ Remote sensing and in-situ instrumentation for resource prospecting, both infrared remote sensing and geophysics e.g. seismology, gravity mapping etc.
- ▶ A range of mass spectrometer-based payloads for identifying and quantifying ices and volatile species present in the sub-surface, surface and atmosphere of Moon, Mars, etc.

What is the current TRL of your technology?

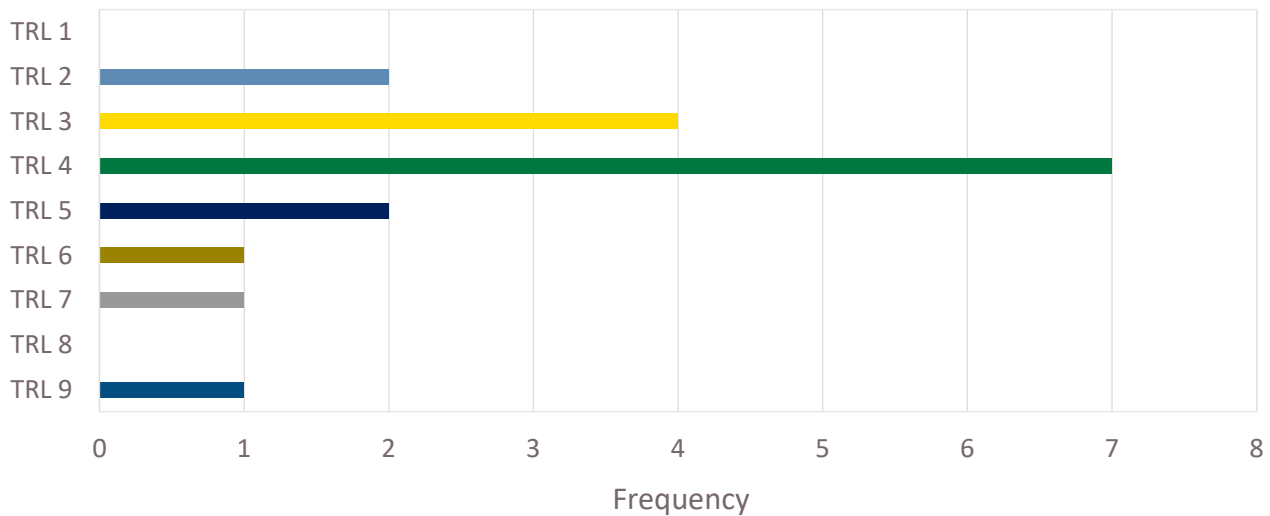


Figure 8: Bars indicate the number of technologies reported at each TRL level (1-9).

4.2.3 Sector Commentary

Within the survey, respondents were encouraged to provide details on:

- Why they are developing ISRU technologies
- What their technology development plans and blockers are
- Non-financial assistance that would support the development of their technology

Sector motivations for ISRU developments varied, but respondents typically valued either:

- Organisational strategic developments aligned to their terrestrial expertise, scientific capabilities, and/or commercial plans; or
- Broader national (or global) objectives, i.e.:
 - ▶ beyond-Earth exploration
 - ▶ supporting the development of permanent Space settlements
 - ▶ alignment to ESA objectives
 - ▶ closing knowledge gaps which could affect larger research activities

Some respondents highlighted where their technology could be applied in non-space (i.e. terrestrial) applications, as well as science objectives such as understanding how planets form and evolve.

With relation to technology development blockers, funding was highlighted most often, with respondents specifying the following as blockers:

- ▶ Lack of funding pathways
- ▶ Current funding calls are heavily over subscribed

- ▶ Split sources of funding with different aims and criteria
- ▶ Funding relies on business cases which are hard to make on such a speculative technology
- ▶ Short term UKSA funding opportunities (year to year) do not provide stability required
- ▶ Time frame to a steady cadence of moon missions is long, and it is difficult to attract investment or talk about ROI without this as an enabler

Technology developers from industry expressed concern that long term funding instability has led to a focus on building singular demonstration prototypes rather than repeatable scalable ISRU solutions. Technology developers from academia noted the impact on short-term contracts for postdoctoral researchers which leads to projects stalling or ending when contracts conclude.

Respondents also raised that routes to commercial exploitation are currently unclear, creating a strong reliance on ESA or NASA missions for in-space technology demonstration.

To support UK ISRU technology development, respondents highlighted the following as key opportunities to improve confidence in investing in ISRU:

- ▶ A clear UK ISRU strategy, i.e.:
 - A pipeline/roadmap of UK (and international) ISRU-related missions and flight demos
 - Recognition of ISRU as a strategic national capability
 - Policy clarity on partnership and frameworks
 - Clear understanding on the technical priorities i.e. water, oxygen, helium, construction, etc.
 - A coordinated institutional framework to facilitate the transition between academic funding (e.g. STFC) and UKSA “high TRL” funding mechanisms for ISRU technology development
- ▶ Access to facilities, e.g. thermal-vacuum, regolith simulant testbeds, operations test beds, reduced gravity facilities such as parabolic flight
- ▶ An initial UK government funded mission
- ▶ Networking to bring UK and international partners together
- ▶ Regulatory clarity around use of orbital material and space resources
- ▶ Common standards baseline

4.3 UK Facilities Map

In this report, a “facility” is defined as a physical location equipped with the tools and infrastructure needed for technology development, testing or fabrication. From the survey and workshop, 21 UK facility owners were identified and have been mapped below in Figure 9; the numbered markers correspond to facility owners, which are described in further detail in Table 2.

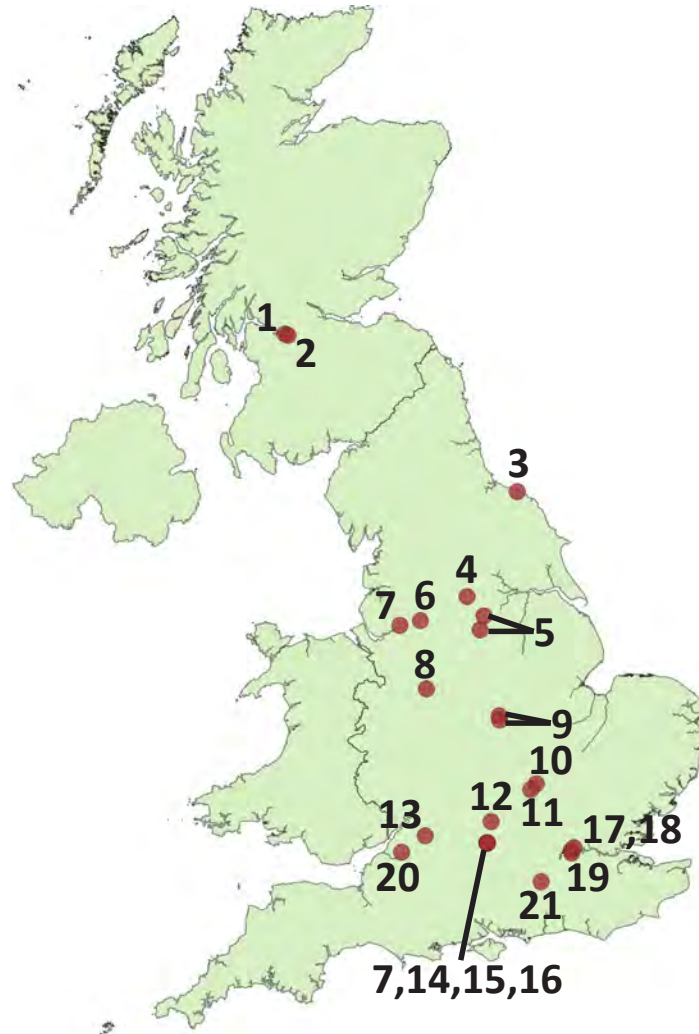


Figure 9: Locations of UK ISRU facilities in the UK (red dots).

Table 2: UK ISRU facilities identified in the UKSA ISRU survey and Technology Review Workshop. The “Facility Map Number” corresponds to the facility numbers plotted on the map in Figure 9.

Facility Map Number	Facility Owner	Organisation Type	Facility Description
1	University of Glasgow	Academia	ESA Plume-Regolith Facility (73 m ³ high vacuum facility) for lunar, Martian and Phobos experiments; dirty facility for plume, regolith, dust, plasma, drones, mechanics, breadboard, electromagnetic, thruster testing [36].
2	University of Strathclyde	Academia	Concurrent and Collaborative Design Studio (CCDS); Mission Laboratory; Strathclyde Radiation Testing Facility (SCAPA); Strathclyde Space Mechatronic Systems Technology Laboratory (SMeSTech) [37].
3	Science and Technology Facilities Council (STFC)	Public Body	Boulby Underground Lab: 1.1 km sub-surface planetary-analogue testing environment (i.e. low radiation, mineral-rich, isolated); ultra-low background radiation material screening [38].
4	Regolithix	Industry	Plasma processing technologies, including a 1kW RF plasma generator and small vacuum test chamber.
5	Metalysis	Industry	FFC Cambridge Electrolysers: 12 Gen 1 units capable of producing grams of outputs per run of oxygen and metal powders; 4 Gen 2 units capable of producing kgs of outputs per run of alloy powders [39]. Fully equipped analytical testing laboratory – for chemical and physical analysis – as well as morphological and structural analysis.
6	University of Manchester	Academia	Lunar mechanical analogue test bed [40].
7	Amentum	Industry	Irradiation facility (gamma) [41]; Sustainability and life cycle analysis; Materials science and testing laboratories; Materials handling and management; Nuclear power development and test laboratories; Radiation shielding modelling (including proprietary tools); gloveboxes; SEMs; autoclaves.
8	Lucideon	Industry	Advanced ceramic pilot scale facility that has a suite of equipment from powder processing and characterisation, forming, drying and de-binding, to sintering. Facility is also applicable to the processing of regolith and its simulants [42].
9	University of Leicester	Academia	Broadly-based facilities supporting the development of hardware for space applications, including lab space and cleanrooms [43].
10	Cranfield University	Academia	General lab and workshop facilities, i.e. clean-room facilities, vacuum chambers. Specialist facilities relevant to Space include the Ballistics and Combustion Laboratory, Characterisation and Ageing Laboratory, Synthesis and Formulation Laboratory and Thermo-Mechanical Laboratory [44]. Cranfield also have built Astra-Lab which replicates the conditions of space to simulate working in free floating conditions [45].

Facility Map Number	Facility Owner	Organisation Type	Facility Description
11	The Open University (OU)	Academia	ISRU facilities for: the extraction of oxygen from lunar regolith by reduction of ilmenite and other metal oxides; microwave heating of extraterrestrial materials for extraction of volatiles. Analytical instruments for analysing feedstock and products of ISRU processes, e.g. various microscopes, mass spectrometry systems. Thermal vacuum facilities for testing hardware and processes; thermal vacuum chamber equipped with sensitive microbalance to measure the mass loss/gain of milligram quantity samples in simulated space conditions [46].
12	University of Oxford	Academia	Laboratory facilities; spaceflight hardware design, test and build facilities [47].
13	Naicker Scientific Ltd	Industry	Hardware prototyping, assembly and testing facilities.
14	Magdrive	Industry	DEEP lab - cleanrooms, vacuum chambers, plasma diagnostics for EP, electrical test facilities, machine shop with 5 axis CNC and 3D printers [48].
15	Science and Technology Facilities Council (STFC)	Public Body	Rutherford Appleton Laboratory (RAL): National Satellite Test Facilities; clean rooms; spacecraft services post-launch support; high powered lasers: VULCAN, EPAC, ISIS neutron spallation facility, DIAMOND light source [49].
16	Orbit Fab Ltd	Industry	Fluidic testing (proof and leak); Air-bearing table for docking simulation; Vacuum chamber.
17	University College London (UCL)	Academia	Environmental Sedimentology Facility: advanced labs for sediment analysis, flume experiments & imaging, supporting research on sediment transport, stratigraphy & earth processes [50]. RIPL (The Rock & Ice Physics Laboratory) Facilities and Equipment [51]. Clean rooms; thermal vacuum chamber; vibration facility [52].
18	Imperial College London	Academia	Lab space, clean rooms, vacuum chambers [53]; mineral processing equipment, advanced material characterisation technologies (e.g. size classification, micro-CT, SEM) [54].
19	Foster + Partners	Industry	Material Research Centre [55].
20	Centre for Modelling and Simulation (CFMS)	Industry	Collaborative Space Data Centre (COSDAC) [56].
21	University of Surrey	Academia	A lab space for lunar construction and In-Situ Resource Utilisation [57]. Plans to build a bespoke microwave and 3D Printing equipment.

4.4 UK Capabilities Map

In this report, a “capability” is defined as a function, skill or competency that enables and/or supports the development of ISRU technology; for example, this can refer to people, processes, software or tools. From the survey and workshop, 16 UK capability owners were identified and have been mapped below in Figure 10; the numbered markers correspond to capability owners, which are described in further detail in Table 3.

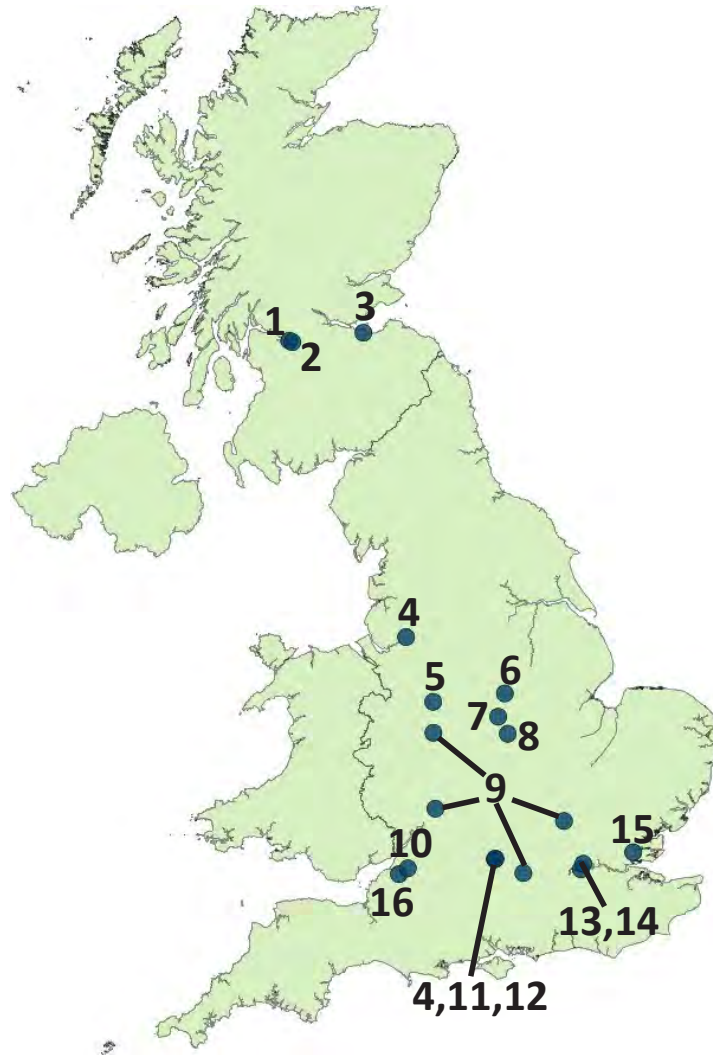


Figure 10: Locations of UK ISRU capabilities in the UK (blue dots).

Table 3: UK ISRU capabilities identified in the UKSA ISRU survey and Technology Review Workshop. The “Capability Map Number” corresponds to the capability numbers plotted on the map in Figure 10.

Capability Map Number	Capability Owner	Organisation Type	Capability Description
1	University of Glasgow	Academia	Diagnostics and modelling capability; Direct simulation Monte Carlo (DSMC) multiphase solvers.
2	University of Strathclyde	Academia	Expertise in Astrophysical Plasma, High Voltage Engineering and Pulsed Power Technology.
3	Neowatt	Industry	Space energy simulation software.
4	Amentum	Industry	Robotics (including space robotics); Space systems engineering; Materials science testing and modelling
5	Lucideon	Industry	Range of analysis and evaluation capabilities, including high temperature and cryogenic mechanical testing capabilities alongside end-to-end processing facility. Technology platforms include additive manufacturing technologies and Flash Sintering development for Regolith ISRU application.
6	OrbitRise	Industry	Space systems, automation and mission control.
7	Third Planet Orbital Ltd	Industry	Authored parts of ESA ISRU Study.
8	Meridian Space Command	Industry	Mission leadership, operations, and systems integration (Mission Control Centre at Space Park Leicester).
9	Moog	Industry	High-performance precision motion and fluid control/control system designer and integrator.
10	Frazer-Nash Consultancy	Industry	Systems, engineering and technology consultancy with relevant experience in plasma processing, process plant design, terrestrial and Space engineering.
11	STFC	Public Body	Spacecraft Services; Post-Launch Support.
12	Orbit Fab Ltd	Industry	In-house machining for some valve parts and seals.
13	University College London (UCL)	Academia	Transferable mining and excavation expertise.
14	Foster + Partners	Industry	Specialist Modelling Capabilities – focusing on extra-planetary habitation, robotic fabrication, and 3D printing.
15	Powerstax	Industry	Industrial Power Supplies – customisable to support ISRU lab-based testing.
16	Centre for Modelling and Simulation (CFMS)	Industry	Large Robotics and AI Simulator (LARS Sim).

4.5 Summary

Survey and workshop participants were from academia, industry and public bodies, with most participants representing small to medium sized enterprises. The key findings from the survey and workshop were as follows:

- ▶ There is a strong focus on lunar-applicable technology development across both academia and industry. This aligns with the current priorities of NASA and ESA, both of which have established lunar programmes that include defined ISRU objectives, creating the most immediate opportunities for technology developers.
- ▶ The survey revealed that UK technology developers were active across multiple ISRU functions rather than concentrating on one single area of development.
- ▶ For the technologies identified in the survey, the TRL distribution forms a characteristic ‘valley of death’ pattern when plotted (Figure 8), with a noticeable decline in UK technologies at TRL 5 and above.
- ▶ The main technology development blockers highlighted by respondents were a lack of available funding and difficulties in accessing the appropriate testing facilities.
- ▶ During the workshop, it was raised that the majority of ISRU or ISRU-applicable facilities in the UK could be exploited further through improved collaboration and awareness. This highlights a practical, near-term opportunity to accelerate ISRU technology development in the UK.

5 Technology Overview and Function Mapping

This report has prioritised ISRU technologies which the UK could capitalise on in the next 10 years. This is in-line with the approach taken in a similar study carried out in 2021 by the International Space Exploration Coordination Group. This study recognised that not every option can be developed and prioritised those that have the greatest influence on mission cost and success, particularly for nearer term missions. This identified that lunar mission consumables including propellants, fuel cell reactants, life support commodities (e.g. oxygen from regolith, water from PSRs) had the highest near-term impact – noting that lunar ISRU would inform future Mars ISRU [3]. The Gap Assessment Report focussed on Strategic Knowledge Gaps (SGKs) relating to the themes of understanding *Lunar Resource Potential* and *How to Work and Live on the Lunar Surface*, dividing ISRU into 5 major categories based on the critical ISRU functions and projects of: Polar Water, Solar Wind Volatiles, Oxygen from Regolith, Construction and Manufacturing, ISRU Operations.

The following sections (5.1 to 5.3.25.4) contain information on technologies relevant to each function and sub-function, in the form of technology summary ‘cards’. Not all functions and sub-functions shown in the Roadmapping Tool dashboard are included – only those with UK owned technologies to aid the illustration of capabilities.

Note that the technology readiness level for each capability noted on the cards was correct at the time of writing.

5.1 Prospecting

5.1.1 Orbital Volatile & Mineral Mapping and Characterisation

Orbital volatile and mineral mapping and characterisation is the initial stage for detecting volatile compounds and minerals from orbital platforms on and around planetary bodies, such as the Moon, Mars and asteroids.

Examples of volatiles directly detected within regolith by orbital instruments include ice water (H₂O), hydroxyl (-OH) and hydrated minerals such as clays and sulfates that incorporate structurally bound water. In atmospheres, detections include carbon dioxide (CO₂), methane (CH₄), and sulfur dioxide (SO₂).

Examples of mineral groups that can be identified via orbital spectroscopy and imaging include silicates (e.g., olivine, pyroxene), feldspars, oxides such as ilmenite and magnetite, and minerals containing iron, titanium, aluminium, and silicon. On the Moon and asteroids, high-resolution multispectral and hyperspectral datasets allow mapping of basaltic, anorthositic and metal-rich terrains, while on Mars they reveal alteration products such as clays, carbonates, and sulfates that record past aqueous environments.

By mapping regolith-hosted volatiles, atmospheric gases and the distribution of mineral resources, orbital remote sensing distinguishes resources that can be extracted directly and those requiring chemical or thermal liberation. This activity supports ISRU by guiding mission planners toward sites with the highest potential for sustainable utilisation.

Technology: Lunar thermal mapper (LTM)
Developers: University of Oxford, NASA
Technology Description: Infrared remote sensing for mineral (e.g. silicic compositions, Mg-spinel lithologies, mantle exposures, and irregular mare patches) mapping and analysis
Notes: LTM was launched aboard NASA's Lunar Trailblazer mission in 2025; however, the instrument could not be demonstrated due to loss of contact with the spacecraft shortly after launch [1]. The development team are exploring opportunities to fly the flight spare on a future mission to recover the intended science.

[2]



TRL: 7



7

[1] <https://science.nasa.gov/mission/lunar-trailblazer/>
[2] <https://www.jpl.nasa.gov/images/pia25831-lunar-trailblazers-thermal-mapper-has-arrived-at-lockheed-martin/> [Image Credit: University of Oxford]

5.1.2 Local Volatile & Mineral Characterisation

Local volatile characterisation is the follow-on stage from orbital mapping, in which volatile compounds and mineralogical compositions are directly measured on or below the surface of a planetary body using lander and/or rover-based instruments. Volatile characterisation determines the presence, form and distribution of volatiles within the upper regolith (such as water ice, hydroxyl-bearing minerals, carbon dioxide frost and gases released during heating). Mineral characterisation quantifies key mineral groups forming the regolith (including mafic silicates, oxides, and alteration minerals such as clays, carbonates and sulfates). By ground-truthing orbital observations and capturing small-scale variations across a landing site, local volatile characterisation clarifies which resources can be extracted directly from regolith and which would require more intensive processing. This activity supports the selection of sites with strong potential for sustainable utilisation.

Technology: ProSPA Developers: The Open University (OU), STFC RAL Space, ESA Technology Description: A miniature sample analysis laboratory designed to determine the chemical composition of subsurface lunar volatiles, such as water ice. It integrates a multispectral 3D camera and two mass spectrometers to analyse gases released from heated regolith samples, alongside a gas processing system for the physical and chemical separation of gases. The system is also capable of hydrogen reduction by heating regolith, reducing metal oxides to produce water [1]. Part of ESA's PROSPECT suite for lunar resource prospecting, ProSPA works in tandem with the ProSEED drill (developed by Leonardo), which retrieves cryogenic samples from depths of up to 1 m and delivers them to ProSPA via carousel for analysis [2]. Notes: ESA's PROSPECT payload is scheduled to reach the lunar south pole in 2027 via the Intuitive Machines' Nova C-Lunar lander as part of a NASA Commercial Lunar Payload Services (CLPS) program [3][4].	 <i>ProSPA subsystem that receives and images samples with a multispectral 3D camera before sealing them in the oven for heating. [5]</i>	TRL: 6  15
[1] H. M. Sargeant, "Hydrogen reduction of lunar samples in a static system for a water production demonstration on the Moon", <i>Planet. Space Sci.</i>, 205 (2021) [2] R. Trautner et al., "PROSPECT: A comprehensive sample acquisition and analysis package for lunar science and exploration", <i>Front. Space Technol.</i>, 5 (2024) [3] https://www.esa.int/Science_Exploration/Human_and_Robotic_Exploration/Prospect_searching_for_water_at_the_lunar_poles [4] https://www.nasa.gov/news-release/nasa-awards-intuitive-machines-lunar-south-pole-research-delivery/ [5] https://www.ralspace.stfc.ac.uk/Pages/prospa-secures-nasa-ride-to-the-moon.aspx [Image Credit: The Open University]		

Technology: Peregrine Ion Trap Mass Spectrometer (PITMS) [1][2] Developers: The Open University (OU), STFC RAL Space, ESA (ESTEC), NASA (Goddard Space Flight Center) [3] Technology Description: A compact ion trap mass spectrometer developed to analyse the composition of the lunar exosphere. PITMS detects and characterises volatile species, such as water and trace gases, with high precision. Notes: PITMS launched on the 8th of January 2024 aboard Astrobot's Peregrine Lunar Lander, NASA's first CLPS mission. Though the lander failed to reach the lunar surface due to a propulsion leak, PITMS operated successfully in cis-lunar space for 10 days, collecting 80 high-quality spectra and detecting outgassing products from the lander including water, MON-25 oxidizer, and trace combustion compounds.	[3] 	TRL: 9    18
[1] https://www.nasa.gov/news-release/nasa-science-astrobot-peregrine-mission-one-concludes/ [2] B. A. Cohen et al., "The Peregrine Ion Trap Mass Spectrometer (PITMS): Results from a CLPS-delivered Mass Spectrometer", <i>Planet. Sci. J.</i>, 6 (2025) [3] https://science.nasa.gov/lunar-science/clps-deliveries/to2-astrobot/#PITMS [Image Credit: NASA]		

Technology: EMS-L (Exospheric Mass Spectrometer for LUPEX) [1][2] Developers: The Open University (OU), RAL Space, ESA Technology Description: A miniature ion trap mass spectrometer designed to detect and analyse volatile compounds in the lunar polar environment. Intended for deployment on the LUPEX rover, EMS-L will operate alongside a subsurface drill to study volatiles, such as water, released from the regolith. Notes: EMS-L builds on the heritage of the Peregrine Ion Trap Mass Spectrometer (PITMS) and is being developed for JAXA and ISRO's LUPEX mission, which will explore the lunar south polar region for water and other volatiles. LUPEX launch is planned no earlier than 2028.	16 TRL: 5-6  
[1] J. D. Cole et al., "The Exploration Mass Spectrometer for LUPEX (EMS-L): Simulations of Detecting Volatiles at the Lunar Poles", <i>The European Lunar Symposium (ELS) 2025</i>, 22-27 Jun 2025, Münster, Germany [2] https://humans-in-space.jaxa.jp/en/biz-lab/tech/lupe/x/	

5.2 Excavation

5.2.1 Regolith & Icy Regolith/Volatiles Excavation, Transfer and Handling

“Regolith, icy regolith and volatiles excavation, transfer and handling” cover the mechanical activities required to collect surface and sub-surface material and deliver it to downstream systems. This includes breaking into compacted soil or ice-rich layers using tools such as scoops, augers, bucket wheels and drills, extracting material, and transferring it to storage, processing units or chemical analysis instruments. As icy regolith can fracture, adhere to tooling or sublimate when disturbed, excavation and transfer systems must manage material fragmentation, acquisition and transport to minimise losses and preserve sample integrity. This enables consistent, predictable delivery of bulk material to downstream processing systems.

Technology: DIGGER: Directed Energy Drilling for Lunar and Asteroid Applications

Developers: STFC RAL Space, University of Strathclyde (UK), UK Atomic Energy Authority (UKAEA), SJE Space
Technology Description: A project developing advanced directed-energy drilling technologies for use on the Moon and asteroids. DIGGER explores two complementary methods: pulsed plasma discharge drilling for penetrating porous rock, and microwave drilling to heat, melt, or fracture regolith and rock without physical contact or transferring mechanical torque to the spacecraft [1][2].

Notes: Funded through the UKSA National Space Innovation Programme (NSIP). The current phase supports early development, with follow-on funding required to progress toward prototype-level demonstrations in lunar-like environments such as vacuum facilities or regolith simulants.

TRL: 3



3

[1] R. Bamford et al., “DIGGER Drilling and Integrated GigaHertz-Generated Energy Resource for Lunar and Asteroid Applications”, Reinventing Space Conference 2024, 11-13 Nov 2024, London, UK
 [2] R. Bamford et al., “A Space Age Drill: DIGGER- Drilling and Integrated GigaHertz-Generated Energy Resource for Lunar and Asteroid Applications”, The European Lunar Symposium (ELS) 2025, 22-27 Jun 2025, Münster, Germany

Technology: Mobile Lunar Excavation and Size Separation System (MoLES³): Robotic Platform Sub-System
Developer: Amentum, University of Manchester

Technology Description: A mobile robotic platform integrating a rover, a semi-autonomous excavation manipulator, and the LES³ end-effector. Building upon the earlier LES³ system [1], it enables remote excavation and transport of lunar regolith to downstream processing units as part of the MoLES³ architecture.
Notes: The robotic platform is the mobile front-end of MoLES³, an integrated system for acquiring lunar regolith and separating it into two size fractions. MoLES³ was demonstrated at the 2025 ESA Space Resources Challenge at the ESA LUNA facility at the EAC in Cologne in October 2025 [2], where the platform demonstrated its ability to deliver the excavation forces required for lightweight robotic systems operating under limited traction conditions.

[3]



TRL: 4



11

[1] G. H. Just et al., “Development and test of a Lunar Excavation and Size Separation System (LES3) for the LUVM-X rover platform”, J FIELD ROBOT, 39 (2022)
 [2] <https://src.esa.int/cradle/>
 [3] https://www.esa.int/ESA_Multimedia/Images/2025/10/Team_CRADLE_-_Space_Resources_Challenge_2025 [Image Credit: ESA/DLR - R. Barbosa]

Mission/Project Name: Pulse Elevator

Developer: University of Glasgow

Technology Description: A non-rotating, solid-state drilling and material-uplift mechanism that uses vertical oscillation to transport granular material along the device. Its internal geometry, which uses alternating opposing scoops inspired by fluidic Tesla-valve designs, allows regolith to move preferentially upward with each vibration cycle. The simple harmonic motion removes torque and reduces mechanical complexity compared with traditional augers [1] [2].

Notes: Demonstrated to penetrate beads, rock dust, regolith simulant, volcanic tuff, and foam-concrete, and shown to operate reliably in vacuum without choking. The Pulse Elevator offers a low-footprint alternative to conventional augers for lunar drilling and terrestrial granular-handling applications.

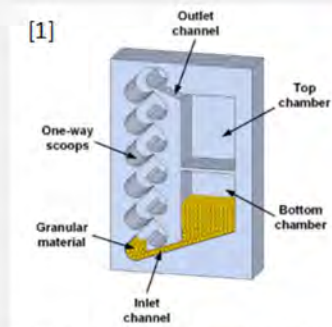


Fig. 1. A pulse-elevator test piece, which is vibrated in the vertical direction to pump the particles upwards.

TRL: 4



19

[1] Image Credit: University of Glasgow
The pulse-elevator: A pump for granular materials, X Li et al, 2022
[2] Space Exploration Technology Roadmap, UK Space Agency, 2023

5.3 Beneficiation

5.3.1 Mineral Separation

Mineral separation uses selective mechanical and physico-chemical processes that isolate resource-bearing mineral grains in regolith prior to chemical processing. Mineral separation systems exploit differences in electrical, magnetic, or compositional properties to distinguish useful grains from inert, low value material. Techniques such as electrostatic mineral enrichment, magnetic separation, and optical or spectral discrimination apply these contrasts to classify and extract specific material fractions. Effective mineral separation increases the proportion of high-value feedstock delivered to processing systems thereby reducing downstream processing demand.

Technology: Electrostatic Mineral Enrichment
Developer: Imperial College London
Technology Description: A dry, low-power beneficiation technique that uses tribocharging and free-fall electrostatic separation to differentially charge and deflect particles, enabling composition-based sorting of lunar regolith [1].
Notes: Currently demonstrated at laboratory scale under Earth conditions, with next steps focused on vacuum and reduced-gravity testing. Once developed, the technology could be integrated into future ISRU systems as a pre-processing step for oxygen and metal extraction from lunar regolith and adapted for dry beneficiation of anhydrous terrestrial ores in water-constrained settings.

[1] J. N. Rasera et al., "Experimental investigation of an optimised tribocharger design for space resource utilisation", *Planet. Space Sci.*, 228 (2023)
[Image Credit: Imperial College London]

1

TRL: 4

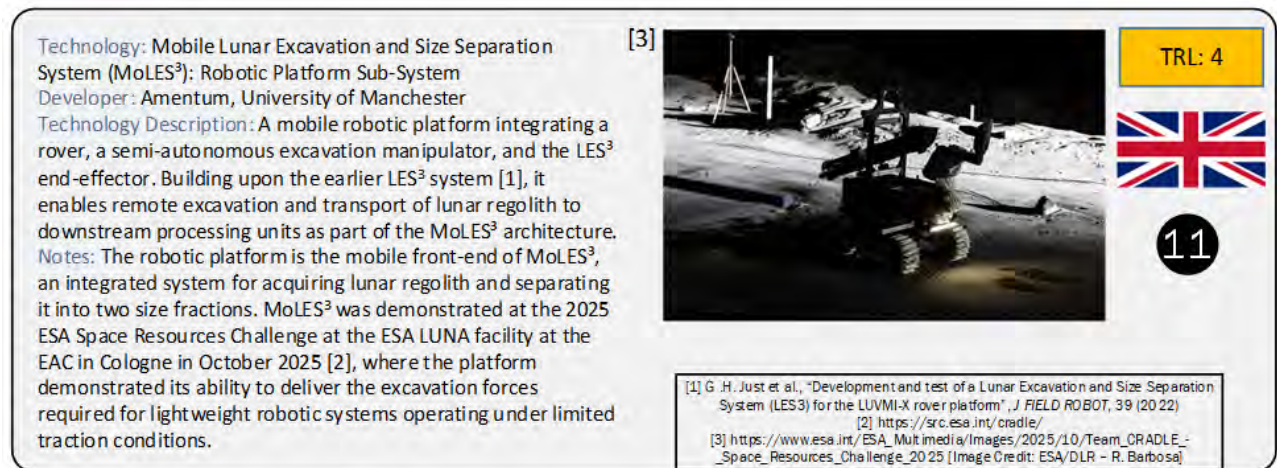
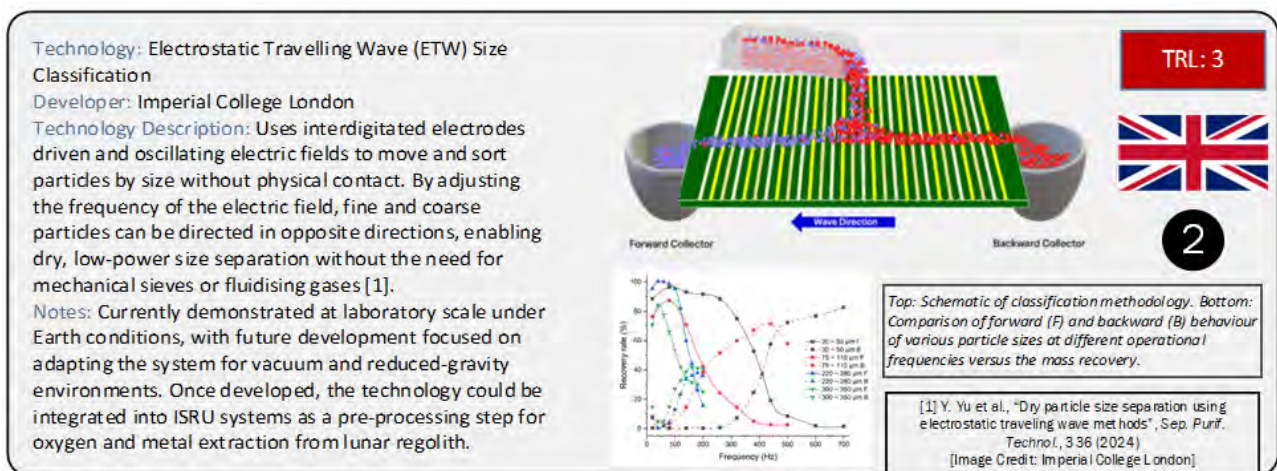


Left: Free-fall electrostatic separator. Right: influence of optimised charging system on separation performance of silica and ilmenite.



5.3.2 Size Sorting

Size sorting separates unprocessed regolith into defined particle-size fractions using mechanical and electrostatic size classification processes. These systems remove oversize clasts, isolate fines and produce more uniform feedstocks for downstream processing that improve flowability, feed-rate control and equipment performance. Techniques such as vibratory or rotary sieving and aerodynamic or gravitational classification sort particles solely according to size-dependent motion and transport behaviour, while electrostatic traveling wave separation operates predominantly as a size-based classifier but may exhibit secondary sensitivity to mineral-dependent electrical properties. Effective particle size sorting stabilises material properties, reduces handling variability and ensures that downstream processing systems receive feedstocks matched to their operational requirements.

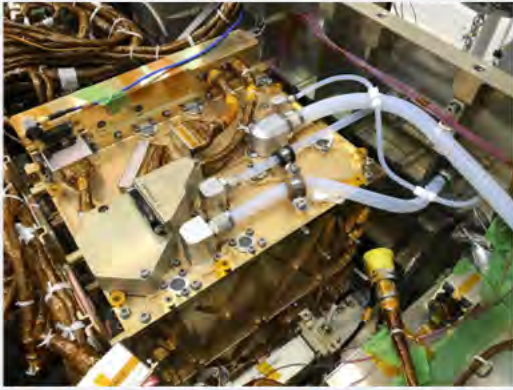


5.4 Processing

5.4.1 Atmospheric Gas Extraction & Processing

Atmospheric gas extraction and processing involve capturing ambient atmospheric gases and converting them into useful resources such as oxygen, nitrogen and carbon-based feedstocks. The gas extraction subsystem draws in the surrounding atmosphere, removes particulates, and regulates pressure, temperature and flow rate to deliver a stable, conditioned gas stream. The processing subsystem isolates target species such as carbon dioxide, nitrogen, argon, methane, or trace volatile compounds. Depending on the environment, separation may be achieved through cryogenic freezing, chemical absorption, pressure-swing adsorption, membrane filtration, or catalytic conversion.

Technology: MOXIE (Mars Oxygen ISRU Experiment) [1][2]
Developer: NASA
Technology Description: A small-scale solid-oxide electrolysis system that extracts CO₂ from the Martian atmosphere and splits it into CO and O₂ to demonstrate in-situ oxygen production [3].
Notes: Was operational on the Perseverance Mars Rover between 2021 and 2023, where it generated a total of 122 grams of oxygen (i.e. roughly the amount a small dog breathes in 10 hours) [2].



TRL: 9

NASA

[1] <https://science.nasa.gov/mission/mars-2020-perseverance/science-instruments/>
[2] <https://www.nasa.gov/missions/mars-2020-perseverance/perseverance-rover/nasas-oxygen-generating-experiment-moxie-completes-mars-mission/>
[3] <https://science.nasa.gov/resource/moxie-all-tucked-in/> [Image Credit: NASA/JPL-Caltech]

1

¹ Note: MOXIE is not a UK-developed technology but has been included in this report as the first ISRU in-Space demonstration.

5.4.2 Water Extraction from Icy Regolith

Water extraction from icy regolith recovers water bound within ice-rich soil and separates it from the surrounding solids for use in subsequent processing steps. The water extraction subsystem uses techniques such as microwave heating, staged thermal extraction or ultrasonic agitation to release water bound within the regolith. The processing subsystem then captures the resulting vapour or liquid and manages phase changes to produce a stable, conditioned water stream. This ensures that downstream processing systems receive water with consistent physical properties.

Mission/Project Name: Static Water Extraction System (SWES)

Developer: Interstellar Mapping Ltd

Technology Description: A static water extraction system designed to recover water and other volatiles from icy lunar regolith using staged heating. Volatiles that sublime at low temperatures are captured first, followed by water steam which is condensed and stored. SWES operates without moving parts using pressure seals and heaters, enabling long-duration operation with minimal maintenance [1].

Notes: SWES has been validated at breadboard level in a relevant environment.

TRL: 5



4

[1] <https://www.gov.uk/government/news/uk-space-agency-awards-ten-technologies-to-purify-water-frozen-in-moons-soil>

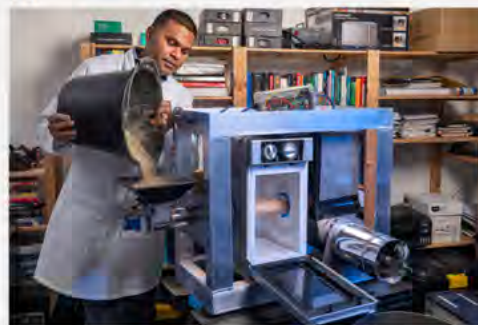
Technology: SonoChem System [1] [2]

Developer: Naicker Scientific Ltd

Technology Description: A compact, energy-efficient system that uses ultrasonic microbubbles to purify water in melted lunar ice. The microbubbles generate intense heat and pressure, breaking down contaminants to produce drinkable water for life support.

Notes: Proof of concept demonstrated at lab scale, with next steps focused on developing a spin-off system and advancing it to TRL 5 for an in-orbit demonstration. Winner of the UK track of the Aqualunar Challenge [1].

[1]



TRL: 3



6

[1] <https://challengeworks.org/news/aqualunar-challenge-winners/>
[Image Credit: Max Alexander/Aqualunar Challenge]
[2] <https://challengeworks.org/news/introducing-the-10-aqualunar-finalist-teams/>

5.4.3 Oxygen, Metal & Silicon Extraction and Water Generation from Regolith

Oxygen, metal & silicon extraction and water generation from regolith converts the oxide-rich minerals in lunar or Martian soil into useful products through high-temperature chemical and electrothermal reduction. Key methods include electrolysis processes (e.g. molten-salt electrolysis, molten-regolith electrolysis and low temperature ionic liquid electrolysis), solid-oxide ion-transport, hydrogen plasma reduction and conventional hydrogen reduction of metal oxides (both of which produce water vapour), carbon monoxide reduction, carbothermal reduction and vacuum pyrolysis. Depending on the technique, these processes can yield products such as oxygen, water, metals – including iron, titanium and aluminium – and a range of silicon species that support downstream ISRU activities such as propellant production, manufacturing, construction and life support.

Technology: Microwave Heating Demonstrator (MHD)[1] Developers: Surrey Space Centre (University of Surrey), The Open University (OU), Added Value Solutions, UK Ltd. Technology Description: An integrated system designed to demonstrate microwave heating as a dual-purpose process for producing structural materials and extracting oxygen, water, and metals from lunar regolith. At its core is the MARVEL subsystem (Microwave heating Apparatus for Regolith Variant Experiments for Lunar ISRU), a microwave generator developed to investigate the heating behaviour of different regolith types. The full system includes a sealed reaction chamber, crucible array, volatile analysis unit (based on ProSPA heritage), and a non-destructive mechanical assessment module. Notes: Upcoming development will focus on measuring the yield of volatiles from mare and highland regolith, demonstrating the fabrication of dense structural materials, and verifying oxygen and water extraction using hydrogen-reduction and methane-carbothermal processes in sealed microreactors under simulated lunar conditions.	5  TRL: 4-5 [2]  CAD model of the MHD payload [1] S. Lim et al., "Challenges in the microwave heating of lunar regolith – Analysis through the design of a microwave heating Demonstrator (MHD) payload", <i>Adv. Space Res.</i>, 69 (2022) [2] [Image Credit: University of Surrey, The Open University, Added Value Solutions, UK Ltd.]
Technology: ISRU-DM/ Molten Salt Electrolysis (FFC) Oxygen Extraction from Regolith Developers: OHB Space UK, Metalysis Ltd, University of Glasgow, The Open University, University of Leicester, AVS, ESA Technology Description: A molten salt electrolysis process adapted from an established industrial method used for large-scale metal production on Earth [1]. It is designed to extract oxygen and produce metals alloys from lunar regolith [2]. Notes: The Metalysis-FFC process was demonstrated in an initial proof-of-concept study, where it achieved 96% oxygen extraction from lunar regolith simulant and produced a mixed metal alloys suitable for in-situ manufacturing [3][4]. Ongoing development aims to adapt the process for lunar conditions, supporting future missions by enabling local production of oxygen for life support and propulsion, and metals for construction and components for solar panel manufacture.	5  TRL: 4  ESA 10 [1] https://metalysis.com/our-technology/ [2] https://www.esa.int/Space_in_Member_States/United_Kingdom/Oxygen_and_metal_powder_extracted_from_moonrocks [3] B. A. Lomax et al., "Proving the viability of an electrochemical process for the simultaneous extraction of oxygen and production of metal alloys from lunar regolith", <i>Planet. Space Sci.</i>, 180 (20 20) [4] https://www.ion3.org/resource/metalysis-gets-esa-development-contract-for-ffc-process.html [5] https://www.esa.int/Enabling_Support/Space_Engineering_Technology/ESA_opens_oxygen_plant_making_air_out_of_moon_dust [Image Credit: Beth Lomax, University of Glasgow]

2

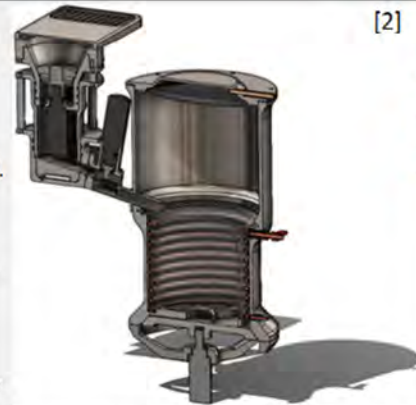
² Note: Image is from an earlier activity conducted by ESA, Metalysis, and the University of Glasgow (Networking/Partnership Initiative: NPI 599 -2018).

Technology: HyPER (Hydrogen Plasma Extraction from Regolith)

Developer: Frazer-Nash Consultancy

Technology Description: HyPER is an oxygen extraction from regolith system utilising hydrogen plasma. This plasma is formed of excited hydrogen ions and electrons which have thermodynamic and kinetic advantages to molecular hydrogen, increasing reactivity with regolith [1]. When this hydrogen plasma interacts with the regolith, it breaks the chemical bonds in the metal oxides, freeing oxygen atoms and forming water vapor. The water can then be collected and electrolysed to separate the oxygen for use in life support systems or rocket fuel, while the remaining metals may be repurposed for construction or manufacturing.

Notes: Frazer-Nash Consultancy funded HyPER Lunar demonstrator concept design and accompanying chemical and cost models to optimise the yield of ISRU oxygen produced per kg of launch payload.



[2]

TRL: 2



13

[1] E. Petersen et al., "Hydrogen Plasma Reduction" (2021)
[Document link: <https://ntrs.nasa.gov/citations/2021024442>]
[2] [Image Credit: Frazer-Nash Consultancy Ltd]

Technology: RIPPLE (Regolith Ice Plasma Purifier for Lunar Exploration) [1][2]

Developer: Regolithix Ltd

Technology Description: A fully autonomous system that extracts oxygen and hydrogen from dirty lunar ice mixed with regolith. Ice is first vaporised, then solids are removed using a vortex separator. The cleaned vapour passes through a plasma torch and is split into hydrogen and oxygen, which are then captured using a molecular sieve. RIPPLE is designed to be scalable and adaptable and supports both life support and rocket fuel production on the lunar surface.

Notes: RIPPLE has been functionally tested, with next steps focused on breadboard development and environmental testing at external facilities



Plasma generating unit currently used for RIPPLE breadboard testing [3]

TRL: 4



14

[1] <https://www.regolithix.com/copy-of-ripple>
[2] <https://challengeworks.org/news/introducing-the-10-aqua-lunar-fire-list-teams/>
[3] [Image Credit: Regolithix Ltd]

5.4.4 Regolith Conditioning

Regolith conditioning encompasses the mechanical and thermal transformation of regolith to prepare it as a stable, predictable feedstock for downstream construction, manufacturing, and chemical extraction processes. Regolith conditioning involves changing key physical properties such as density, porosity, cohesion and microstructure, which is achieved through processes such as sintering, thermal pre-conditioning, compaction, pelletising and homogenisation.

Technology: Densification of Lunar Regolith via Flash Sintering [1]
Developer: Lucideon Ltd
Technology Description: An advanced Sintering technique that applies an electric field with precise, real-time control to a ceramic body, enabling rapid densification of lunar regolith simulants. The resulting densified material can be used for construction or as porous structures to support oxygen extraction. With no requirement for applied pressure or binder use, it offers reduced furnace temperatures, 40% faster processing times and 50% energy reduction compared to conventional sintering. Microstructural control has also been demonstrated relative to other sintering techniques.
Notes: Flash Sintering has demonstrated its feasibility for sintering lunar regolith for ISRU structural materials at laboratory scale under Earth conditions. Future development will focus on simulating the process in lunar vacuum, scaling up sample size and geometry for mechanical testing, and performing detailed characterisation of the sintered microstructure.

Top: 20 mm diameter x 5 mm height EAC-1A pellet [2]
Bottom: Flash Sintering scale-up furnace [2]



TRL: 3-4



8



[1] <https://www.lucideon.com/technologies/flash-sintering>
[2] [Image Credit: Lucideon Limited]

5.4.5 Post-Processing Metals

Post-processing of ISRU-derived metals refers to the suite of technologies used to refine, condition, and transform metallic materials after they have been extracted. These processes improve purity, tailor microstructure, produce usable intermediate forms, and prepare metals for downstream manufacturing, construction, or chemical applications. Post-processing encompasses physical, thermal, mechanical, and chemical treatments designed to achieve mission-ready metal feedstocks in challenging off-Earth environments.

Project: Horizon DEXTER
Developer: Magdrive, Cranfield University
Technology Description: Multiple technologies that convert in-situ or recycled metals (such as aluminium from end-of-life satellites or spent rocket stages) into reusable resources for space applications, such as reusable propulsion [1]. By enabling spacecraft to utilise locally sourced or recovered materials, the system aims to support longer missions and reduce the need to launch consumables from Earth.
Notes: The DEXTER project includes lab-based demonstrations of robotic harvesting tools, laser cutting and welding in a vacuum, and conversion of scrap aluminium into fuel for a prototype thruster [1]. Magdrive's high-thrust electric propulsion systems use solid metals (such as aluminium, copper, iron and nickel) converted into plasma to generate thrust. This concept was successfully demonstrated in space by Magdrive with their first metal-propelled thruster in June 2025 [2] [3]. The consortium plans to mature the technology to TRL 4 by 2029, integrating it with robotic tooling and the next-generation SuperMagdrive platform.

A concept image of Magdrive's large, refuellable SuperMagdrive developed under the DEXTER project [4]



TRL: 2



9



[1] <https://cordis.europa.eu/project/id/101223360>
[2] <https://www.bbc.co.uk/news/articles/c14e8d30jmr0>
[3] <https://www.ukspace.org/mag-drive-launches-first-flight-of-next-generation-plasma-thruster/>
[4] [Image Credit: Magdrive]
[5] <https://dexter-space.eu/> [Image Credit: Dexter Consortium]

6 Process Roadmapping Tool

This section outlines how to use the Process Roadmapping Tool developed in this project. As outlined in earlier sections, it is not an exhaustive list of relevant technology areas within the ISRU technology realm; instead, the tool deals only with UK owned technologies for the purposes of this UK technology review.

The Process Roadmapping Tool is a visual framework designed to support a range of ISRU stakeholders, from national programmes assessing their strategic position to technology developers analysing where their solution fits within the wider system. Users begin by selecting an ISRU objective – such as producing oxygen, extracting water, or manufacturing construction materials – and then build the sequence of steps required to achieve it using a set of cards that each describe one of the required functions (see Section 6.2 for further details). Once this chain of functions has been built, technology cards (see Section 5) can be placed under each function to show how the pathway could be implemented. This allows agencies to understand how their national capabilities compare globally and enables developers to see which upstream technologies their own solution depends on, which downstream steps it must feed into, and how it compares with alternative approaches currently in development worldwide.

This section provides a practical user guide for the Roadmap Tool and covers the following:

1. **ISRU Sub-Function Cards:**
High level detail for sub-functions that are needed at each stage, including indications of relevance to key objectives such as producing oxygen.
2. **Process Roadmapping Tool:**
A visual depiction of all elements of ISRU processing, split into five ISRU functions presented as “rows”, with sub-function cards placed within each lane.
3. **Roadmap Tool Worked Example:**
A step-by-step worked example showing users how to use the tool to build an ISRU functional chain, position technologies within it, and interpret the results.

6.1 Process Roadmapping Tool: ISRU Sub-Function Cards

For this tool, we have grouped by function and not by technology. This means that each card on the tool covers a single sub-function, which can relate to multiple technologies. It is also possible that technologies may be applicable across multiple cards. An example of an ISRU sub-function card from the Roadmap Tool is given in Figure 11.

Each card has the following four features:

► **The name of the ISRU sub-function**

The card presented in Figure 11 is for the sub-function “Orbital Volatile Mapping & Characterisation”, which belongs to the ISRU function “Prospecting”.

► **The resource that is applicable to that function**

The icons indicate the type of resource: the bubbles icon represents gas (e.g. oxygen, methane), a droplet represents water and a crane represents construction materials.

A green icon shows that the resource is applicable to the sub-function, whereas a grey icon indicates it is not.

The resource icons on the card in Figure 11 show that ISRU sub-function “Orbital Volatile Mapping & Characterisation” applies to gas and water resources but not construction materials.

► **The overall technology readiness level (TRL) for NASA, the UK and ESA**

The TRL is represented using a Red-Amber-Green (RAG) gradient, e.g. Figure 11 shows that the TRL ranges for technologies within the “Orbital Volatile Mapping & Characterisation” subfunction are TRL 9 for NASA and the UK and TRL 6-7 for ESA. Note that the analysis of NASA and ESA capabilities were conducted internally and supplied to the UK Space Agency independently of this report.

► The ID of UK technologies that fall under the ISRU sub-function named on the card

Each UK ISRU technology identified in the survey has been assigned a unique ID; see Table C 1 (Annex C) for technology descriptions. By adding the unique IDs applicable to the sub-functions, the Roadmapping Tool supports understanding around the types of technologies referenced at this stage and will support the user in associating links to other dependencies.

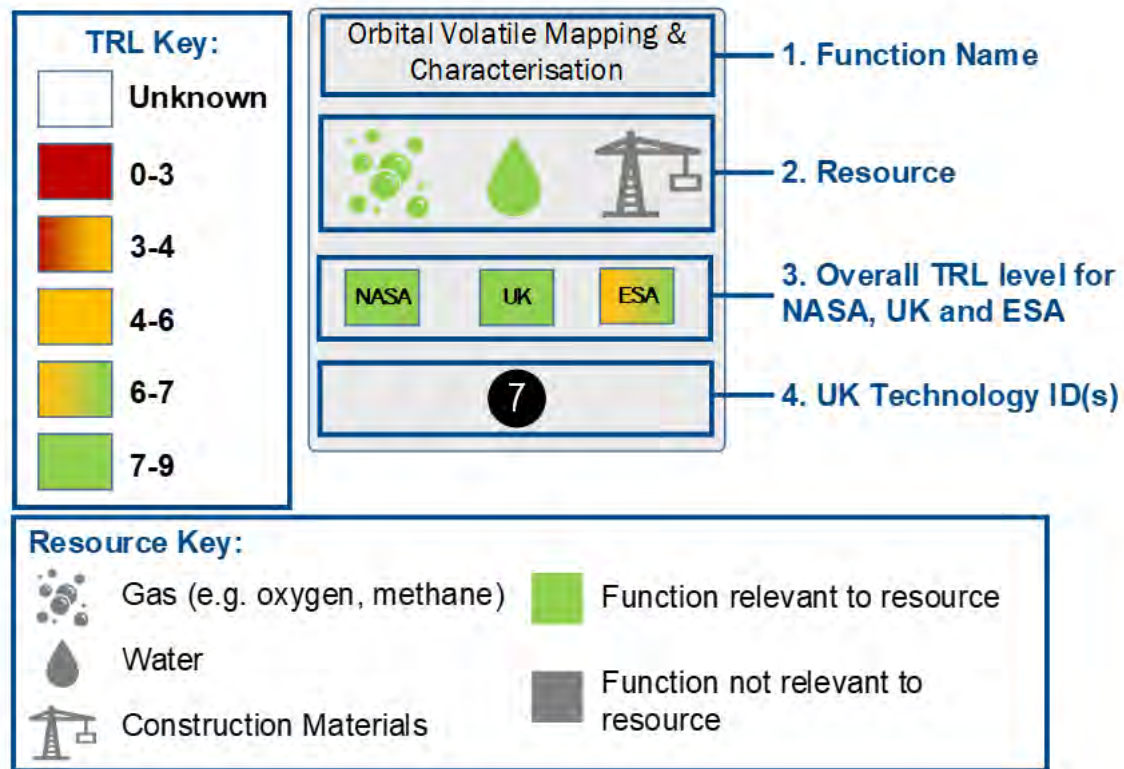


Figure 11: An example of an ISRU sub-function card from the Roadmap Tool, which has the following 4 features: 1. The name of the ISRU function; 2. The resource that is applicable to that function; 3. The overall TRL level of that function for NASA, the UK and ESA

6.2 Process Roadmapping Tool – Overall Dashboard

The Process Roadmapping Tool presents the set of ISRU sub-function cards used in this tool, arranged within the five ISRU functions outlined in the report: Prospecting, Excavation, Beneficiation, Processing, and Products & Purification. Within each ISRU function row, the relevant sub-function cards are grouped together, giving developers a clear view of the activities they can draw on when constructing an ISRU roadmap. The board is currently provided as a Visio diagram, presenting the available sub-functions in a simple, static format. The ISRU sub-function card set shown is not exhaustive, and developers are free to introduce additional sub-functions where needed.

An image of the overall dashboard which makes up the basis of the Process Roadmapping Tool is shown in Figure 12.

UK ISRU Roadmapping tool

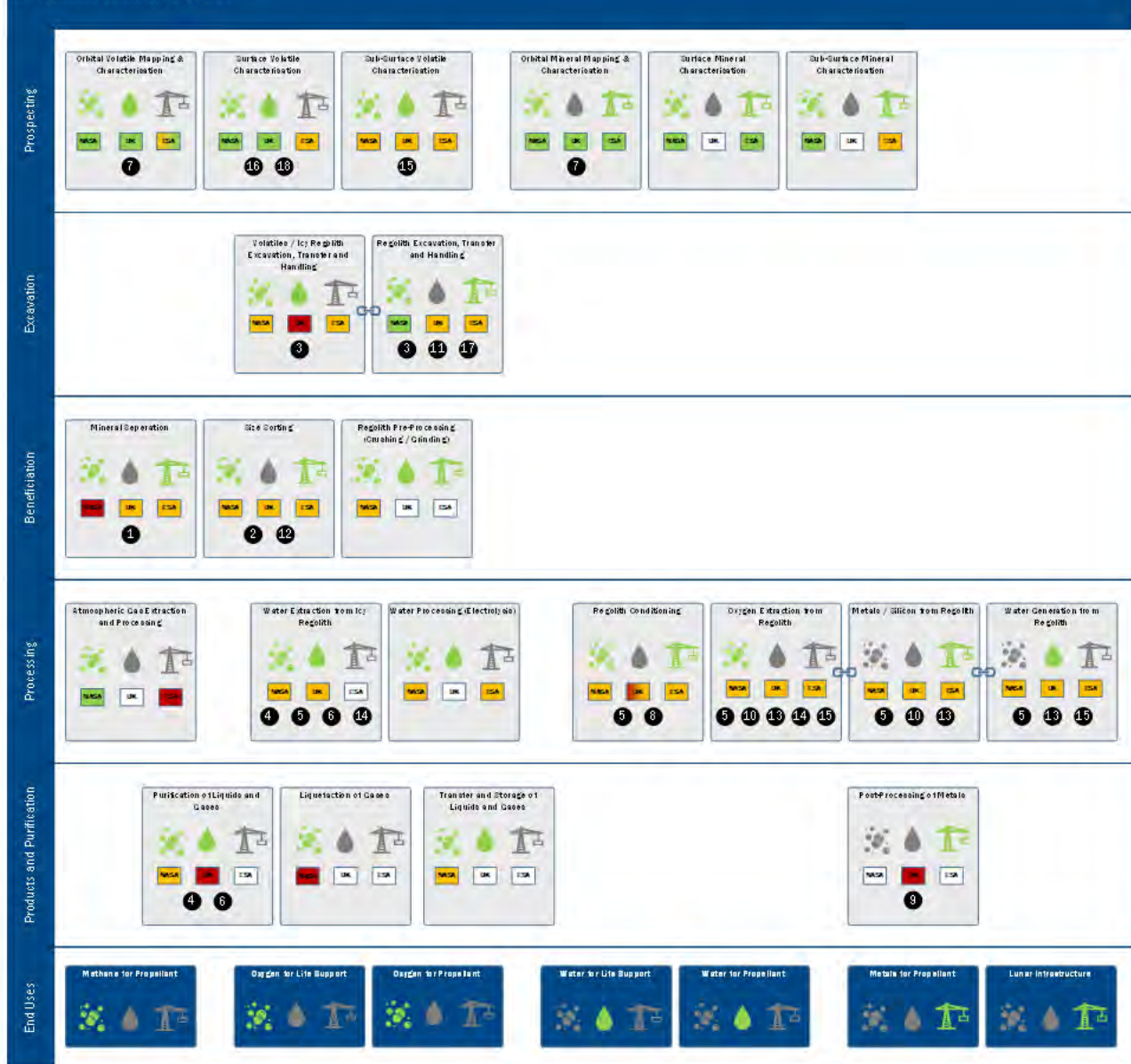


Figure 12: The dashboard which acts as the main Process Roadmapping Tool, showing the ISRU sub-function cards organised by function area.

6.3 Example: Creating a Functional chain Using the Roadmap Tool

The following section demonstrates how to use the Roadmap Tool to build and analyse an ISRU functional chain for a specific objective. It shows how to select and arrange the relevant subfunction cards, map candidate technologies onto each step, and then use the completed chain to compare technology options and pinpoint where essential capabilities, processes, or technologies are missing.

Using the ISRU objective “Oxygen for Life Support” as an example, this section illustrates how the tool supports both technology assessment and assessing whether the overall ISRU pathway is complete and technically coherent.

This example is designed to support two types of users:

1. **National programmes and space agencies**, who want to map their current ISRU capabilities, compare them with global developments, and identify strategic gaps or investment priorities.
2. **Technology developers**, who want to understand where their technology fits within the full ISRU chain, what upstream and downstream steps it depends on, and how it compares with alternative approaches.

The example covers the following steps:

1. **Selecting relevant sub-function cards from the Process Roadmapping Tool (dashboard)**
2. **Arranging sub-function cards into a coherent chain**
3. **Mapping candidate technology cards onto each sub-function**
4. **Identifying missing capabilities or processes**
5. **Comparing alternative technologies within the chain**
6. **Refining the overall ISRU pathway**

Though the steps outlined above apply to both technology developers and national programmes/space agencies, the difference will manifest in how each user interprets the outputs. Where helpful, brief perspective notes are provided to explain how each step may be applied differently by the two user groups.

6.3.1 Constructing an ISRU Chain from a System-Level View

From a system-level perspective, the goal is to understand the full sequence of activities required to produce a specific ISRU product, such as oxygen, water or construction materials. The process begins by defining an ISRU objective, such as “Oxygen for Life Support”; example ISRU Objectives are presented as dark blue cards in the “End Uses” row of the Process Roadmapping Tool dashboard. After selecting an ISRU objective, the user must determine the final step or “sub-function” in the functional chain that delivers this product. This is done by examining the Process Roadmapping Tool (see Figure 12), and selecting the card that best represents the final function in the process – which for most objectives, will be a sub-function card from the “Products & Purification” row.

Once the endpoint card has been identified, the remainder of the chain is constructed by working backwards through the preceding ISRU functions to outline the major steps required to reach the final product. The resource icons on the sub-function cards, which indicate gas, water or construction material applicability, provide a quick visual cue for determining whether a function is relevant to the chosen objective. While these icons can help guide the selection of applicable sub-function cards, they cannot be used in isolation to construct the chain. The user still needs a high-level understanding of the sequence of steps required to achieve the ISRU objective to select the appropriate sub-function cards.

The example below demonstrates how to construct a functional chain for a specific ISRU objective:

1. Define the ISRU objective:

- ▶ In this example, the objective is “Oxygen for Life Support”, i.e. breathable oxygen supplied to a habitat or life-support system.

2. Identify the final function on the Process Roadmapping Tool:

- ▶ For ISRU objective “Oxygen for Life Support”, the end point function is best defined by the sub-function card “Transfer and Storage of Liquids and Gases” (belonging to the “Products & Purification” ISRU function) from the ISRU Process Roadmapping Tool.
- ▶ Any supporting purification or production steps should also be captured here. This selection is indicated in [Figure 13](#).
- ▶ Note that users can create their own cards if none of the pre-existing sub-function cards are suitable.

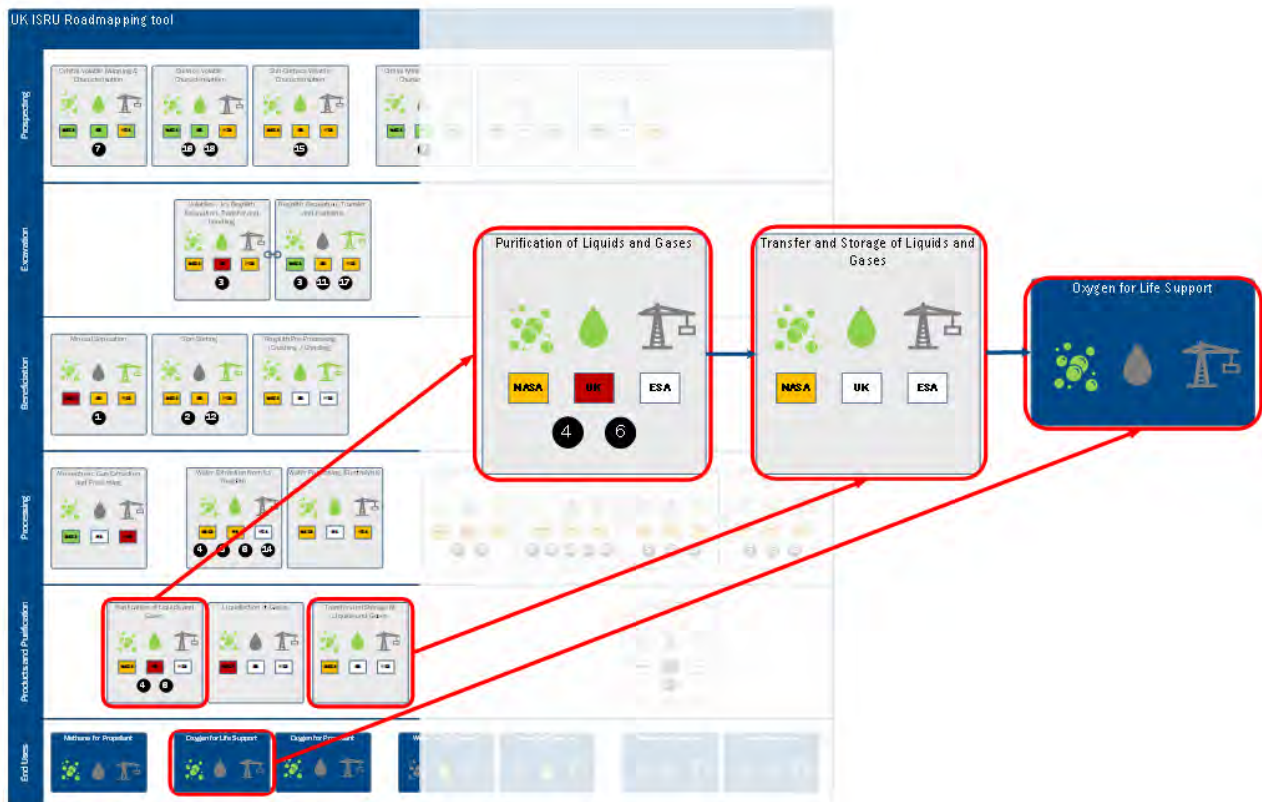


Figure 13: Selection of end point sub-function card on the Process Roadmapping Tool.

3. Identify the required processing step(s):

- ▶ Move one step upstream on the board to the “Processing” row. Select the sub-function card(s) that represent how oxygen is produced, e.g.: “Oxygen Extraction from Regolith”, “Water Extraction from Icy Regolith” / “Water Processing (Electrolysis)” or “Atmospheric Gas Extraction and Processing”.
- ▶ As multiple but separate oxygen extraction methods exist, the resulting chain may branch; this can be drawn out as shown in Figure 14. For example, one branch may represent a water-ice extraction and electrolysis pathway, while another may represent a regolith-reduction pathway that simultaneously produces oxygen and metals. The tool accommodates these parallel routes by allowing the selection of multiple sub-function cards where appropriate.

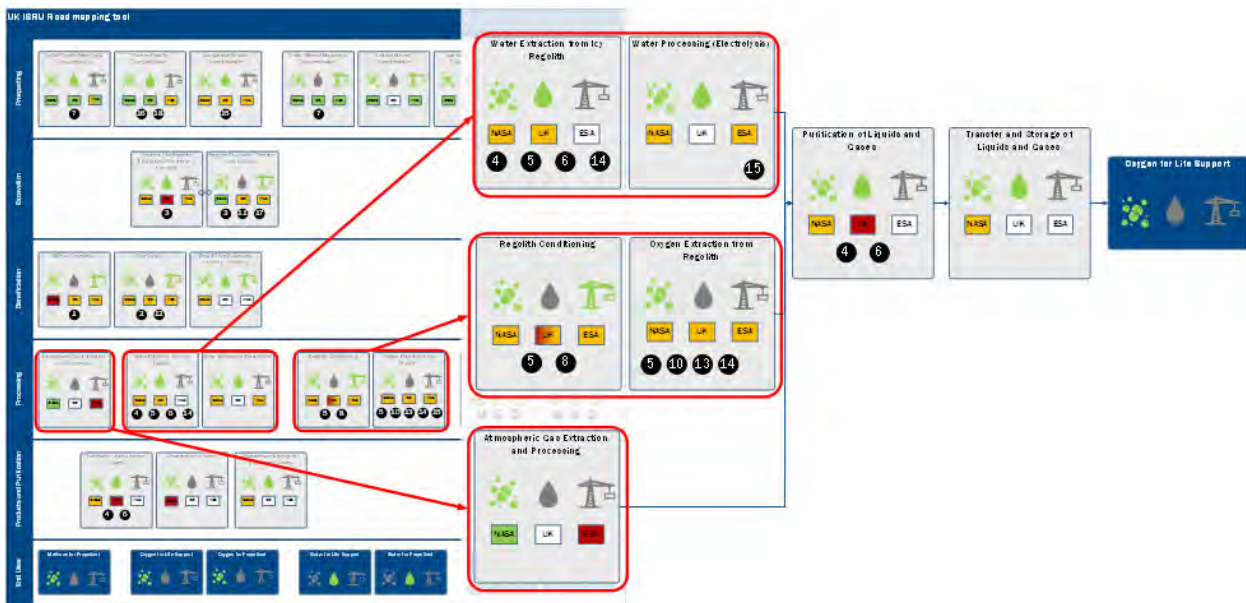


Figure 14: Selection of relevant sub-function cards from the Processing row to support production of oxygen for life support, from the Process Roadmapping Tool.

4. Determine feedstock preparation (beneficiation) step(s):

- ▶ Repeat the process for the next row - “Beneficiation” – selecting the appropriate sub-function card(s).
- ▶ Note that for this example, there are no relevant “Beneficiation” sub-function cards for the “Atmospheric Gas Extraction and Processing” branch of the process chain. This can be drawn out as shown in Figure 15.

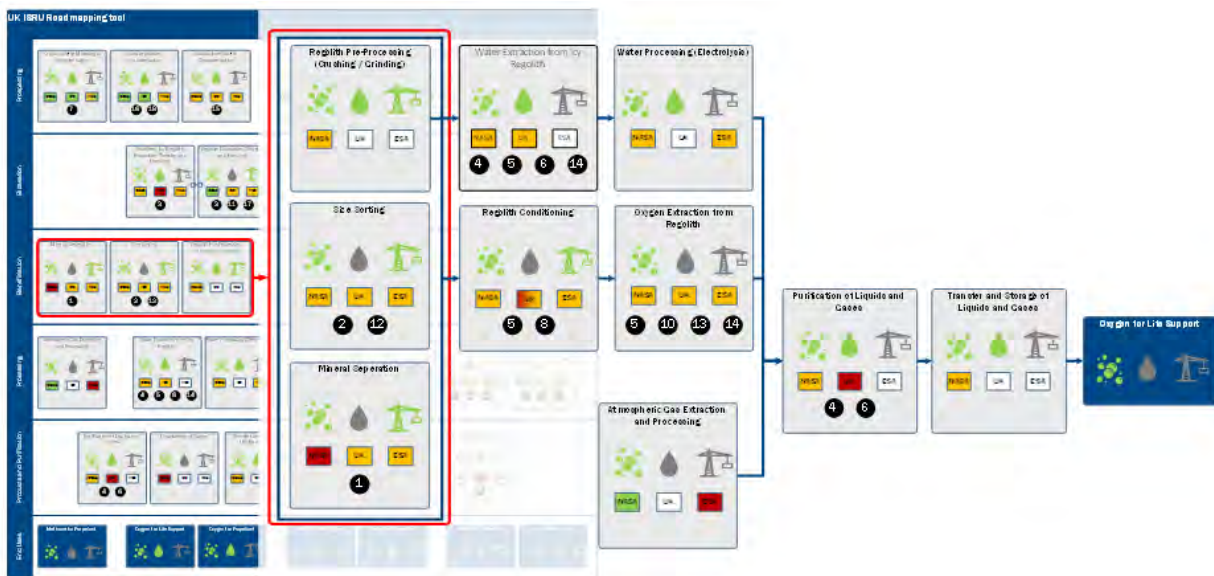


Figure 15: Selection of relevant sub-function cards from the Beneficiation row to support production of “Oxygen for Life Support”, from the Process Roadmapping Tool.

5. Repeat sub-function selection through the remaining rows (excavation & prospecting):

- Repeat the process for the remaining rows - “Excavation” and “Prospecting” - selecting the appropriate sub-function card(s).
- This will provide a complete functional chain for the chosen objective, such as that shown in Figure 16. The chain can look complex at this stage but acts as a visual aid to identifying the potential routes and mix of technologies needed. At this point, a high-level view should allow the user to identify repeated uses of technologies, common sub-functions, and other insights.

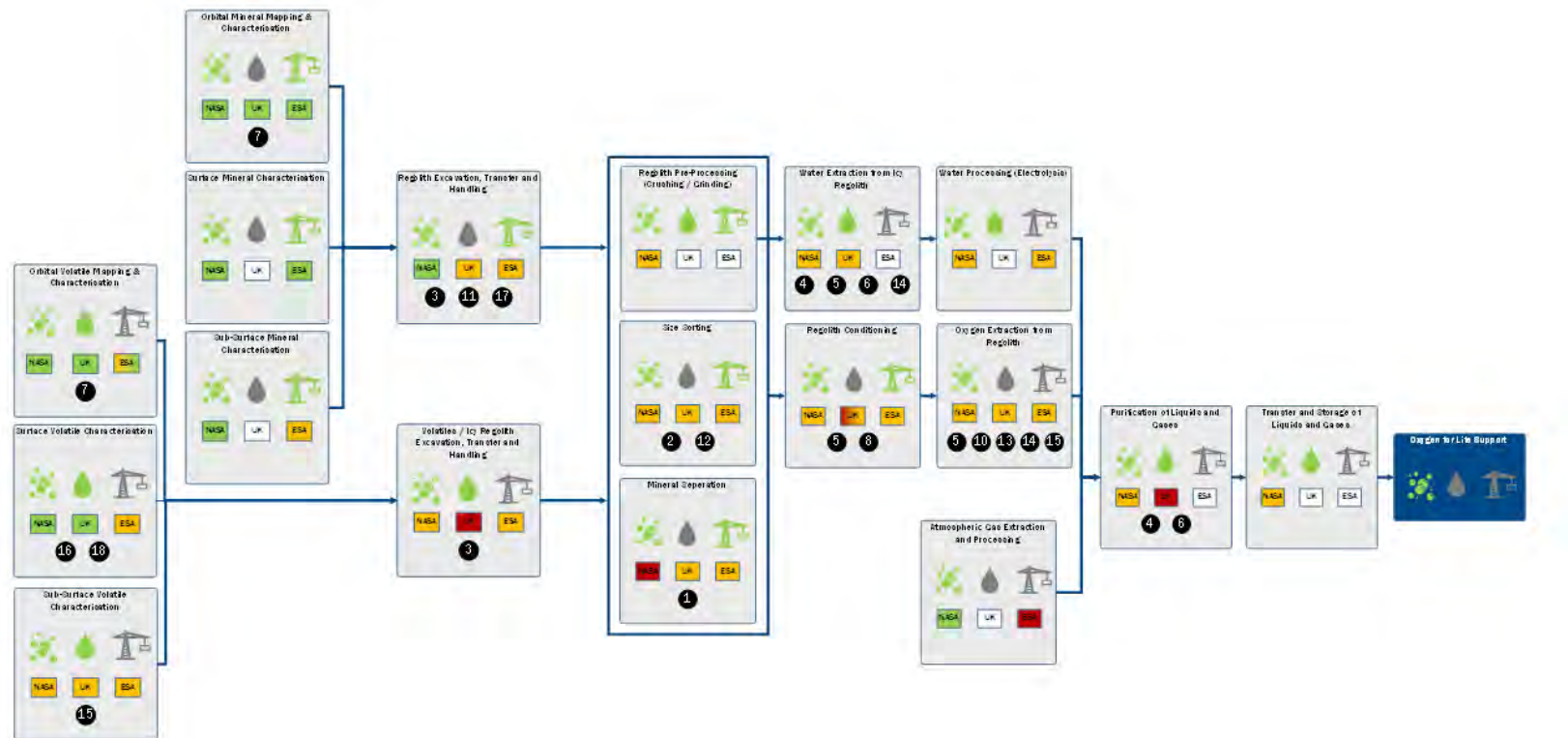


Figure 16: Complete functional chain for the ISRU objective “Oxygen for Life Support”, with multiple branched options.

6. Review and refine the functional chain:

- ▶ It may be useful at this point for the user to review the functional chain as a whole and make conscious decisions to eliminate some branches.
- ▶ Using the functional chain shown in Figure 16 as an example, the user may decide to eliminate the bottom branch as the “Atmospheric Gas Extraction and Processing” function card has no UK based technologies associated with it. Alternatively, the user may decide to eliminate the upper and middle branches as they involve more steps, resulting in a more complex solution with a greater number of interfaces.
- ▶ In this demonstration, we have chosen to reduce to the bottom “Atmospheric Gas Extraction and Processing” branch as shown in Figure 17. By choosing this pathway, we can see that the UK is missing technologies in both “Atmospheric Gas Extraction” and “Transfer and Storage of Liquids and Gases” but has a couple of TRL 1-3 technologies that fall under Purification

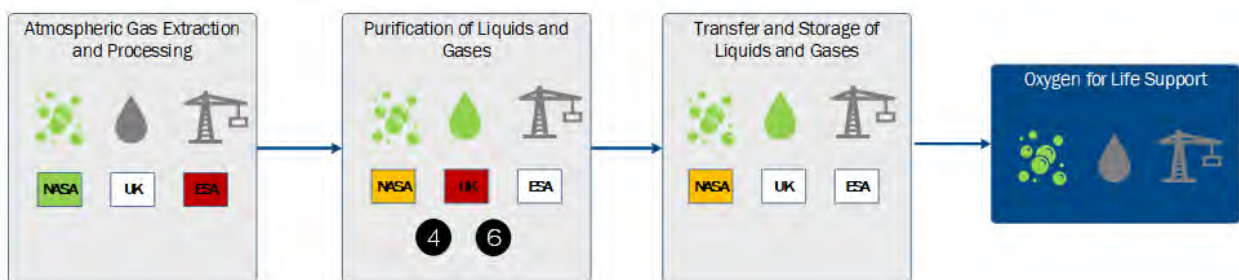


Figure 17: Simplified functional chain for ISRU objective “Oxygen for Life Support” via the “Atmospheric Gas Extraction and Processing” route.

6.3.2 Constructing an ISRU Chain Around an Existing Technology

An alternative method to build a functional chain, could be to focus on a single technology. This might be something a manufacturer of a particular technology could carry out, looking for other complimentary technologies or gaps in the chain which could act as blockers.

This kind of functional chain can be created in a similar manner to system-level approach outlined in the previous subsection. Instead of working backwards through the chain identifying necessary pre-cursor work, instead work outwards from the starter card(s) looking for compatible adjacent steps. Taking technology reference number 6, the chain can be constructed as shown in Figure 18 and Figure 19. Starter cards involving technology number 6 are highlighted in red, while compatible adjacent steps are highlighted in blue in Figure 18.

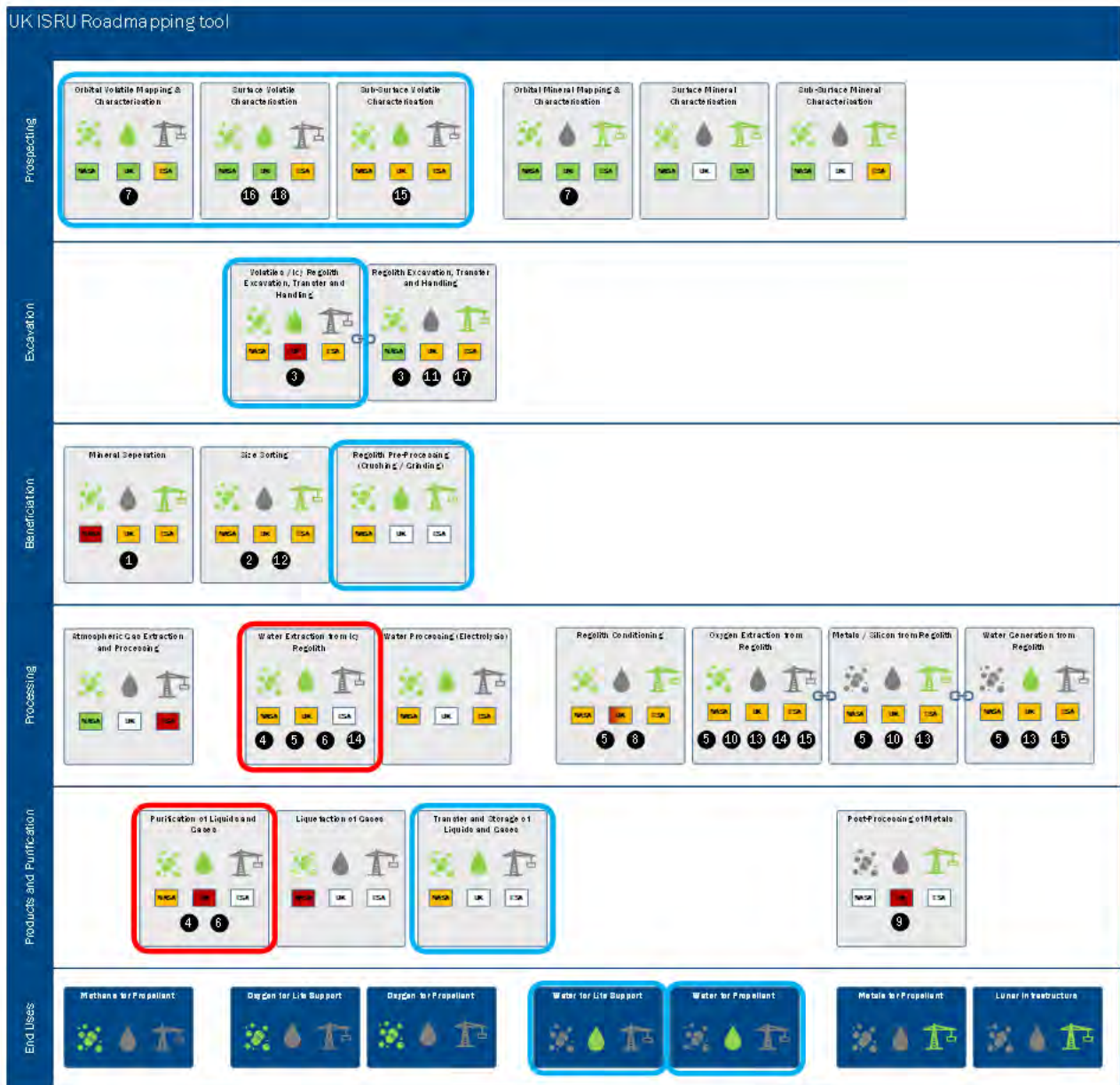


Figure 18: Process Roadmapping Tool with cards selected for building a functional chain focussed on technology 6.

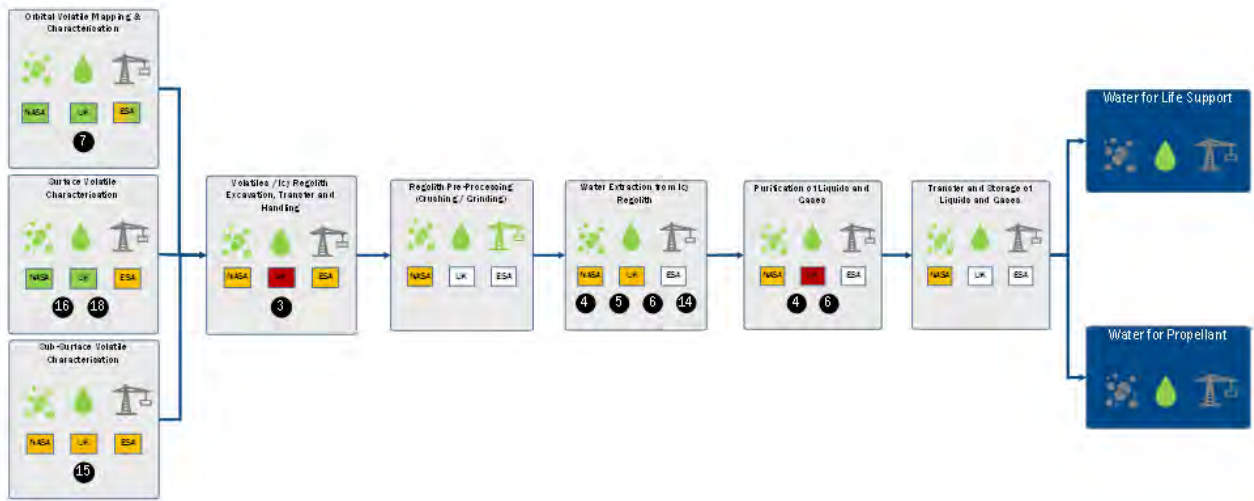


Figure 19: Functional chain built from a single technology focus using technology number 6.

6.3.3 Mapping candidate technologies onto each sub-function

After building a functional chain, the technologies identified in the black circles can be mapped to each of their corresponding sub-function cards. This combination of information can be used by technical teams and subject matter experts, to explore system level challenges, breaks in the chain, and interdependencies. The figure below (Figure 20) shows an example of how this may be done, using a simplified chain developed in section 6.3.1 above (i.e. middle branch, “Oxygen Extraction from Regolith”), and the technology cards from this report. Note that the function chain shown in Figure 20 is illustrative example; not all applicable technologies have been mapped to avoid overcrowding. In practice, several technologies may map to a single function.

While the function cards identify all the technologies that can deliver the specified function, the user must use appropriate judgement when mapping candidate technologies to a specific function chain. For example, Technology IDs 4 and 6 are listed on the “Purification of Liquids and Gases” card; however, as these technologies focus on water purification, these technologies are not appropriate for the function chain shown in Figure 17, where atmospheric gas is an input for oxygen production.

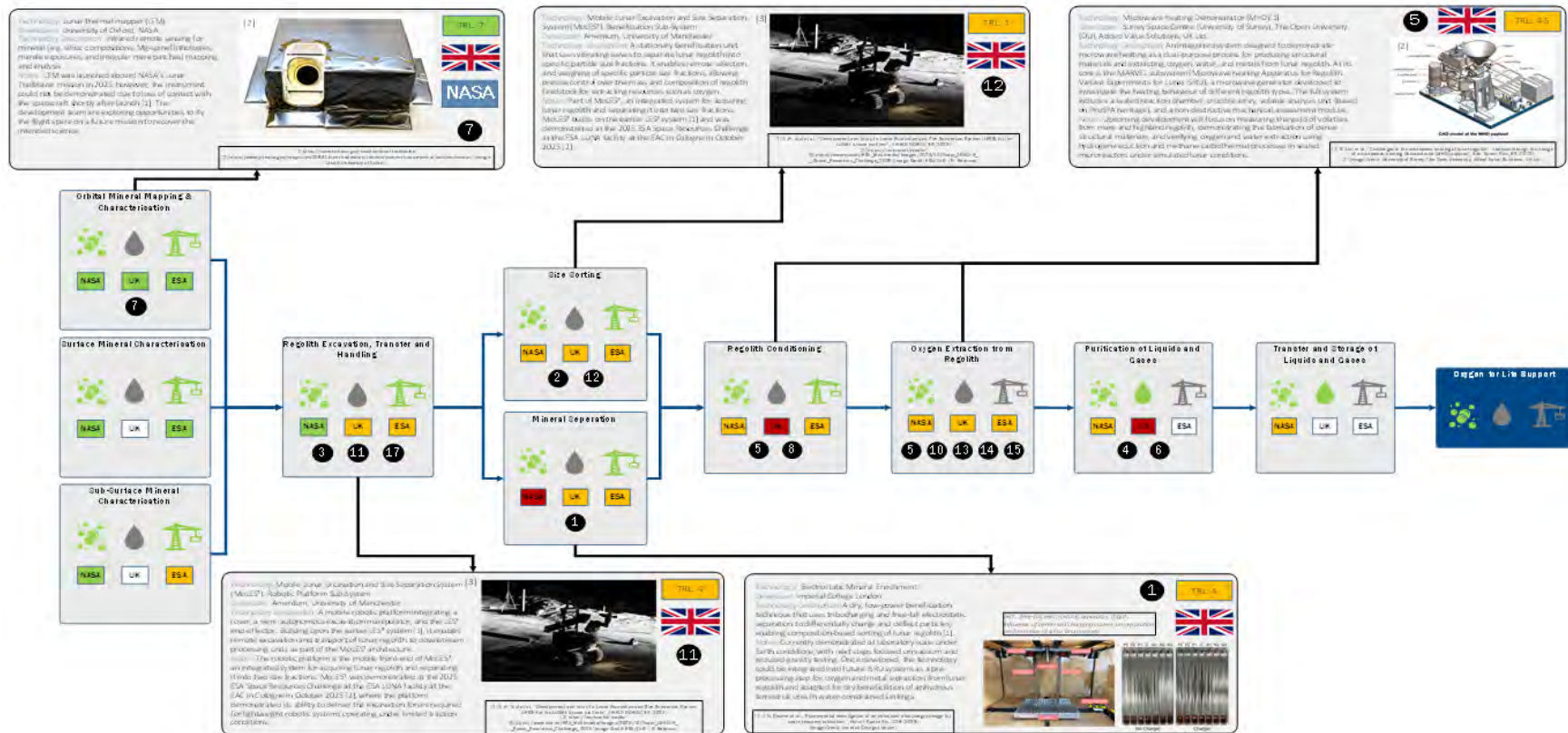


Figure 20: Example of mapped technologies applied against a simplified functional chain for the ISRU objective "Oxygen for Life Support".

6.3.4 Additional Uses

The Process Roadmapping Tool can be used in other ways separate to building functional chains for ISRU. These include:

- ▶ **Identifying missing capabilities or processes:** By considering sub-function cards in the tool which indicate low TRL across agencies with no associated technologies. This can be considered within a built functional chain, identifying areas where further research and development is needed.
- ▶ **Comparing alternative technologies within a chain:** Once a functional chain has been constructed and technologies mapped against them, technical comparison of the technologies can be made more readily. This could include considering which technologies are more broadly applicable, or which technologies could be preferable to include in a target functional chain.
- ▶ **Refining the overall ISRU pathway:** By plotting out potential functional chains and considering the benefits and challenges of different options, developers may be able to identify and resolve technology and function mismatches earlier, and determine areas of collaboration or partnering that may be required.

7 Conclusions

ISRU is a growing area in the UK with diverse capabilities, albeit with some barriers to overcome. The Process Roadmapping Tool outlined in this report allows analysis of UK areas of strength, and comparison against both ESA and NASA capabilities as the two most likely organisations for cooperation on ISRU for the UK in the near term.

As part of this report, a survey of stakeholders was carried out, with a follow-on workshop to discuss results. Participation was spread across a range of organisations, but mainly involved small and medium enterprises, with significant input from academia. 85% of all responses featured a technology which was applicable in the Lunar environment, with almost half of responses suitable for the Martian environment. This aligned with both ESA and NASA strategies, of a return to the moon this decade with stretch goals for Martian missions, which could potentially be supported by Lunar or Martian ISRU.

There remains a significant opportunity for the UK to play a key part in NASA / ESA activities going forward. A clear UK strategy would broaden visibility, enabling UK strengths in process engineering and materials science to play a critical role. The Process Roadmapping Tool outlined in this report can be used to better understand the opportunity, and to inform strategy development going forward.

7.1 Conclusions from Community Engagement

Throughout the workshop and survey, participants were encouraged to share any blockers inhibiting technology development. A consistent theme was a need for **clear future plans**, both nationally and internationally, which could provide clarity on timelines for undertaking technology development in alignment with global missions and provide certainty required to secure private sector investment in ISRU technology. Whilst most respondents had focussed technology development on Lunar applications due to global strategies, certainty about the **UK's position on ISRU** would enable further confidence in continued investment and focus on these areas – to remove dependency on larger agencies and international partners.

Participants were eager for clarity and a national strategy, to identify whether this issue should be addressed by providing larger, longer-term investments to areas of national importance, or identify opportunities for export of UK-driven early TRL concepts for international development.

The workshop and surveys identified broader capabilities and facilities within the UK. This has been highlighted as an opportunity for the **UK to become an ISRU testbed** with existing ISRU-specific facilities and adaptation of manufacturing facilities and laboratories. This would encourage better collaboration and integration across the UK sector and open our existing facilities to a greater range of international users – although this would need a driving force and direction from the sector and providers.

7.2 Conclusions from Capability Analysis

The UK has demonstrated its strength in **prospecting** with key projects. The function is crucial in developing the data to understand the business case for ISRU, and this could be an opportunity for the UK to cement itself as a key partner supporting larger missions.

Other areas of technology concentration include **regolith excavation, transfer and handling**. This avenue of development likely has applications beyond ISRU alone, as all lunar and Martian missions will have to handle the abrasive regolith and could be worthy of a further focused investigation. Oxygen and metal extraction could act as a hub of development due to the international prioritisation, notably as the UK is leading the European development with a largely British consortium involved in the ISRU-DM mission. Across other elements of the value chain, there are few mature technologies. This has been highlighted in our workshops both as a problem, due to the “the TRL valley of death”, and an **opportunity for British scientific excellence** to support international technology development.

Annex A – ESA and NASA: ISRU-related Missions and Programs

Table A 1: ESA's ISRU-related missions that are currently active or have ended within the past five years, alongside currently planned and upcoming ISRU demonstration missions.

Mission Name	Technical focus area(s)	Description	Timeline
Prospect	Prospecting: Local Volatile Characterisation Excavation: Solid Resource Excavation & Acquisition	Mission Type: Lunar polar volatile-prospecting payload Mission aim: To drill into the Moon's south polar regolith, extract samples, and analyse volatile content (such as water ice) to assess ISRU potential. Key ISRU Technologies: • ProSPA (miniature sample analysis laboratory designed to determine the chemical composition of subsurface lunar volatiles, such as water ice) [58]. • ProSEED drill designed to extract samples from the lunar subsurface down to 1 m [58]. • Notes: ESA's PROSPECT payload is scheduled to reach the lunar south pole in 2027 via the Intuitive Machines' Nova C-Lunar lander as part of a NASA Commercial Lunar Payload Services (CLPS) program [59] [60].	Mission Status: Planned [Launch by 2027]
Lunar Volatile and Mineralogy Mapping Orbiter (VMMO)	Prospecting: Orbital Volatile Mapping and Characterisation; Orbital Mineral Mapping and Characterisation	Mission Type: Orbiter Mission aim: To map the distribution of water ice and ilmenite (FeTiO ₃) in permanently shadowed regions near the lunar south pole. The mission will also study the lunar water cycle, nighttime surface frosting, and cis-lunar radiation environment [61]. Key ISRU Technologies: • Multi-wavelength Lidar (LVMM): maps surface composition and topography, including ice and ilmenite signatures. • Compact LunAr Ionizing Radiation Environment (CLAIRE): monitors radiation in cis-lunar space • GNSS receiver: supports precise navigation and mapping. Notes: A potential launch opportunity is being explored for Q4 2028 via NASA's Commercial Lunar Payload Services (CLPS).	Mission Status: Pending [Potential launch opportunity Q4 2028]

Moonraker	Enabling	Mission Type: Orbiter Mission aim: To generate high-resolution 3D maps of the lunar polar regions and other regions of interest to support landing site selection, base planning, and surface operations for future exploration. Key ISRU Technologies: • LiDAR payload for topographic mapping, capable of 4 m ground sampling distance, <1 m vertical accuracy, and <1 cm precision [62].	Mission Status: Proposed [Launch date TBC]
Mission for Advanced Geophysics and Polar Ice Exploration (MAGPIE)	Prospecting: Local Volatile Characterisation Excavation: Solid Resource Excavation & Acquisition	Mission Type: Rover Mission aim: To investigate the presence of water ice, map hydrogen distribution, and study the geological history of the Moon's south polar region. Key ISRU Technologies: • Lunar Volatile Scout drill for extracting and analysing regolith samples for volatiles such as water. • HardPix neutron spectrometer for detecting hydrogen – a key indicator of subsurface water ice. • Lunar RIMFAX ground-penetrating radar for mapping subsurface layers and identifying potential volatile-rich zones. Notes: MAGPIE is Europe's first in-situ lunar polar rover mission, led by ispace-EUROPE and funded by ESA's Small Missions for Exploration [63].	Mission Status: Proposed [Targeting a launch window in 2028]
ExoMars Rosalind Franklin Mission (RFM)	Prospecting: Local Volatile Characterisation; Local Mineral Characterisation Excavation: Solid Resource Excavation & Acquisition	Mission Type: Rover Mission aim: To search for signs of life on Mars. Key ISRU Technologies: • ExoMars Drill System for extracting core samples from the Martian subsurface [64] • Ma_MISS (Mars Multispectral Imager for Subsurface Studies) for analysing minerals in borehole walls during subsurface sampling [65]. • WISDOM (Water Ice and Subsurface Deposit Observation on Mars), a ground-penetrating radar for detecting buried volatiles such as water ice or hydrated minerals [66]. Notes: The ExoMars Rosalind Franklin rover mission, a joint endeavour between ESA and NASA, is planned to launch in 2028 [67].	Mission Status: Planned [Launch in 2028]

ISRU Demonstration Mission (ISRU-DM) [68] [69]	Excavation: Solid Resource Excavation & Acquisition Processing: Water Extraction from Icy Regolith; Oxygen Metal & Silicon Extraction from Regolith	Mission Type: Lander-based surface experiment (technology demonstration plant) Mission aim: To demonstrate the extraction of oxygen and water from lunar regolith to enable future production of propellant, breathable air, and raw materials on the Moon. Key ISRU Technologies: • Robotic sampling arm to collect and deliver lunar regolith to the processing unit. • FFC Molten Salt Electrolysis Reactor for extracting oxygen and metal byproducts from lunar regolith. • Gas and water capture system for collecting oxygen and water produced from the reaction • Chemical analysers to verify purity and composition of extracted oxygen and water. • Integrated demonstration plant in the form of a compact, lander-mounted facility to showcase end-to-end ISRU operations. Notes: Funded by ESA under the European Exploration Envelope Programme (E3P). Originally lead by Thales Alenia Space UK, the mission is now headed by OHB, with contributions from AVS, Metalysis (UK), Open University (OU) (UK) and Redwire Space Europe (Luxembourg).	Mission Status: Proposed [Launch date TBC]
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Table A 2: NASA's ISRU-related missions and programs that are currently active or have ended within the past five years, alongside currently planned and upcoming ISRU demonstration missions.

Mission / Program Name	Technical focus area(s)	Description	Timeline
Lunar Reconnaissance Orbiter (LRO) [70]	Prospecting: Orbital Volatile Mapping and Characterisation; Orbital Mineral Mapping and Characterisation	Mission Type: Orbiter Mission aim: To map the lunar surface and environment to guide safe landings and resource exploration. Key ISRU Technologies: • DLRE (Diviner Lunar Radiometer) for surface/sub-surface thermal mapping [71] • LAMP (Lyman Alpha Mapping Project) uses UV light to find water ice in deep polar craters [71]. • Mini-RF synthetic aperture radar (SAR) instrument for subsurface water ice deposit detection [71]. • LEND (Lunar Exploration Neutron Detector) for high-resolution hydrogen distribution maps [71]. • LROC (Lunar Reconnaissance Orbiter Camera) for capturing high resolution black-and-white images of the lunar surface [71]	Mission Status: Ongoing Launch date: 18 June 2009
Lunar IceCube [72]	Prospecting: Orbital Volatile Mapping and Characterisation	Mission Type: SmallSat/Orbiter Mission aim: To estimate the quantity and composition of water ice deposits on the moon. Key ISRU Technologies: • Broadband InfraRed Compact High Resolution Exploration Spectrometer (BIRCHES) instrument Notes: NASA established contact briefly after deployment on 16 Nov 2022, but subsequent attempts to communicate and place satellite into science orbit were unsuccessful. No further mission updates were provided by NASA after 29 Nov 2022.	Mission status: Ended Launch date: 16 Nov 2022 Mission end date: Unknown [last update from NASA: 29 Nov 2022]

Mission / Program Name	Technical focus area(s)	Description	Timeline
Lunar Flashlight [73]	Prospecting: Orbital Volatile Mapping and Characterisation	Mission Type: Technology Demonstration Mission Mission aim: Orbit Earth's Moon to map ice in permanently shadowed regions near the lunar south pole. Key ISRU Technologies: Near-infrared Spectrometer installed on a nanosatellite Notes: Satellite failed to enter Moon's orbit due to propulsion system failure, resulting in the mission being terminated.	Mission Status: Ended Launch date: 11 Dec 2022 Mission end date: 12 May 2023
Lunar Trailblazer [74]	Prospecting: Orbital Volatile Mapping and Characterisation	Mission Type: SmallSat/Orbiter Mission aim: Orbit Earth's Moon to detect and map water on lunar surface. Key ISRU Technologies: - High Resolution Volatiles and Minerals Moon Mapper (HVM³) - Lunar Thermal Mapper (LTM) Notes: NASA lost contact with spacecraft shortly after launch, ending the mission prematurely.	Mission Status: Ended Launch date: 26 Feb 2025 Mission end date: 31 Jul 2025
PRIME-1 [75]	Prospecting: Local Volatile Characterisation Excavation: Solid Resource Excavation & Acquisition	Mission Type: Lunar Drilling Experiment Mission aim: To demonstrate the ability to extract and analyse lunar soil. Key ISRU Technologies: - MSolo mass spectrometer [75]. - TRIDENT drill [76]. Notes: The mission ended prematurely as lander tipped over after landing, preventing operations [77].	Mission Status: Ended Launch date: 26 Feb 2025 Mission end date: 06 Mar 2025

Mission / Program Name	Technical focus area(s)	Description	Timeline
VIPER [78]	Prospecting: Local Volatile Characterisation Excavation: Solid Resource Excavation & Acquisition; Resource Delivery from Mine Site and Removal	Mission Type: Rover Mission aim: To map the location of lunar water ice and other potential resources. Key ISRU Technologies: - NSS: Neutron Spectrometer System for water detection in soil [79]. - NIRVSS: Near-Infrared Volatiles Spectrometer System for classifying hydrogen-bearing species [79]. - MSolo mass spectrometer [79] [80]. - TRIDENT drill [76]. Notes: In 2024, NASA announced the cancellation of the VIPER mission, though the VIPER payload is now scheduled to launch in 2027 onboard Blue Origin's CLPS lander [81].	Mission Status: Cancelled and reassigned to Blue Origin [with VIPER payload scheduled to launch in 2027 onboard Blue Origin's CLPS lander [81]]
Artemis [82] [83]	Enabling	Program aim: To return humans to the Moon and build a sustained lunar presence as a foundation for future Mars missions. Key ISRU Technologies: TBC Notes: Artemis III was originally planned as the first crewed landing at the lunar south pole, but NASA has now reassigned this mission to a low-Earth orbit test mission focused on practicing docking with a lunar lander. Artemis IV is now planned as the first crewed lunar landing, targeted for 2028. Artemis V is planned as the second crewed lunar landing and will expand surface operations toward establishing long-term lunar infrastructure. After Artemis V, NASA intends to move to an annual cadence of crewed lunar missions [83].	Artemis III Mission Status: Planned [Launch by 2027] Artemis IV Mission Status: Planned [Launch by 2028] Artemis V Mission Status: Planned [Launch by 2028]

Mission / Program Name	Technical focus area(s)	Description	Timeline
Mars Reconnaissance Orbiter (MRO) [84]	Prospecting: Orbital Volatile Mapping and Characterisation; Orbital Mineral Mapping and Characterisation	Mission Type: Orbiter Mission aim: Gain better knowledge of the distribution and history of water on Mars. Key ISRU Technologies: • HiRISE (High Resolution Imaging Experiment) high-resolution camera that captures detailed images of Mars' surface [85] • CRISM (Compact Reconnaissance Imaging Spectrometer for Mars) for tracing past water activity [85] • SHARAD (Shallow Radar) for identifying liquid/frozen water up to 1 km of Mars' crust [85]	Mission Status: Ongoing Launch date: 12 Aug 2005 Orbit insertion date: 10 March 2006
Mars Curiosity rover [86]	Prospecting: Local Volatile Characterisation; Local Mineral Characterisation	Mission Type: Rover Mission aim: To determine if Mars was ever able to support microbial life Key ISRU Technologies: • CheMin (X-ray diffraction to determine mineralogy) [87]. • SAM (volatile and organics detection) [87].	Mission Status: Ongoing Launch date: 26 Nov 2011 Landing date: 06 Aug 2012

Mission / Program Name	Technical focus area(s)	Description	Timeline
Mars 2020: Perseverance Rover [88]	Prospecting: Local Volatile Characterisation; Local Mineral Characterisation Excavation: Solid Resource Excavation & Acquisition Products & Purification: Carbon Dioxide (CO₂) to product conversion	Mission Type: Rover Mission aim: To seek signs of ancient life and collect samples of rock and regolith for possible Earth return. Key ISRU Technologies: • PIXL (fine-scale chemical mapping) [89]. • SHERLOC (organics and mineral detection) [89]. • SuperCam (laser-induced breakdown spectroscopy) [89]. • MOXIE (electrochemical conversion of CO₂ into O₂) [89] [90]. • Sample Caching System (three robotic systems): robotic arm with rotary-percussive drill and hollow coring bit; drill bit and sample tube carousel; sample handling arm [91]. Notes: MOXIE demonstrated small-scale oxygen production by electrochemically extracting O₂ from CO₂ in the Martian atmosphere.	Mission Status: Ongoing Launch date: 30 Jul 2020 Landing date: 18 Feb 2021

Table A 3: ESA Technology Readiness Level (TRL) scale with definitions [2].

TRL	Definition
1	Basic principle
2	Application formulated
3	Proof-of-concept
4	Functional verification
5	Breadboards (reduced scale) verification in relevant environment
6	Models (full scale) demonstration in relevant environment
7	Model demonstration for operational environment
8	Flight qualified
9	Flight proven

Annex B – UK In-Situ Resource Utilisation (ISRU)

Landscape: Survey Questions

Respondents were asked to provide the following organisational information:

- ▶ Name of Organisation
- ▶ Type of Organisation
 - Small (<50 employees)
 - Medium (50-250 employees)
 - Large (>250 employees)
 - Academic
 - Other
- ▶ Primary Location
- ▶ Facilities and Capabilities

The following prompts were used to gather detail on technologies:

- ▶ Where in the ISRU value chain does your technology sit (select one of the following options)?
 - Prospecting (i.e. resource identification and characterisation)
 - Excavation (i.e. physical removal of material from the surface or subsurface)
 - Beneficiation (i.e. separation or concentration of valuable components from excavated materials)
 - Processing (i.e. conversion of materials into usable forms/resources)
 - Products & Purification (i.e. end results of ISRU operations, useable products and any necessary post-processing)
 - Enabling Technology (i.e. technologies that support ISRU activities, e.g. power, communications, thermal management, etc.)
 - Other (where the user could provide a response to give further details)
- ▶ For what ISRU environment is your technology envisioned?
 - e.g. lunar, Martian etc.
- ▶ Please describe the core functionality of your technology.
 - e.g. a prospecting tool to identify water ice deposits, a technology to extract oxygen from lunar regolith, etc.
- ▶ Why is your organisation developing this technology? E.g. how does it align with your mission? What is your goal for this technology?
- ▶ What is the current TRL of your technology?
 - As aligns to [ESA TRL guidance](#)

-
- ▶ Does your technology have any other use cases?
 - E.g. terrestrial applications which could unlock other funding streams

The following prompts were then used to gather further information on the development plan:

- ▶ What is your current revenue stream to support ISRU technology development?
 - e.g. internal investment, external investment, grant funding
- ▶ Please provide a breakdown of the investment required for each stage in your TRL development plan.
 - e.g. in 2025, funding of £200,000 is required for testing to achieve proof of concept, achieve TRL 3 and unlock X opportunity.
- ▶ What non-financial assistance would enable development?
- ▶ e.g. regulatory/legislative/policy considerations, a forward-looking pipeline of UK opportunities gives security to our investors.
- ▶ Are there any major blockers currently impacting development or deployment of your technology?
- ▶ Please provide any other relevant commercial information.
 - Details of key partnerships, previous funding applications and funded projects. All information collected here will not be published.
 - Note: if commercially sensitive information is included which is not suitable for publication, either specify here, or reach out to the project team to discuss confidentiality agreements. Alternatively, contact UKSA if more comfortable.
- ▶ Is there any additional information you would like to provide that has not been captured in this survey?
 - Please provide any information you think would support development of the technology report that hasn't been included in the form.

There was an option at the end of this form to populate details for a second technology.

Annex C – UK Technology Tables

Table C 1: UK ISRU technologies that were identified in the UKSA ISRU survey and Technology Review Workshop. The applicable ISRU functions and subfunctions are provided for each technology, alongside the unique “Roadmap Tool ID” applicable to both the UK technology cards and technology roadmap tool presented in Sections 5 and 6 respectively.

Roadmap Tool ID	Technology	UK Developer(s)	International Partner(s)	ISRU function(s)	ISRU sub-function(s)
1	Electrostatic Mineral Enrichment	Imperial College London	-	Beneficiation	Mineral Separation
2	Electrostatic Travelling Wave (ETW) Size Classification	Imperial College London	-	Beneficiation	Size Sorting
3	DIGGER (Directed Energy Drilling for Lunar and Asteroid Applications)	RAL Space (STFC)	-	Excavation	a. Volatiles / Icy Regolith Excavation, Transfer and Handling b. Regolith Excavation, Transfer and Handling
4	Static Water Extraction System (SWES)	Interstellar Mapping Ltd	-	1. Processing 2. Products & Purification	Processing: 1a. Water Extraction from Icy Regolith Products and Purification: 2a. Purification of Liquids and Gases
5	Microwave Heating Demonstrator (MHD)	Surrey Space Centre, University of Surrey, The Open University (OU)	-	Processing	a. Water Extraction from Icy Regolith b. Regolith Conditioning c. Oxygen Extraction from Regolith d. Metals / Silicon from Regolith e. Water Generation from Regolith

Roadmap Tool ID	Technology	UK Developer(s)	International Partner(s)	ISRU function(s)	ISRU sub-function(s)
6	SonoChem System (Volatile extraction, separation and purification of trapped volatiles in lunar regolith)	Naicker Scientific Ltd	-	1. Processing 2. Products & Purification	Processing: 1.a. Water Extraction from Icy Regolith Products and Purification: 2.a. Purification of Liquids and Gases
7	Lunar Thermal Mapper (LTM)	University of Oxford	NASA	Prospecting	a. Orbital Volatile Mapping & Characterisation b. Orbital Mineral Mapping & Characterisation
8	Densification of Lunar Regolith via Flash Sintering	Lucideon	-	Processing	Regolith Conditioning
9	Horizon DEXTER	Magdrive, Cranfield University	-	Products & Purification	Post-Processing of Metals
10	ISRU-DM: Molten Salt Electrolysis (FFC)	OHB Space UK, Metalysis Ltd, University of Glasgow, The Open University (OU)	ESA	Processing	a. Oxygen Extraction from Regolith b. Metals / Silicon from Regolith
11	Mobile Lunar Excavation and Size Separation System (MoLES ³): Robotic Platform Sub-System	University of Manchester, Amentum	-	Excavation	Regolith Excavation, Transfer and Handling
12	Mobile Lunar Excavation and Size Separation System (MoLES ³): Beneficiation Sub-System	University of Manchester, Amentum	-	Beneficiation	Size Sorting

Roadmap Tool ID	Technology	UK Developer(s)	International Partner(s)	ISRU function(s)	ISRU sub-function(s)
13	HyPER (Hydrogen Plasma Extraction from Regolith)	Frazer-Nash Consultancy	-	Processing	a. Oxygen Extraction from Regolith b. Metals / Silicon from Regolith c. Water Generation from Regolith
14	Regolith Ice Plasma Purifier for Lunar Exploration (RIPPLE)	Regolithix	-	Processing	a. Water Extraction from Icy Regolith b. Oxygen Extraction from Regolith
15	ProSPA	The Open University (OU), RAL Space	ESA	1. Prospecting 2. Processing	Prospecting: 1.a. Sub-Surface Volatile Characterisation Processing: 2.a. Water Generation from Regolith
16	Exospheric Mass Spectrometer (EMS)	The Open University (OU)	NASA	Prospecting	Surface Volatile Characterisation
17	Pulse Elevator	University of Glasgow	-	Excavation	Regolith Excavation, Transfer and Handling
18	Peregrine Ion Trap Mass Spectrometer (PITMS)	The Open University (OU), RAL Space	ESA, NASA	Prospecting	Surface Volatile Characterisation

Table C 2: UK ISRU technologies that were identified outside of the UKSA ISRU survey and Technology Review Workshop. The applicable ISRU functions and subfunctions are provided for each technology. Note that these technologies do not have a technology card and are not represented on the Roadmapping Tool.

Technology	UK Developer(s)	ISRU function(s)	ISRU sub-function(s)	Description
Advanced Closed-Loop Life Support System (ACLS)	MAC SciTech	Processing	Atmospheric Gas Extraction & Processing	A closed-loop life-support system that converts CO ₂ from extraterrestrial atmospheres into oxygen and carbon-based compounds for life support, fuel and manufacturing [92].
All-in-one Mars in-situ resource utilisation system using non-thermal plasma	University of Southampton (SOTON)	Processing	a. Atmospheric Gas Extraction & Processing b. Purification of Liquids and Gases	An integrated, non-thermal-plasma ISRU system that purifies water extracted from Mars and produces oxygen and rocket fuel from the Martian atmosphere [93] [94].

Table C 3: UK “ISRU-enabling” technologies that were identified in the UKSA ISRU survey and Technology Review Workshop.

Technology	UK Developer(s)	International Partner(s)	Description
DUSTER instrument (removing dust from sensitive surfaces)	The Open University (OU)	ESA	A means of concentrating Mars atmosphere for later release in a pressurised pulse to remove dust from sensitive surfaces e.g. solar panels, thermal control surfaces etc. This could enable more efficient/long-lived Mars assets especially rovers by recovering the performance of systems otherwise progressively degraded by dust deposition.
Power systems	NeoWatt	-	Solar energy collection and wireless power transfer.
Short Period Seismometer	Imperial College London, University of Oxford	-	Sub-surface sounding and tomography. Successfully demonstrated on Mars (2018-2022). Planned lunar mission (2028) as part of the Far Side Seismic suite (led by NASA/Caltech/JPL).
AEGIS (Active Electromagnetically Generated Inductive Shield)	RAL Space (STFC)	-	Active radiation protection for astronauts and spacecraft during lunar and Mars missions
RAFTI (Rapidly Attachable Fluid Transfer Interface)	OrbitFab	-	A refuelling port that enables the transfer of liquids and gases between spacecraft without requiring complex grappling or manoeuvring.
GRASP (Grappling and Refuelling Active Solution for Propellants)	OrbitFab	-	An active docking and fluid transfer interface designed to enable spacecraft or surface systems to connect and refuel using ISRU-derived liquids and gases.

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Rear Cover Image: **Plasma Micro-bubble Water (PMW) Reactor**
Credit: University of Southampton

