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EUROPEAN SPACE AGENCY

HUMAN SPACEFLIGHT, MICROGRAVITY AND EXPLORATION PROGRAMME BOARD

Exploration and Utilisation Board (PB-HME/EUB)

ESA 10-year Roadmap for Lunar Surface Science and Technology – Follow-up

Summary

This revised document refines the objectives, principles, and options to define a comprehensive and focused roadmap for Science and Technology activities on the Moon in the next 10 years as part of Cornerstone 3 of the Terrae Novae Programme. This document considers the past and ongoing activities, the outcome of the Council meeting at Ministerial level in November 2022 (CM22), and the need to prepare for the future.

Following iterations and discussions at the May EUB and PB-HME meetings and during a dedicated PB-HME workshop organised in July 2023, this version of the document proposes a prioritisation of the Lunar Pathways introduced in the January EUB document for Period 3 (see section 4). This prioritisation enables to derive new science/technology flight development activities for approval as part of the workplan, taking into account the budgetary situation.

It is to be understood that all budgetary projections presented in this document are only indicative and require further assessment.

Required Action

The Human Spaceflight, Microgravity and Exploration Programme Board is invited to provide comments on the content of the document which aims at serving as a reference document for Period 3, including the prioritisation proposed in section 4. The document may be updated at a later stage in the frame of the preparation of the next Council at ministerial level.

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1. Introduction

Following CM22 and the approval of the Argonaut development to provide access to the surface of the Moon to Europe at the beginning of the next decade, the goal of this document is to integrate all current and future ESA lunar surface exploration activities into a consistent roadmap. It aims to mature the objectives, the principles, and the content of these activities to ensure consistency with the Terrae Novae 2030+ strategy for lunar exploration published in 2022.

Considering the limited budget available in Period 3, a careful prioritisation is required in order to ensure that investment in new activities focuses on the highest priorities and are both affordable and relevant in the international context. This document is intended to help structure the ESA activities and assist in making future decisions.

The Approach for Science and Technology on the Moon discussed at the January 2023 EUB meeting in EUB/W54-02document has presented the overall context (see section 5) and the Lunar Pathways (see section 3 and Annex 2).

The Draft ESA 10 Year Plan presented at the May 2023 EUB and PB-HME meetings (ESA/PB-HME(2023)11) has introduced:

- Six lines of activities with various programmatic frames and various timeframes, and associated budgets (see section 6)
- Three scenarios across the lines and overall indicative budget projections until Period 7 (see sections 7 and 8)
- a refinement of the Lunar Pathways in an update of Annex 2

Twelve key questions have also been put forward by the Executive.

Finally, a dedicated workshop was organised in July 2023 allowing extensive exchanges on the topic.

This updated version aims to take stock of the situation and to reflect the outcomes of the various discussions and the comments received. A section on the link with the Terra Novae strategy is added (section 2) and a prioritisation of the Lunar Pathways (section 4) is proposed. This prioritisation enables to derive new science/technology flight development activities for approval as part of the workplan, taking into account the budgetary situation. In addition, a few refinements of the Lunar Pathways description in Annex 2 are implemented

2. Terrae Novae and the 10-year Roadmap

Figure 1 below illustrates where the 10-year Roadmap implements the Terrae Novae strategy. The document provides axes of reflection to take decisions on which **science/technology surface activities, i.e. development of systems for flight** ESA will invest, at which scale and in which target timeframe.

The 10-year Roadmap for Science and Technology on the Moon supports:

- prioritising and establishing a few targeted domains of European excellence on the lunar surface for the next 10 years
- continuing gathering knowledge about the Moon
- preparing incrementally full-scale capabilities/larger missions
- participating to a crewed campaign on the surface of the Moon

based on current budgetary constraints and projections.

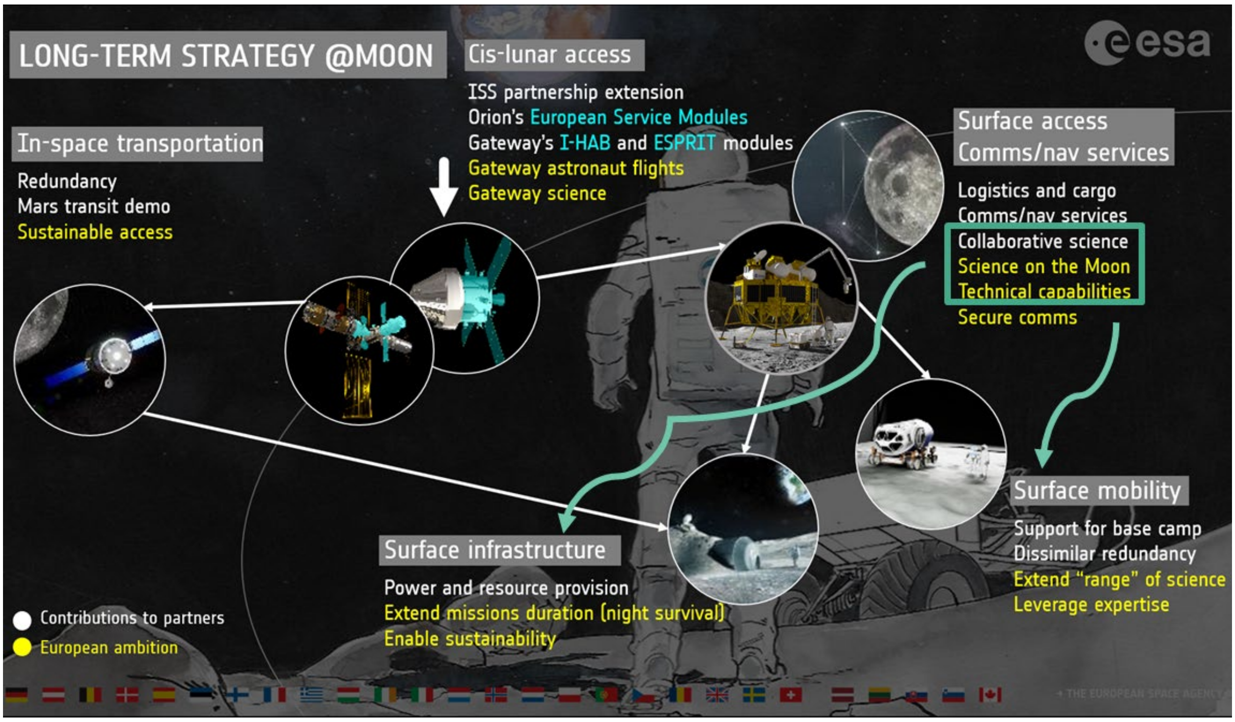


Figure 1: *Roles and benefits enabled by the Terrae Novae Moon strategy, through a stepwise build-up of capabilities in cis-lunar space and on the Moon surface, with 10-year Roadmap elements highlighted in green .*

3. The Lunar Pathways

In line with the Terrae Novae strategy and in order to establish and maintain a focused, consistent and effective investment roadmap for Science and Technology activities on the Moon for Period 3 and beyond, a series of lunar surface exploration capabilities that ESA seeks to master in the future has been laid out in the E3P Period 3 Programme Proposal (ESA/PB-HME(2021)23, rev.5) as listed in the first column of the table below. The exploration capabilities common to Moon to Mars are contained in the Annex of the document ESA/PB-HME(2023)20 "Synergies between E3P and the Inspirator Initiative”:

Lunar Pathways	Exploration Capabilities common to Moon and Mars
Science	CAP-12: Surface Science
Transportation	CAP-7: Precision Entry, Descent and Landing
Communications and Navigation	CAP-6: Communications and Navigation
Energy Management	CAP-5: Power
ISRU	CAP-9: ISRU and ISM
Surface Mobility	CAP-1: Mobility
Crew and Habitation	CAP-10: Crew Elements
Robotics	CAP-3: Drilling, CAP-4: Robotics

Table 1: *Lunar Pathways and Terra Novae capabilities common to Moon and Mars*

For each of these areas, a consistent, affordable and flexible development pathway shall be established, which takes Europe from today's maturity level to an implemented capability consistent with the Terrae Novae 2030+ strategy and with the Exploration Capabilities common to Moon and Mars shown in the second column of the table above.

These development pathways may include technology development, ground testing facilities, flight demonstrations as appropriate, and the eventual development of complete systems for implementation on the Moon, including the possible establishment of services. These complete systems/services may be contributions to international missions and architectures (particularly Artemis) or may be associated with future standalone ESA missions. There are links between the various pathways.

The pathways aim to be a tool to identify options and to support the selection of activities to be covered by the Cornerstone 3 Period 3 budget and later periods in the future, consistent with other activities of Terrae Novae (in particular ExPeRT and SciSpacE), and the relevant multi-directorate initiatives (ENDURE and Moonlight). The nature and extent of the financial and management involvements of ESA in those activities, from a classical ESA development approach to the provision of commercial services, and other schemes in between, are open, to be discussed at a later stage specifically to each activity.

This "pathways" approach allows:

- to derive priorities and keep track of them, thus adapting to budget availability and to modulate the level of investment over time (P3 and beyond), within and between pathways
- to adapt to an evolving European and international context
- to adapt to uncertainties in current and future project timing

A detailed description of each of the Lunar Pathways is provided in Annex 2.

4. Lunar Pathways Prioritisation

The two sub-sections below group the Lunar Pathways into categories of respectively of the highest priority and of medium priority, and provide the rationales for it.

Considering the limited budget currently available in Period 3 (see indications at the beginning of section 7) and the need for timely availability in the global landscape, it is proposed to focus the investment and initiate new activities targeting flight in the Category 1 (highest priority) Lunar Pathways:

- Science: more particularly environment characterisation and monitoring, volatiles characterisation, return of new lunar samples
- and Energy Management

In principle, the Transportation Pathway is considered covered with Argonaut, as well as the Communications & Navigation Pathway with Lunar Pathfinder and Moonlight; certain Technology Payloads may be considered later in Period 3 if the need arises.

4.1 Category 1: Highest Priority

Science

This Lunar Pathway at the heart of exploration encompasses, as mentioned in its description in Annex 2, focused science activities on the Moon, as derived from the overall approach outlined in the Moon annex to the Roadmap for Implementation of the SciSpacE Strategy (ESA/PB-HME/EUB(2023)24) and in more details in the ESA Strategy for Science at the Moon (ESA/PB-HME(2019)11, rev. 1). Prioritisation of science on the Moon is based on the principle of science as an enabler of sustainable exploration, where sustainability includes understanding and managing risks, delivering benefits, responsibly using local resources, and interacting with responsible custodianship of the local environments. On this basis a broader scientific utilisation of the Moon can be established through in situ activities and sample return.

Noting the development needs and the scope and timeframe of opportunities expected in the coming decade (see section 5), the following scientific areas are considered as highest priority (Category 1) since all meaningful if prioritised now:

- Environment characterisation and monitoring
- Characterising lunar resources (in particular polar ice and volatiles)
- The selection and return of new lunar samples through participation in crewed missions

These areas will be complemented later by biology and human health and performance research.

Environment characterisation and monitoring
An important step towards sustainable exploration is understanding the environments we encounter, their impacts on our activities, and our impacts on those environments. ESA and the European scientific community are already working to understand exploration environments and their effects through radiation and other environmental measurements on the ISS, Gateway, Moon surface (NILS payload), TGO and ERO.

It is important to extend this capability further to the Moon’s surface to ensure global knowledge. Here the environment is defined by complex interactions between radiation, plasma, dust and fields. This complex and dynamic environment needs to be precisely understood, for scientific purposes and for design, verification and operational purposes, considering its impacts on the operation of systems, technologies and crew.

Activities to measure and monitor as continuously as possible the lunar environment will provide a visible European contribution on robotic and crewed missions, and could become part of a lunar weather network supporting science and operations. Such a surface payload is envisaged as a package of instruments covering several environment measurements, and as such should federate different scientific communities in an interdisciplinary manner.

As exploration activities increase, the environment of the Moon will be rapidly and permanently changed. The tenuous exosphere for example will quickly become dominated by the products of human activity. If we want to understand the environment scientifically while it is pristine, to understand our impacts upon that environment, and perhaps at some point regulate human impacts on the lunar environment, then measurements from the outset of exploration are essential.

Characterising lunar resources
If we are to conceive of using lunar resources in the future, then ESA needs to prepare and secure the capabilities and roles that will make Europe an important and influential actor in the years to come. The search for lunar resources has become a driver for exploration internationally and is the primary motivation for

the many missions that are targeting the lunar South Polar region, where water ice is known to exist.

The first key step to resource utilisation is understanding precisely the resources that we find. This requires multiple and various investigations to establish whether resources are, or could be, reserves, can be economically extracted, processed and used. ESA has begun this work with PROSPECT and EMS (to fly on CLPS and LUPEX) as part of an ongoing, but not yet coordinated, global campaign to understand ice and other volatile resources at the lunar poles. This will bring also additional knowledge on the regolith properties useful to devise regolith-based ISRU processes. Many more in-situ measurements of different types and at different lunar locations are needed.

An important European scientific community is already very active in this area, with many ground research and laboratory experiments on their way.
An important future step in resources exploration would be a complex mobile mission to a possible ice deposit, but is beyond ESA's near-term horizon.

Selection and return of new lunar samples
Sample return has been and will always be at the heart of scientific discovery in exploration and samples on Earth are a visible, tangible and inspirational product from exploration missions. Europe has led the world in analysing samples from space for hundreds of years, starting with meteorites and engaging since the 1960s in international sample return missions from the Moon, asteroids and cosmic dust. Around 40% of all Apollo samples come to European science labs, and Europeans are deeply involved in multiple international sample return missions. Through MSR, ESA continues building capability in this area. The selection, extraction and return of lunar samples is deeply connected with crew operations, training and capability. A role in sample return connects science, technology, and astronaut activity.

Energy Management

This Pathway encompasses power generation, power distribution, energy storage and thermal properties / thermal control systems for extremely low / high temperature environments, including the transition from one to the other.

Developing advanced capabilities and gaining flight experience in this Pathway is key to gain more European autonomy in lunar surface activities. Exploring the Moon in a sustainable manner at various locations requires long-term viable energy management solutions, in order to enable long operations (much beyond one Lunar day, as mostly possible today) and to serve larger and larger, more and more complex payloads/infrastructures. As such, it is an enabler of the other Pathways, like Science, ISRU etc.

This Pathway presents also multiple synergies with other exploration destinations like Mars, as well as with terrestrial applications. It has also a potential for commercial services as a later stage.

Relying solely on standard technology (batteries and solar cells) will not be feasible and sizing and developing entire systems using as well regenerative fuels cells and nuclear processes are a must.

As the next strategical capability to acquire after landing in order to maximise the return on investment, other players (public and private) are logically placing effort into it as well. It is now up to ESA and the European industry, which presents extensive competences both in terrestrial and space applications to come up with smart and competitive solutions.

Based on all the above, the Energy management Pathway is considered as highest priority (Category 1).

One key flight development is already ongoing with "ENDURE" while ExPeRT is conducting and coordinating several study/technology level activities (RFCS, flexible solar array, charging station study). It is proposed:

- in the short term to complement those with additional activities for flight: surface technology payload(s) as demonstrator(s) and a first flight system enabling night survival for science
- targeting in the medium term the development of a Lunar Power Plant (noting that surface communications network capabilities could be integrated with it)
- in parallel defining and adopting interfaces and interoperability standards for power systems will be needed.

4.2 Category 2: Medium Priority

In Situ Resource Utilisation

This Pathway encompasses all the technical capabilities needed to use local lunar resources as characterised within the Science Pathway (priority Category 1), particularly the development of processes that can be handled in lunar conditions, for consumables production as well as for manufacturing. Extraction and other robotic manipulations are included as part of the Robotics Pathway.
Mastering ISRU would substantially increase the scope of what can be achieved in exploration and marking an important and profound transition in the way we explore.

A first demonstration of resource extraction and processing on the Moon will be performed by PROSPECT, through both heating of water ice and through reduction of lunar materials to extract oxygen. Later activities could focus on preparation of efficient and effective processes, possibly for mineral reduction, which may be scaled to an ISRU plant as a long-term goal, once all the supporting infrastructures are in place.

The interested community is very active and growing in Europe, attracting many new players outside of the space sector, also in synergy with terrestrial applications. This domain is a driver of innovation and certain European actors present specific and unique competences for it.

It is important to highlight that commercialisation of ISRU services on the long term may be the most viable implementation scheme, ESA needs to prepare for it.
A first demonstration of resource extraction and processing on the Moon will be performed by PROSPECT, through both heating of water ice and through experimental reduction of lunar materials to extract a small amount of oxygen. Several activities at study/technology/ground demonstration level have already been initiated in Period 2 (e.g. ISRU-DM and other ExPeRT activities, diverse activities in the frame of ESRIC, TDE activities).

At that point in time, noting that certain types of resources at the Moon (particularly water) are still uncertain and need to be further characterised (see above as part of the Science Pathway), and considering the long-term timeframe for ISRU, this Pathway is considered of medium priority (category 2). The overall ISRU-DM status will be evaluated once the outcomes from the ongoing Phase B1 study and associated technology maturation activities will be available in the course of Period 3. Other activities are proposed to be advanced in Period 3 focusing on technology de-risking and ground research / demonstration, while maturing ESA’s approach to support commercialisation and to engage with a broad community.

Later activities may include:

- small-scale technology payloads in the medium-term, to flight-prove specific equipment or to demonstrate a function or a part of one ISRU process of interest, providing the rationales to test it on the lunar surface are sufficiently strong
- an ISRU plant as a long-term goal, once all the supporting infrastructures are in place.

Surface Mobility

This Pathway refers to mobility on the lunar surface as an enabler for scientific activities, allowing access to different geological units and environments and allowing the deployment of scientific instruments across distributed areas. Mobility, including autonomous GNC, will also be needed for future resource extraction activities (in relation to the ISRU Pathway) and to support human missions.

Robotic mobility on Mars has been developed by ESA for Rosalind Franklin and it is logical to consider advancing this capability further in the lunar context. Several companies and institutes in Europe are investing in this domain as well, most of them focusing on rather small rovers. The potential for commercial services exists also for this Pathway.

In the frame of Artemis, capabilities that have been identified to support human missions include an unpressurised rover to carry crew (so-called Lunar Terrain Vehicle, in preparation within the USA), a pressurised rover (planned to be developed by Japan), within which crew can live and work, and a robotic utility rover (planned to be developed by Canada).

Robotic mobility capabilities to support science and resource exploration that have not been assigned at this time may still be opportunities for ESA in the future. In particular, long range mobility and access to challenging environments (e.g. permanently shaded regions) would be the medium/long term goal for such capabilities, depending on how Artemis evolves.

Various activities at study/technology/ground demonstration level are already on-going under ExPeRT (e.g. European Moon Rover Systems currently in PrePhase A with two parallel contracts).

At that point in time, considering affordability and the long-term timeframe for a European mobility in Artemis, this Pathway is considered of medium priority (category 2) and is proposed to be continued at study/technology/ground demonstration level in Period 3 in ExPeRT. The situation might be re-examined at a later stage in case commercial mobility services become more mature in Europe and depending on the available budget.

Robotics

This Pathway encompasses robotics arms and other types of manipulator / deployment / off-loading / positioning systems, drilling and other sampling / extraction / distribution systems, both from a hardware and software point-of-view, including the associated control algorithms implementing a certain level of autonomy.

It is supporting other Pathways: Science, ISRU, Surface Mobility.

Those systems will be needed on many coming missions, if not all, growing in importance and serving scientific payloads, crew operations and the set-up of large infrastructures on the surface. One long-term goal may be to contribute to the capability of deep drilling.

The drill of Rosalind Franklin is qualified for Mars and operations experience will be built up. Two flight developments are on-going: one about drilling for the Moon in the frame of PROSPECT, one about a robotic arm for STA in the frame of MSR. Other activities at study/technology level are being performed in ExPeRT (e.g. Robotic Manipulator).

At that point in time, while recognising the interest and unique experience in Europe in Robotics, noting that those types of systems are very dependent on the final application they serve and that a number of flight developments are already ongoing, this Pathway is considered of medium priority (category 2) and it is proposed to continue advancing it at study/technology level in Period 3 in

ExPeRT. In particular, a deployment mechanism for the Argonaut missions will be developed in the frame of the Argonaut Mission Phase A/B1.

Crew and Habitation

This Pathway encompasses

- systems, subsystems, tools and equipment (e.g. handheld scientific instruments) supporting the crew operational activities during surface exploration campaigns;
- Human Health Care systems and exercise equipment;
- Module(s) for a lunar habitat and related environmental control and life support (ECLS) systems.

While the first two will be needed as of the first Artemis mission, the last two are longer term since required by missions implementing a longer stay of the crew. Still, physical-chemical life support systems are expected to be used in a fist stage, supplemented by the provision of LSS consumables by logistic services if required.

This Pathway presents a synergy with the ECLS systems needed for crew transportation, as well as with certain functions with the ISRU Pathway (e.g. electrolyser, water treatment).

There is already flight development in this area: ACLS is flying on the ISS and the experience gained in demonstrating such a complex closed-loop system is very valuable; ANITA is also onboard of the ISS and being upgraded; last but not least, elements of an Exploration Medical System (ExMS) are being tested on the ISS and will fly on the Gateway and Artemis 2 and 3 missions. ESA will also provide an Exploration Exercise device for testing on the ISS and operational use on the Gateway. Europe has developed habitat modules for the ISS and soon for the Gateway. Thus one logical long-term goal may be to contribute to a surface habitat.

Other activities at study/technology/ground demonstration level are being performed in ExPeRT (e.g. Inspirator vehicle concept CDF studies, LSS technologies including MELiSSA, Electronics Field Book).

At that point in time, considering the relevant timeframes, this Pathway is considered of medium priority (category 2) and is proposed to be advanced at study/technology/ground demonstration level in Period 3 in ExPeRT.

5. Programmatic Considerations

Budget

A systematic prioritisation within and between the Lunar Pathways is required to be compatible with the expected budgetary conditions in Cornerstone 3 Period 3 for the Science and Technology activities on the Moon ("non-Argonaut" activities). This prioritisation requires a long-term planning in order to take into account realistic budget corridors to be foreseen for P4, P5 and even beyond.

Effective internal coordination with all relevant activities of the Terrae Novae Programme, in particular ExPeRT (technology maturation up to TRL 5) and SciSpacE is essential and is being systematically implemented by the Executive.

Timeframe

The first ESA activities on the lunar surface have been started in E3P Periods 1 and 2 through missions of opportunity with international and commercial partners identified in a relatively ad-hoc manner. Pending a successful launch and landing, the first ESA payload (EMS-CLPS) should be operated on the Moon by the end of 2023 and all the already committed Mission of Opportunity payloads will be delivered and brought to flight by 2026/27. This is shown in Annex 1.

Any new payload development starting at the beginning of P3 will probably not be ready for flight before 2027-28 (assuming about 6 months procurement, about 3-5 years development, and about 9 months before launch for the delivery/integration). As a result, it is urgent to update ESA's objectives for lunar Science and Technology activities on the Moon, and, within budget constraints, select new projects for implementation. These shall:

- bridge the gap in the 2027-2030+ timeframe for robotic missions, between the last delivery of already approved ESA payloads and the Argonaut Mission #1
- ensure the effective use of Artemis human missions; Argonaut robotic missions; and any other relevant lunar mission opportunities to advance the implementation of the ESA science and technology objectives.

Lunar Transportation

In the next 10 years, possible transportation options include: US (Commercial Lunar Payload Services (CLPS)) and non-US commercial landers, Artemis Human Landing Systems (HLS), projected large NASA cargo landers, the ESA Argonaut Lunar Descent Element (LDE), and other international landers (from Agencies other than NASA such as Japan and South Korea).

As shown in Annex 1, following the termination of the cooperation with Roscosmos on the Luna missions, all of the already committed "Mission of Opportunity payloads" except two (NILS and EMS-LUPEX) will fly on NASA CLPS missions, and all except one (LandCam-X) in a cooperation framework with non-exchange of funds. This type of access to CLPS flights for ESA science payloads may become more difficult from now on. This is because, as the CLPS programme becomes more established, NASA already has a large payload pool for future missions. It should be noted that – until the availability of Argonaut in the 2030s -- commercial delivery will be the most feasible option for ESA technology payloads since flights in cooperation with international partners for technology demonstrations are unlikely to be secured.

Regarding the ESA approach to commercial landing services, the outcome of the fast-track pilot phase with each of the three proposers has been presented at the PB-HME (see ESA/PB-HME(2023)13). More information is also provided as part of Line 4 in section 4. In summary, several commercial landers with varying degrees of European content are or could be available, subject to budget availability.

6. Lines of Development Activities for Flight and Operations on the Moon in the Next 10 Years

<u>Important Note:</u> all the budget figures in this document are notional and need to be consolidated and revised progressively, in parallel to the maturation of the scope of the activities.

Based on the programmatic considerations above, ESA development activities for flight and operations on the Moon in the next 10 years have been categorised in the following six (6) lines, each being described below.

Line 1: European Payload Onboard Argonaut Missions #1, #2 and #3	
Strategic Assumptions	ESA will reserve 100-150kg (TBC) for European Science and Technology payloads on each of the three (3) first Argonaut missions as complementary to the NASA Artemis payload. Note: <u>It is assumed that:</u> - the primary payload of the first 3 Argonaut missions will be NASA-driven in support of the Artemis missions - an ESA-driven mission, for which different options have been studied in Period 2, would not be affordable before Argonaut #4, Argonaut#4 not being in the scope of this document.
Strategic Rationales	Line 1 enables a minimum European-driven utilisation onboard the new and key ESA Argonaut capability approved at CM22 It makes sense that the scientific and technological community at large in Europe benefits directly from this unique ESA access to the lunar surface.
Description	There are multiple options to define a complementary European payload onboard the first Argonaut missions, combining Science and/or Technology payload(s), as one package or several independent elements. It must be compatible with the NASA Artemis primary payloads for these missions.

Line 1: European Payload Onboard Argonaut Missions #1, #2 and #3	
	Based on studies conducted during Period 2, the following candidate Science and Technology payload options are identified: a. Space weather station (Science Pathway, Energy and Communications Pathways TBD): - synergy with space weather station deployed on the surface by an Artemis crew (also under consideration, see Line 5); meaningful if at a different location - TBD need for a self-standing onboard power/communications package depending on the Argonaut CPE capabilities b. Biology laboratory (Science Pathway) - Synergy with Gateway and Low Earth Orbit research, addressing science and exploration needs c. Geophysics package (Science Pathway, Energy and Communications Pathways TBD): - deployed on the lunar surface - TBD need for a self-standing onboard power/communications package depending on the Argonaut CPE capabilities d. Surface mobility demonstration (size TBD) (Surface Mobility Pathway) e. Scaled regenerative fuel cells system (or part of it) (Energy Pathway) - to be determined if a useful sized system can be accommodated on Argonaut as a complementary payload - possibly as a charging station in combination with surface mobility f. Scaled ISRU system (or part of it), including regolith extraction e.g. arm, scoop, or drill) (ISRU and Robotic Manipulation Pathways) - TBD if this can work as a complementary payload given the system implications for the Argonaut CPE - TBD need for a self-standing onboard power/communications package depending on the Argonaut CPE capabilities a., b. and c. are consistent with the lunar science prioritisation suggested in Annex 4 of the Roadmap for Implementation of the SciSpacE Strategy document.

Line 1: European Payload Onboard Argonaut Missions #1, #2 and #3	
CS#3 ROM Budget	100-150 M€per mission with average of 120M€ assumed It is assumed that the cost to accommodate/integrate the payloads with Argonaut and to provide certain generic services is covered on the Argonaut side at mission level.
Funding / Procurement Approach	All the interfaces on the Argonaut side (LDE and CPE) are assumed to be under the control of ESA. Different schemes for payload funding exist. Payloads could be funded entirely through ESA, co-funded by national agencies, or entirely contributed by national agencies or international partners. It is assumed that ESA would provide the payload(s) as Customer-Furnished-Item(s) (CFIs) to the Argonaut mission Prime Contractor.
Selection Process	ESA would first define a model payload for the first Argonaut mission following an assessment of the benefits, drawbacks, costs and maturity of the above options. Following consultation and approval by PB-HME a comprehensive definition and selection will be undertaken.
Advantages	The concept is scalable and can be adapted to the specificities of each Argonaut mission and to other programmatic conditions, including budget. It is versatile: a single element might be considered or multiple ones; the scope can be adapted to the primary NASA Artemis payload.
Risks / Open Points	The accommodation/integration of the European payload may add complexity the Argonaut mission design, particularly the CPE, which must serve the Artemis payload with potentially incompatible requirements. In case of resource limitations once the design is consolidated (mass, energy), the European complementary payload may not have priority. It will require a timely coordination of each of the Argonaut development activities: LDE, mission and payload(s).

Two different options for the preliminary budget allocation for *Line 1: European Payload Onboard Argonaut Missions #1, #2 and #3* are considered as a starting point:

<u>Option 1.a: minority ESA financial contribution</u>
This option assumes that two-thirds (2/3) of the payload funding comes from other sources than E3P (other ESA budgets, national, tbd international partner, etc.). ESA’s role may be more considered as a “lunar transportation provider” and “payload aggregator”.

Option 1.b: majority ESA financial contribution

This option assumes that one-third (1/3) of the payload funding comes from other sources than E3P (other ESA programmes, national, international partner etc.). ESA would be in a more leading role than in option 1.a, driving the objectives and the development.

The level of co-funding and its implementation needs to be discussed and may be modulated, depending on the Argonaut mission and on the type of payload within a mission (e.g. science or technology).

ESA E3P CS#3 funding
Other funding sources: other ESA programmes, national, international partner

Line 1 Option 1.a	P3 (2023-2025)	P4 (2026-2028)		P5 (2029-2031)		P6 (2032-2034)		P7 (2035-2037)			TOTAL	
Payload Argonaut #1		30	60	10	20						40	80
Payload Argonaut #2				30	60	10	20				40	80
Payload Argonaut #3						30	60	10	20		40	80
TOTAL		30	60	40	80	40	80	10	20		120	240

Table 2: *a: Preliminary budget allocation for Line 1: European Payload Onboard Argonaut Missions #1, #2 and #3 – Option 1.a: minority ESA financial contribution*

Line 1 Option 1.b	P3 (2023-2025)	P4 (2026-2028)		P5 (2029-2031)		P6 (2032-2034)		P7 (2035-2037)			TOTAL	
Payload Argonaut #1		60	30	20	10						80	40
Payload Argonaut #2				60	30	20	10				80	40
Payload Argonaut #3						60	30	20	10		80	40
TOTAL		60	30	80	40	80	40	20	10		240	120

b: *Preliminary budget allocation for Line 1: European Payload Onboard Argonaut Missions #1, #2 and #3 – Option 1.b: majority ESA financial contribution*

Line 2: Astronaut Tools and Equipment For Lunar Surface Campaigns	
Strategic Assumptions	There will be an ESA astronaut on the surface of the Moon by the beginning of the next decade and ESA will contribute substantially to the mission in which they will participate.
Strategic Rationales	Line 2 allows: - to ensure ESA participates in and drives its first human mission to the lunar surface and is more than a passenger - to advance ESA's astronaut operations and training capabilities
Description	In general, ESA will provide tools and equipment that astronauts will use to conduct lunar surface campaigns and that will support surface operations involving the crew. These tools could include: - An Electronic Field Book (EFB) which provides a suite of instruments (analytical tools, imaging devices) and visualisation/documentation tools providing both field and remote science support personnel situational awareness and rapid decision support - LESA (Lunar Equipment Support Assembly / Lunar Evacuation System Assembly) is an innovative mobile modular equipment transport system for lunar EVA astronauts providing both functions in a single device. - Hand-held scientific instruments (e.g. for geological surveys)
	Some ESA tools and equipment must be used in earlier Artemis surface missions not involving ESA crew in order to become part of the architecture from the very beginning.
CS#3 ROM Budget	20 M€ per period starting in Period 4. 10 M€ tentatively allocated in Period 5 to prepare a European crew member in an Artemis surface mission.
Funding / Procurement Approach	The development of the tools and equipment would be funded by E3P. Some options could exist for individual devices or elements to be provided as national contributions.
Selection Process	n/a

Line 2: Astronaut Tools and Equipment For Lunar Surface Campaigns	
Advantages	A modular, flexible and scalable tool kit that can be adapted to future missions could provide a visible and affordable ESA contribution to all Artemis surface missions.
	It could give a direct access to mission, operational, scientific and engineering data.
Risks / Open Points	Adoption of these contributions into a crewed mission requires that NASA accept this and lead the integration of these ESA operational capabilities into the crewed surface scenario.

The preliminary budget allocation for *Line 2: Astronaut Tools and Equipment for Lunar Surface Campaigns* is provided below, assuming there is about 25% co-funding from sources other than E3P (other ESA programmes like GSTP, national, etc.). The level of co-funding and its implementation shall be discussed with delegations.

ESA E3P CS#3 funding
Other funding sources: other ESA programmes (GSTP), national

Line 2	P3 (2023-2025)	P4 (2026-2028)		P5 (2029-2031)		P6 (2032-2034)		P7 (2035-2037)			TOTAL	
Astronaut Tools and Equipment	(ExPeRT)	15	5	15	5	15	5	15	5		60	20
Special allocation for European Astronaut Mission				10							10	0
TOTAL		15	5	25	5	15	5	15	5		70	20

Table 3: *Preliminary budget allocation for Line 2: Astronaut Tools and Equipment for Lunar Surface Campaigns*

Line 3: Large ESA Facilities/Infrastructures	
Strategic Assumptions	In the long term, ESA will contribute to a (few) large infrastructure(s) on the surface of the Moon.
Strategic Rationales	Full-scale surface elements supporting a Moon base-camp or another ambitious lunar initiative will be the end objective on (a few of) the Lunar Pathways. This long- term vision needs to be progressively developed, taking into account the progress of Artemis as well as the European will to develop greater autonomy.
Description	Options include: - Charging station (ECSM Pre-Phase A ongoing) (Energy Pathway) - Large mobility rover (EMRS Pre-Phase A ongoing) (Surface Mobility Pathway) - ISRU plant (CDF completed in 2022) (ISRU Pathway) - Habitation module (Habitation Pathway) - Life support systems (Habitation Pathway) For some options, studies in ExPeRT have already been started. Note: there could be synergies with a potential ESA-driven Argonaut mission
CS#3 ROM Budget	550 M€ total allocation.
Funding / Procurement Approach	100% E3P funding is assumed. This could evolve, for example if more commercial approaches are adopted.
Selection Process	n/a
Advantages	To be determined once the scope of the large facility/infrastructure is better known.
Risks / Open Points	To be determined once the scope once the scope of the large facility/infrastructure is better known.

The preliminary budget allocation for *Line 3: Large Facilities/Infrastructures* is provided below, assuming all until Period 7 is funded by E3P (no co-funding). The situation may evolve depending on the extent lunar commercial activities on the surface may become viable.

ESA E3P CS#3 funding
Other funding sources

Line 3	P3 (2023-2025)	P4 (2026-2028)	P5 (2029-2031)		P6 (2032-2034)		P7 (2035-2037)			TOTAL	
Large Infrastructure(s)		(ExPeRT)	50	0	250	0	250	0		550	0
TOTAL			50	0	250	0	250	0		550	0

Table 4: *Preliminary budget allocation for Line 3: Large Facilities/Infrastructures*

Line 4: Small-Class Opportunity Payloads	
Strategic Assumptions	ESA will continue flying several small-class opportunity payloads to the surface of the Moon within this decade before Argonaut#1, both for science and technology purposes. A decision is made whether ESA shall support the “Europeanisation” of one existing landing services provider through purchase of services.
Strategic Rationales	Line 4 allows: - to gain rapid experience in developing for and operating in lunar conditions - to provide continuity with respect to the already approved lunar payloads under implementation (see Annex 1) - to be agile in the uncertain environment. Depending on the option chosen for commercial transportation (see option 4.b below the table), this Line may also enable an existing commercial landing services provider (none based in Europe today) to make more use of European competences and equipment, broadening his footprint in ESA Member States. Possible consortia are presented in ESA/PB-HME(2023)13, each with their own distinct implementation idea. Such small-class opportunity payloads may be feasible at national level but ESA can bring added value in certain ad-hoc frameworks (e.g. technology payload, small/medium entities, entities with limited space experience).

Line 4: Small-Class Opportunity Payloads		
	Beyond 2030, with Argonaut becoming available and assuming that Artemis and other initiatives mature, this line may become less important for ESA. Still, there may be an interest to keep it since it offers flexibility and is independent of the Argonaut missions.	
Description	A small-class Science/Technology payload is considered to be in the order of +/-20kg. This line has already been started in Period 1 and Period 2 with 5 payloads already committed (see Annex 1).	
	The most feasible flight opportunities by 2030 for such small-class payloads are: - onboard a non-ESA lander/rover via cooperation with a space agency (no budget needed for lunar transportation) - or via a commercial procurement (budget required for lunar transportation)	
	It is expected that onboard those missions, no long-duration operations on the surface of the Moon will be possible still for some time, until night lunar survival technologies are available.	
CS#3 ROM Budget	See tables below (2 options: 45/90 MEuros per period from Period 4). In Period 3, the budget is adjusted specifically for each scenario in section 6 to what is remaining once the other relevant lines have been covered.	
Science Payloads	Funding Approach	E3P/national co-funding. Funding from other ESA programmes (PRODEX) to be discussed. ESA support to a nationally funded payload flying with a non-ESA landing entity, on a case by case basis.
	Selection Process	Selected from a 3-year rolling pool resulting from a Lunar Small-Class Science Payload Announcement of Opportunity; the first one was conducted in 2022, (see ESA/PB-HME(2023)9.) Flight opportunities identified as they arise, on the basis of “first come, first served” provided interest is confirmed, until depletion of the budget earmarked for science payloads.

Line 4: Small-Class Opportunity Payloads		
	Time to flight	~3 years between selection for an identified flight opportunity and delivery of the FM
	Candidates	Candidates (Science Pathway) are described in the Selection of Proposals from the Reserve Pool of Science Activities for the Moon 2022 Announcement of Opportunity (AO) document (ESA/PB-HME(2023)9).
Technology Payloads	Funding Approach	Nominally, E3P funding but funding from other ESA programmes (GSTP) to be discussed. Industrial co-funding not excluded, particularly in later periods if techno payloads with a commercial interest become viable.
	Selection Process	Scope and main boundary conditions to be proposed by the Executive and approved by the EUB/PB. Selected from a future focused Lunar Small-Class Technology Open Call; the first one would need to be organised in the 2nd half of 2023
	Time to flight	~4 years between selection for an identified flight opportunity and delivery of the FM
	Candidates	Candidates are listed in section 6 of the document ESA/PB-HME(2022)18 (Candidate ESA payloads for delivery by commercial lunar transportation services). This list will be updated to include a landing navigation payload using an existing model of the PILOT-D camera, complemented with visual algorithms (one step beyond LandCam-X). This will address some Pathways among the Navigation, Energy, ISRU, Surface Mobility and Robotic Manipulation ones.
Commercial Transportation	Funding Approach	In principle E3P. TBD funding from GSTP and/or ScaleUp.
	Procurement Approach	Restricted ITT (with potential bidders identified in ESA/PB-HME(2023)13) for accommodation, flight, operations and data provision of Techno payloads, with a mixed offer/partnership.

Line 4: Small-Class Opportunity Payloads	
Advantages	This Line includes multiple small elements and is scalable “on-the-go” according to the budget available.
	A riskier development approach may be acceptable, resulting in a faster delivery of flight hardware.
Risks/ Open Points	ESA internal effort needed to set up each relatively small project with both the payload and transportation providers (space agency, commercial provider, or both).

The preliminary budget allocation for *Line 4: Small-Class Opportunity Payloads* includes not only lines for the payloads themselves (Science and Technology), but also for the transportation. Two different options are considered:

<u>Option 4.a: limited use of existing commercial transportation</u>
Budget is spent on transportation for Technology payloads (not for science payloads). About 1M€/kg is assumed.

<u>Option 4.b: extended use of existing commercial transportation and support to their development in Europe</u>
A higher budget allocated towards at least one commercial lander provider, ensuring their expansion of activities, services, and procurement of software/hardware in ESA Member States.

The level of co-funding assumed for the Science Payloads and their implementation needs to be discussed.

ESA E3P CS#3 funding
Other funding sources: Prodex, national, industry

Option 4.a	P3 (2023-2025)	P4 (2026-2028)		P5 (2029-2031)		P6 (2032-2034)		P7 (2035-2037)			TOTAL	
Science Payloads		10	10	10	10	10	10	10	10		40	40
Techno Payloads		20		20		20		20			80	0
Commercial Transportation		15		15		15		15			60	0
TOTAL		45	10	45	10	45	10	45	10		180	40

Table 5: a: *Preliminary budget allocation for Line 4: Small-Class Opportunity Payloads, Option 4.a: <u>limited use of existing commercial transportation</u>*

Option 4.b	P3 (2023-2025)	P4 (2026-2028)		P5 (2029-2031)		P6 (2032-2034)		P7 (2035-2037)			TOTAL	
Science Payloads		20	15	20	15	10	10	10	10		60	50
Techno Payloads		30		30		20		20			100	0
Commercial Transportation		40		40		15		15			110	0
TOTAL		90	15	90	15	45	10	45	10		270	50

b: *Preliminary budget allocation for Line 4: Small-Class Opportunity Payloads, Option 4.b: extended use of existing commercial transportation*

Line 5: Medium-Class Strategic Payload for Artemis Missions	
Strategic Assumptions	ESA shall fly a medium-class payload to the surface of the Moon within this decade before Argonaut #1, as a strategic and visible investment in Artemis surface mission(s) with near-term benefits. ESA shall prioritise investigations that support exploration and the capability of lunar night survivability on the Energy Path. Night survivability is the next enabler after landing, increasing the surface mission duration from several days, as of today, to several months/years, and thus a must to make lunar exploration sustainable on the medium/long term. ESA shall start investing as soon as possible in developing a flight system.
Strategic Rationales	Line 5 enables: - to have ESA visibly involved in Artemis crewed missions on the lunar surface - to fly a payload suite answering to a set of key exploration and science objectives at Agency level - to start developing night survival/energy management capabilities in an incremental approach with ESA-added value considering the size and complexity.
Description	A medium-class payload is considered to be in the order of +/- 100kg. It is a step beyond the most complex lunar surface payloads suite under development by ESA today (PROSPECT, ~45kg, no lunar night survivability).

Line 5: Medium-Class Strategic Payload for Artemis Missions	
	The most feasible flight opportunity by 2030 for such a medium-class payload is in the frame of an Artemis crewed surface mission in cooperation with NASA, who would cover the transportation cost, while sharing the benefits of long-duration surface operations. The delivery of the Flight Model is targeted for mid-2028. Note: NASA has expressed their general interest.
	It could consist of an instrument package combined with a power/communications servicing package, deployed on the surface by the crew, standalone (reducing the risk of uncertain interfaces with the lander).
	Based on payload studies conducted in Period 2 and in line with the first lunar science prioritisation outlined in Annex 4 of the Roadmap for Implementation of the SciSpacE Strategy, a Lunar 'Weather Station' is proposed as the first medium-class strategic payload. It will include a suite of instruments to investigate the radiation, dust, plasma, and charging environment on the Moon. This provides characterisation of the environment where crew and robots will need to live and work. It also addresses fundamental science questions about the Moon and all airless bodies in the Solar System, measurements that are essential before this environment is forever changed by human activity. The package would use a power/communications package using mature technologies to ensure a timely and competitive development.
	A subsequent, second medium-class payload (for the next decade) could address other scientific objectives identified in the ESA Lunar Science Strategy (Annex 4 of the Roadmap for Implementation of the SciSpacE Strategy), for example in geophysics or biology (exposure facility). It could use a power/communications servicing package with European RHUs or even RTG. A possible ESA cryogenic lunar sample return capability for use within the Artemis programme may also be considered, with a view to cover on the long-term the end-to-end chain (until return to the Earth).

Line 5: Medium-Class Strategic Payload for Artemis Missions	
Funding / Procurement Approach	The power/communications servicing package is expected to be funded by ESA (E3P mainly, GSTP tbd) while the instruments could be funded in an ad-hoc manner: nationally, by international partners (NASA others), or co-funded with ESA to a tbd level. Note: the interfaces on the power/communications servicing package side would be under the control of ESA.
Science Selection Process	An Open Call to be organised with a focus on the domains pre-identified for the payload model. The way to coordinate with the NASA science selection process needs to be determined.
Advantages	The concept is scalable, depending on the selected sizing of the power/communications package based on its potential instrument users and can adapt to the available mission resources and other programmatic conditions, including budget.
	It is versatile: it could also be a candidate for the ESA secondary payload on Argonaut.
	The power/communications package is a “utilisation enabler”, of interest for other missions, also in an evolved version.
	It is a potential user of the European lunar asset Moonlight, and possibly of Lunar Pathfinder.
Risks / Open Points	This line of activity is NASA-driven. The compatibility with the NASA science selection process and its timeline is to be discussed with NASA, noting that two separate science calls from NASA for Artemis 3 and Artemis 4 will be imminently released and open to the international community at large.
	The sizing considering the number and characteristics of the instruments and the feasibility of the power/communications servicing package is to be iterated.
	The requirements related to handling by an astronaut and safety need to be tackled early.
	- Timeline of ESA science selection process - Procurement approach and acceptable level of risks for a fast development - Level of modularity/genericity - Instruments tethered or included in a single enclosure with the power/communications package

The preliminary budget allocation for *Line 5: Medium-class Strategic Payload for Artemis Missions* is provided below. The level of co-funding for the instrumentation package and its implementation needs to be discussed.

ESA E3P CS#3 funding
Other funding sources: other ESA programmes, national, international (TBD)

Line 5	P3 (2023-2025)		P4 (2026-2028)		P5 (2029-2031)		P6 (2032-2034)		P7 (2035-2037)			TOTAL	
Lunar Weather Station	5		15	5	5							25	5
Power/comms Package #1	5		65		5							75	0
Instruments Suite #2			5		15	5	5					25	5
Power/comms Package #2			5		55		5					65	0
TOTAL	10	0	90	5	80	5	10	0				125	10

Table 6: *Preliminary budget allocation for Line 5: Medium-class Strategic Payload for Artemis Missions*

Line 6: Small Lunar Mission	
General	See document Selection Process for Small Mission Studies (ESA/PB-HME(2023)17, rev.1 , which describes the overall approach regarding the small mission concept in general, including to the Moon.
Strategic Assumptions	ESA will offer an alternative at mission-level to large and complex end-to-end landing missions with Argonaut.
Strategic Rationales	A small mission should address European actors that are not involved or have limited involvement in Argonaut and lunar payload activities described above. A small mission may allow new procurement approaches and partnership schemes.
Description	Such a small lunar mission may be a small orbiter (e.g. cubesat) or a small surface mobile element.
	It is assumed that a first small lunar mission should fly in this decade in order to boost the development of competences in Europe and to keep up with other small lunar initiatives worldwide.
	The approach for transportation to lunar orbit or to the lunar surface would need to be established.
CS#3 ROM Budget	120 M€ for one mission (could be less cf. Lunar Pathfinder)

Line 6: Small Lunar Mission	
Funding / Procurement Approach	It is assumed that ESA would fund roughly 5/6 of the mission through E3P as the main contributor in order to manage and support directly new actors in the lunar exploration field. 1/6 is assumed to be funded via other ESA programmes, nationally, or possibly with an international contribution. Depending on the exact scope, a more commercial approach could also be considered.
Advantages	To be determined once the mission scope is better known.
Risks / Open Points	To be determined once the mission scope is better known.

The preliminary budget allocation for *Line 6: Small Lunar Mission* is provided below, assuming the first small mission is to the Moon in this decade (no other planned to the Moon afterwards).

ESA E3P CS#3 funding
Other funding sources: other ESA programmes, national, tbd international

Line 6	P3 (2023-2025)	P4 (2026-2028)		P5 (2029-2031)		P6 (2032-2034)		P7 (2035-2037)			TOTAL	
Small Lunar Mission	(ExPeRT)	90	15	10	5						100	20
TOTAL		90	15	10	5						100	20

Table 7: *Preliminary budget allocation for Line 6: Small Lunar Mission*

7. Indicative Scenarios

Based on the lines identified above, several scenarios have been built covering Period 4 until Period 7, corresponding to different priorities and budgetary envelopes starting from Period 4. Once established and as a last step, the constrained budget available in Period 3 is distributed in order to prepare consistently the next periods. Table 1, below, presents possible Period 3 financial allocations for non-Argonaut CS#3 activities.

Budget released from PILOT cancellation (E3P1)	+ 25 MEuros
New budget from E3P3 CM22	+ 9 MEuros
E3P3 ISRU activities pre-allocation	- 5 MEuros
Allocation for existing (committed) payloads	- 3 MEuros
Assumption for new budget available in 2024 (release of Period 3 contingency)	+ 14 MEuros
TOTAL	40 MEuros

Table 8: *Working assumptions regarding non-Argonaut Cornerstone 3 budget availability following CM22.*

All the scenarios presented below assume that:

1. A European payload onboard Argonaut (Line 1) is planned for each of the first three missions in order to ensure, from the beginning, a significant European-driven utilisation of this new ESA capability approved at CM22.
2. Tools and equipment for astronauts' activities on the Moon (Line 2) are planned every Period, supporting the longer-term vision of the programme to have European boots on the Moon and ensuring there is also a European contribution to their "utilisation" during the lunar surface campaigns.
3. The development of a larger surface facility/infrastructure (Line 3) starts only in Period 5.

Scenario 1: Minimum ESA presence on the Moon

Option 1.a with a minority ESA financial contribution to the European payload onboard Argonaut is assumed for this minimum scenario.

In addition to Lines 1 (Option 1.a), 2 and 3, *Line 4: Small Opportunity Payloads* is added. It allows:

- to avoid a gap after the last already committed payload (PROSPECT FM delivery end 2025) and to implement a second wave of ESA small opportunity payloads to fly by the end of the decade until the Argonaut mission #1 (corresponding to P4 budget and possibly partly P5)
- to still offer some flexibility in parallel to the Argonaut missions later in the 2030s

Option 4.a (no direct support to a commercial landing service provider with an acceptable footprint in Europe) is assumed for this minimum scenario.

In this scenario, ESA presence on the lunar surface remains limited and sporadic until Argonaut#1. There is little incremental preparation of future larger surface elements via return of flight experience and operations. The ramp-up starts from Argonaut#1, noting the significant contribution assumed from funding sources outside of E3P.

ESA E3P CS#3 funding
Other funding sources (see details in section 5)

Scenario 1	P3 (2023-2025)*		P4 (2026-2028)		P5 (2029-2031)		P6 (2032-2034)		P7 (2035-2037)		TOTAL	
Line 1: European Payload for Argonaut #1, #2 and #3	(ExPeRT)		30	60	40	80	40	80	10	20	120	240
Line 2: Astronaut Tools and Equipment for Lunar Surface Campaigns	(ExPeRT)		15	5	25	5	15	5	15	5	70	20
Line 3: Large Facilities/Infrastructures			(ExPeRT)		50		250		250		550	0
Line 4: Small-class Opportunity Payloads	40	5	45	10	45	10	45	10	45	10	180	40
TOTAL	40	5	90	75	160	95	350	95	320	35	920	300

*Available to be invested during Period 3 (not all part of P3 subscription)

Table 9: *Scenario 1 Preliminary Budget Projection from P3 to P7*

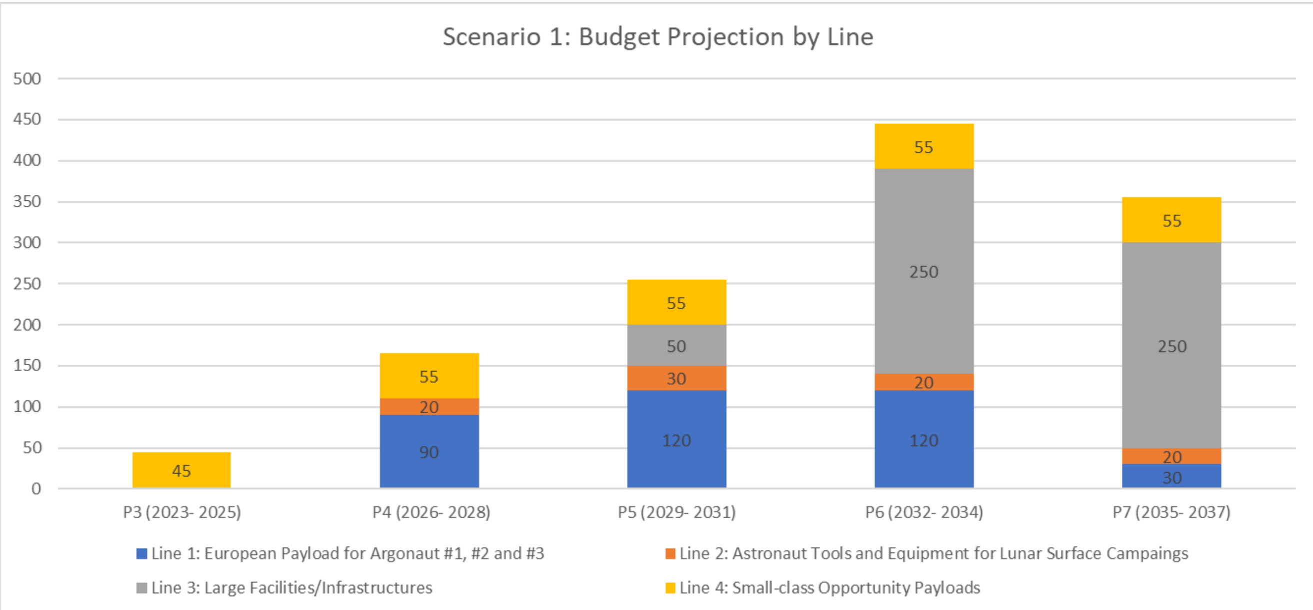


Figure 1*: Scenario 1 Preliminary Budget Projection from P3 to P7*

Scenario 2: ESA on the Moon in this decade and beyond

Compared to Scenario 1, scenario 2 considers:

- Option 1.b (and not 1.a) with a majority ESA financial contribution to the European payload onboard Argonaut is assumed for this scenario
- Option 4.a, with no direct support to a commercial landing service provider with an acceptable footprint in Europe, is still assumed
- In addition to Lines 1 (Option 1.b), 2, 3 and 4 (Option 4.a), *Line 5: Medium-class payload for Artemis Missions* is added

In this scenario, ESA presence on the lunar surface becomes already visible on an Artemis crewed mission in this decade, with a key first step on the Energy Path, while working in parallel on the European payload for Argonaut #1. Such a scenario allows the progressive build-up, in this decade and in the next one, of a robust ESA roadmap for Science and Technology of the Moon, with a few types of investment. The funding assumed from sources outside of E3P, although less than in Scenario 1, should still be noted.

ESA E3P CS#3 funding
Other funding sources (see details in section 5)

Scenario 2	P3 (2023-2025)*		P4 (2026-2028)		P5 (2029-2031)		P6 (2032-2034)		P7 (2035-2037)		TOTAL	
Line 1: European Payload for Argonaut #1, #2 and #3	(ExPeRT)		60	30	80	40	80	40	20	10	240	120
Line 2: Astronaut Tools and Equipment for Lunar Surface Campaigns	(ExPeRT)		15	5	25	5	15	5	15	5	70	20
Line 3: Large Facilities/Infrastructures			(ExPeRT)		50		250		250		550	0
Line 4: Small-class Opportunity Payloads	30	5	45	5	45	10	45	10	45	10	180	40
Line 5: Medium-class Strategic Payload for Crewed Artemis	10		90	5	80	5	10				190	10
TOTAL	40	5	210	45	280	60	400	55	330	25	1230	190

**Available to be invested during Period 3 (not all part of P3 subscription)*

***Table 10:** Scenario 2 Preliminary Budget Projection from P3 to P7*

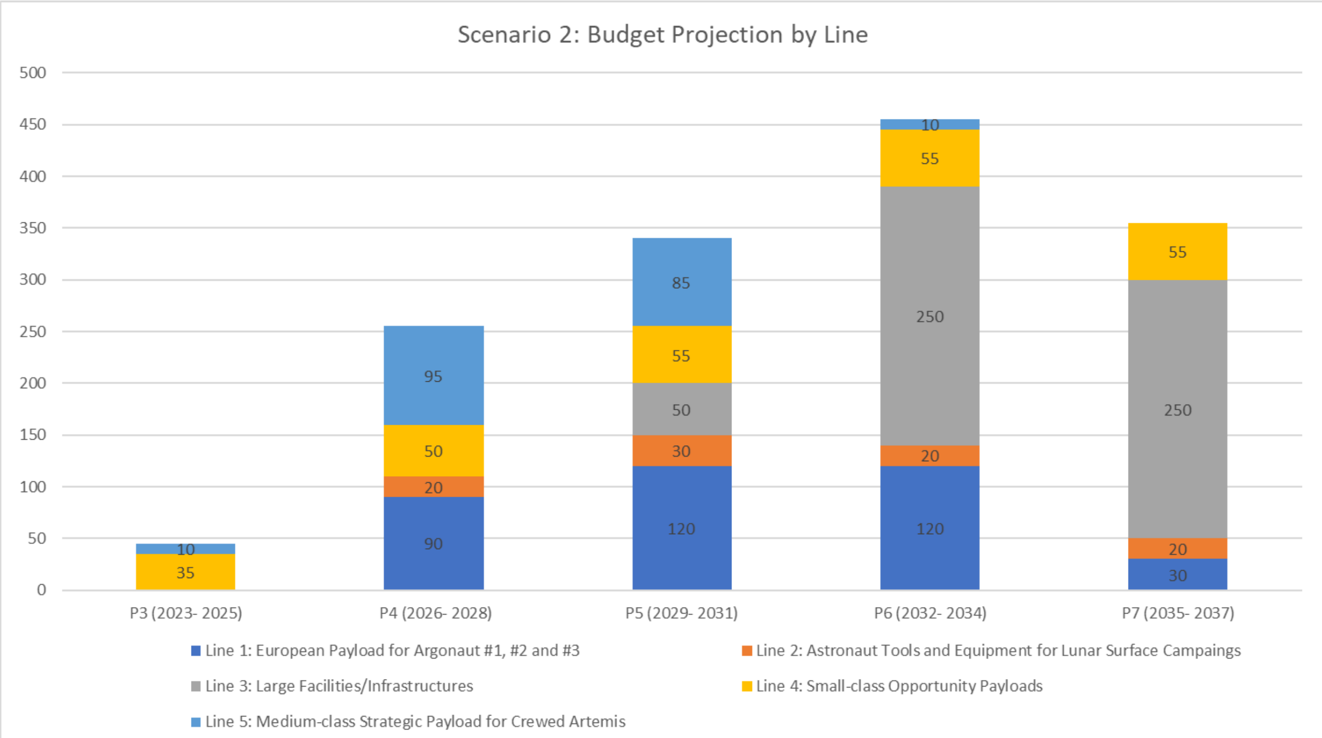


***Figure 2**: Scenario 2 Preliminary Budget Projection from P3 to P7*

Scenario 3: ESA establishing a strategic role on the Moon

This scenario includes all the lines identified in Section 5., in particular:

- Option 1.b with a majority ESA financial contribution to the European payload onboard Argonaut (as in scenario 2)
- Option 4.b, with a direct support to a commercial landing service provider with an acceptable footprint in Europe
- In addition to Lines 1 (Option 1.b), 2, 3, 4 (Option 4.b) and 5, *Line 6: Small Lunar Mission* is added

In this scenario, ESA deploys more elements to be present on and at the Moon, supporting from P4 a more Europe-based commercial service provider and also implementing an additional small mission. Such a scenario allows a more aggressive build-up, in this decade and in the next one, of a robust ESA roadmap for Science and Technology of the Moon, with a large portfolio of investments. There is a strong incremental preparation of future larger surface elements via return of flight experience and operations. This highlights ESA's ambitions and offers more flexibility and risk mitigation to the uncertain European and international context. The funding assumed from sources outside of E3P, although less than in Scenario 1, should still be noted.

ESA E3P CS#3 funding
Other funding sources (see details in section 5)

Scenario 3	P3 (2023-2025)*		P4 (2026-2028)		P5 (2029-2031)		P6 (2032-2034)		P7 (2035-2037)		TOTAL	
Line 1: European Payload for Argonaut #1, #2 and #3	(ExPeRT)		60	30	80	40	80	40	20	10	240	120
Line 2: Astronaut Tools and Equipment for Lunar Surface Campaigns	(ExPeRT)		15	5	25	5	15	5	15	5	70	20
Line 3: Large Facilities/Infrastructures			(ExPeRT)		50		250		250		550	0
Line 4: Small-class Opportunity Payloads	30		90	15	90	15	45	10	45	10	270	50
Line 5: Medium-class Strategic Payload for Crewed Artemis	10		90	5	80	5	10				190	10
Line 6: Small Lunar Mission	(ExPeRT)		90	15	10	5					100	20
TOTAL	40	5	345	70	335	70	400	55	330	25	1420	220

**Available to be invested during Period 3 (not all part of P3 subscription)*

***Table 11:** Scenario 3 Preliminary Budget Projection from P3 to P7*

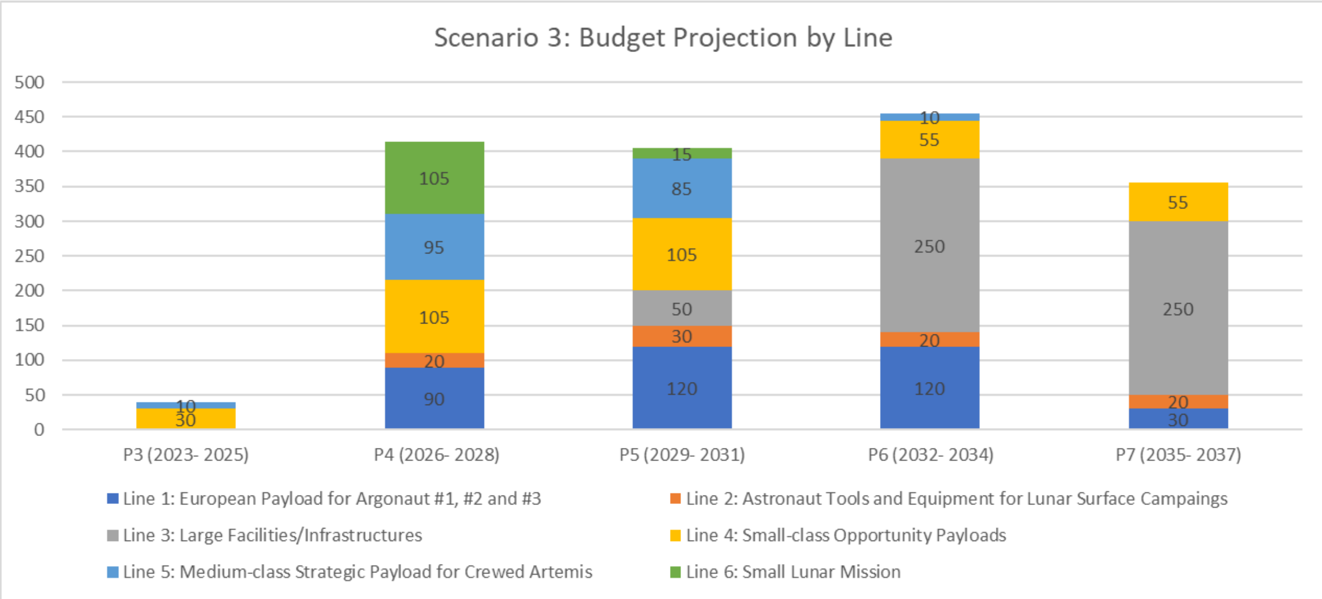


Figure 3: *Scenario 2 Preliminary Budget Projection from P3 to P7*

8. Summary of the Scenarios

Important assumption: Argonaut #1, #2 and #3 are NASA-driven and in support of Artemis; Argonaut #4 may be an ESA-driven mission (see the mission studies performed in Period 2), noting it is not in the scope of this document.

Lines of Development Activities For Flight and Operations on the Moon		Scenario 1: Minimum ESA presence on the Moon	Scenario 2: ESA on the Moon in this decade and beyond	Scenario 3: ESA establishing a strategic role on the Moon
Line 1: European Payload for Argonaut #1, #2 and #3	1.a: minority ESA contribution	X		
	1.b: majority ESA contribution		X	X
Line 2: Astronaut Tools and Equipment for Lunar Surface Campaigns		X	X	X
Line 3: Large Surface Facilities/ Infrastructure(s)		X	X	X
Line 4: Small-class Opportunity Payloads	4.a: limited use of existing commercial transportation	X	X	
	4.b: extensive use of existing commercial transportation			X
Line 5: Medium-class Strategic Payload for Artemis Missions			X	X
Line 6: Small Lunar Mission				X
P4 CS#3 budget corridor (ROM)		~100 M€	~200 M€	~350 M€
P4 to P7 CS#3 budget corridor (ROM)		880 M€	1190 M€	1380 M€
Co-funding outside of E3P from P4 to P7 (ROM)		295 M€	185 M€	215 M€

Table 12: *Summary of the Scenarios*

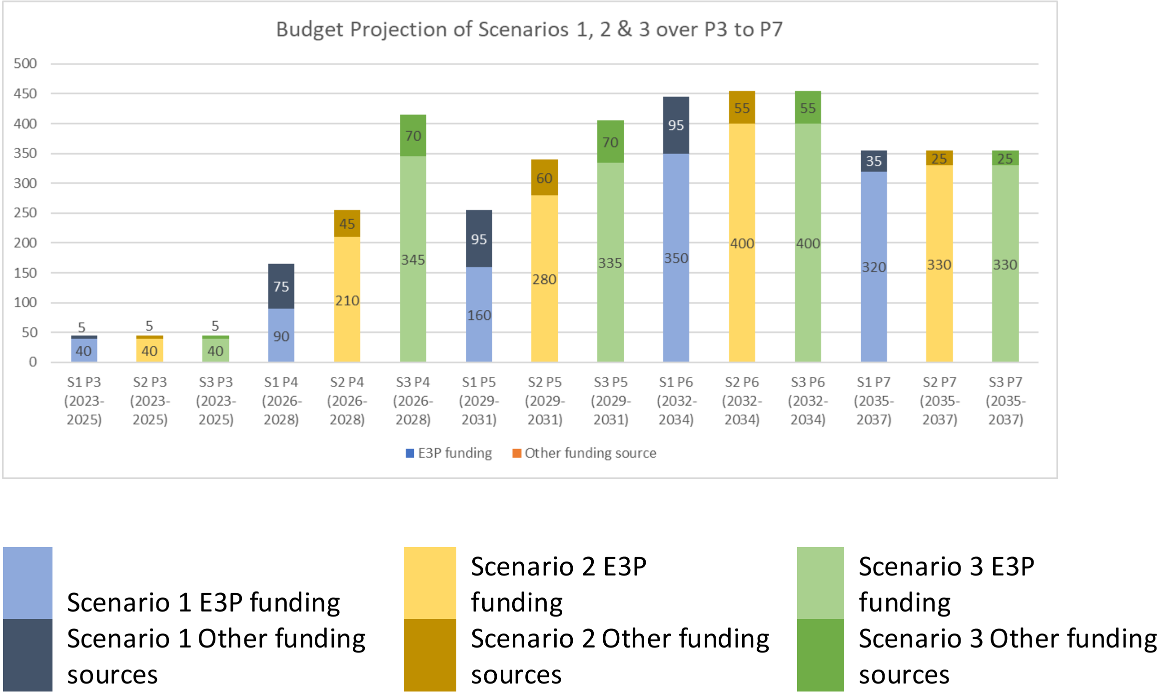


Figure 4: *Overall Budget Projections of the Scenarios*

The P4 budget will play a determinant role. Certain lines/options will make little sense in the overall expanding lunar exploration context if not started in P4, i.e. Line 4 / Option 4.b and Line 5.

Intermediate scenarios with other combinations of lines are possible, as is the tailoring of the ratio of co-funded activities.

The time to FM delivery, then to launch will need to be actively controlled, and the project procurement, organisation and management tuned accordingly.

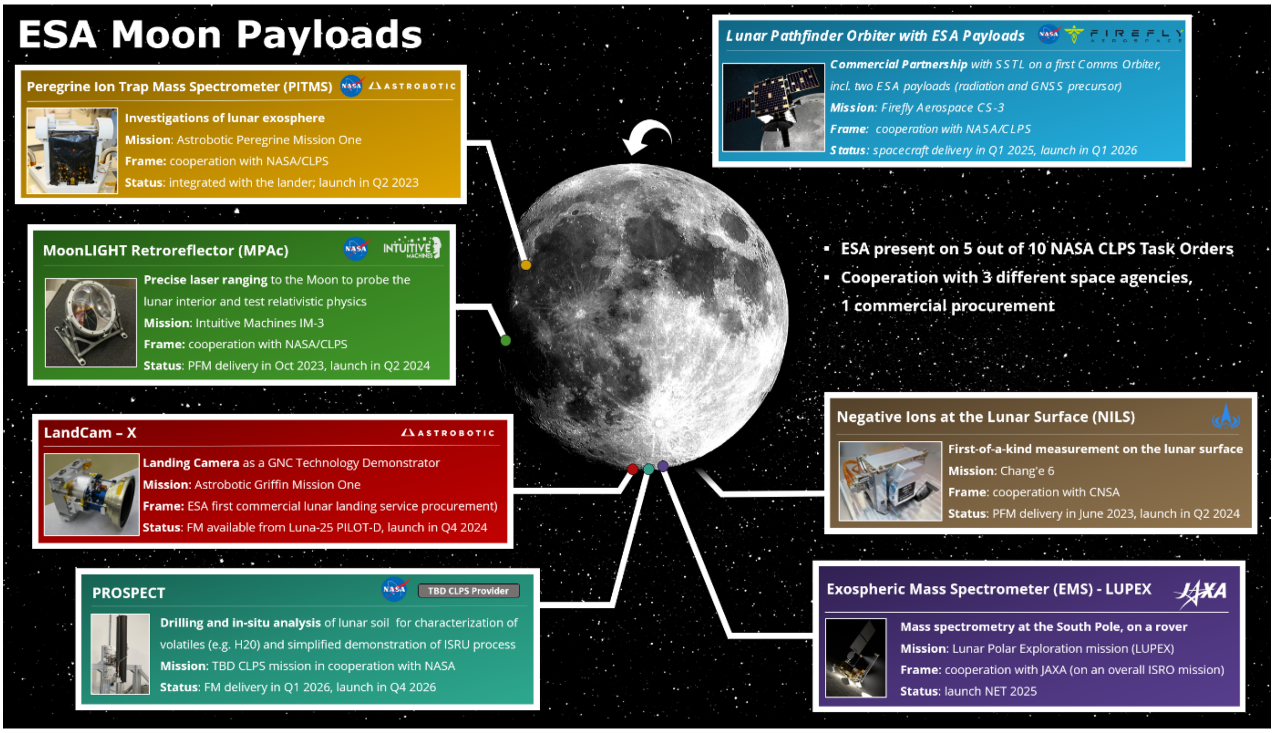
9. Conclusion

The Human Spaceflight, Microgravity and Exploration Programme Board is invited to provide comments on the content of the document which aims at serving as a reference document for Period 3, including the prioritisation proposed in section 4.

Crossing this prioritisation with the programmatic lines described in section 6, new science/technology flight development activities will be selected and proposed for approval as part of the workplan, taking into account the latest budgetary situation.

The document may be updated at a later stage in the frame of the preparation of the next Council meeting at ministerial level.

Annex 1: ESA Committed Payloads



Annex 2: Lunar Pathways Detailed Description

While section 4 focuses on explaining the prioritisation of certain of the Lunar Pathways and providing the rationales for it in a synthetic manner, this Annex, presented in the earlier versions of the document, provides a detailed and comprehensive description (without prioritisation aspects) of each of the Lunar Pathways listed in section 3.

Science Pathway

The aim of the science pathway, at the heart of exploration, is to grow progressively a programme of targeted scientific activities on the lunar surface that generates knowledge supporting exploration, delivers high impact science and benefits from capabilities developed in Europe, including for other destinations like LEO.

The scope of scientific activities at the Moon in this decade has been first described in the ESA strategy for Science at the Moon (ESA/PB-HME(2019)11, rev.1). Activities that might be extended beyond this horizon have been investigated following community consultation through mission studies performed during E3P Period 2 (see EUB/W54-06 - Report on Lunar Surface Payload Studies). The scope and priorities for science at the Moon have been recently reviewed as part of the activity to establish an integrated science roadmap for the HRE programme across all destinations (see Annex 4 of the Roadmap for Implementation of the SciSpacE Strategy document):

- Analysis of new and diverse samples from the Moon
- Detection and characterisation of polar water ice and other lunar volatiles
- Identification and characterisation of potential resources for future exploration
- Characterisation of the dynamic dust, charge and plasma environment
- Characterisation of biological sensitivity to the lunar environment
- Deployment of geophysical instruments and the build up a global geophysical network
- Deployment of long wavelength radio astronomy receivers on the lunar far side

Analysis of new and diverse samples from the Moon

ESA's cooperation with NASA on Artemis will provide access to new lunar samples. While the approach to sample receiving, curation and distribution has not yet been established by or with NASA, ESA's aim would be to secure access to samples for European science and to contribute to their selection, collection and the return chain of the samples to Earth.

ESA could provide a number of different contributions to surface geology activities and the selection and extraction of samples by crew. Such contributions could include hand-held instruments, capabilities to enhance surface science operations, sampling equipment including drills and equipment to support the return and handing of samples in space and on ground. Various options are being investigated and assessed against the surface science needs of Artemis. Options exist for fully robotic platforms to perform this function as stand-alone missions or as supporting elements in an integrated human robotic scenario.

Detection and characterisation of polar water ice and other lunar volatiles

This is achieved in E3P Period 3 through the ongoing projects PROSPECT and EMS-LUPEX as described in the ISRU Pathway, and later on eventually through access to returned samples from the Lunar South Pole as described just above.

Identification and characterisation of potential resources for future exploration

The identification and characterisation of potential resources on the Moon as part of the science path has substantial synergies with the ISRU pathway and the science of polar volatiles.

The characterisation of polar volatiles is an important step for potential future resource utilisation. This is described in the ISRU pathway and the above section on polar volatiles. Another aspect is understanding the resource potential of other lunar materials including regolith and pyroclastic deposits. This will be achieved through geological investigations at the lunar surface, in situ geochemical and geophysical measurements and the analysis of new samples returned to Earth. Crew surface activities and sample return will also contribute to this.

Characterisation of the dynamic dust, charge and plasma environment

The integrated environment at the lunar surface combines solar wind plasma, radiation, the Earth's magnetic field, neutral and charged exosphere species, dust and surface charging in complex and dynamic processes that change during the lunar day. This provides a test bed for fundamental physical processes, provides an analogue for the environments of airless bodies in the Solar System. It is also an environment in which astronauts and surface systems must operate. An integrated helio-plasma payload to monitor and characterise this environment and its dynamics will address both scientific and exploration needs.

A preparatory study was conducted in Period 2 to define scientific needs, requirements, instrument candidates and development plan (see EUB/W54-06 - Report on Lunar Surface Payload Studies). Different instruments could be contributed from partners and integrated into one international environment package. Night survival for such investigations is mandatory and this is one of the candidate scientific packages to be combined with an ESA standalone power and communications system (see Energy Pathway).

Characterisation of biological sensitivity to the lunar environment

A surface exposure facility would allow biological and biochemical samples to be exposed at the lunar surface and the biological responses to lunar environmental factors to be measured, including radiation and partial gravity. The effects would be investigated remotely by a suite of instruments, without the inherent need to return the samples. This would complement measurements to be made on ISS and perhaps on Gateway and could support both fundamental exobiology and address risk factors for human exploration of Moon and Mars. It would be a payload investigating the in-situ effects of the lunar environment, radiation and lunar gravity through a suite of instruments which can measure the effects remotely without the inherent need to return the samples.

A preparatory study was conducted in Period 2 to define scientific needs, requirements, instrument candidates and development plan (see EUB/W54-06 - Report on Lunar Surface Payload Studies). This is one of the candidate scientific packages to be combined with an ESA standalone power and communications system (see Energy Pathway), to keep the biological samples at the correct temperature and condition throughout the lunar night as well as to keep the analysis instruments alive.

Deployment of geophysical instruments and the build up a global geophysical network

In E3P Period 2 an industrial study has been performed into a possible long lived geophysical payload making both seismic and heat flow measurements at the lunar surface. The study investigated both the scientific instrumentation that would be needed and the provision of power provision through the lunar night and communications with Earth through a self-standing package (see EUB/W54-06 - Report on Lunar Surface Payload Studies). The power and communications aspects of the study have produced outcomes that are of broader applicability (see the Energy Pathway).

While geophysics measurements remain a high priority and are highlighted in the Moon science strategy, developments are underway already between NASA and CNES to prepare a similar seismic station for delivery to the Moon in this decade via NASA’s CLPS programme. There is a strong rationale for multiple geophysical stations to be deployed, and the evolution of the capabilities these stations have.

Deployment of long wavelength radio astronomy receivers on the lunar far side

A radio observatory on the lunar far side could be a major international scientific project in the coming decades. Activities in Europe, USA and China are preparing concepts and the capabilities needed for such a development are being advanced globally This is clearly a long-term possibility and based on the recent US astrophysics decadal survey this will not be a priority for NASA in this decade. It thus presents an opportunity for Europe to take a leading role in building the case, perhaps through cooperation with the Science Directorate and/or in the context of an expanded programme of human and robotic exploration emerging from the HLAG reflection.

Studies performed by ESA and with the scientific community in E3P Period 2 have provided a technical reference for what this might be, identifying challenges and activities that would need to be performed to prepare such an observatory (see EUB/W54-06 - Report on Lunar Surface Payload Studies). A precursor instrument is one of the candidate scientific packages which could be combined with an ESA standalone power and communications system (see Energy Pathway).

Transportation Pathway

As the pillar of Cornerstone 3 in the Terrae Novae programme proposal at CM22, this pathway is in an advanced status. Transportation is the entry point for robotic and human exploration: access to the Moon surface must be assured for any surface activities to be conducted. This capability is an enabler for ESA and can be bartered with international partners.

The objective for Transportation is to establish a European robotic landing capability of medium size at the beginning of the 2030s, called “Argonaut”. This lander will provide Europe with autonomy in accessing the lunar surface and will enable regular deliveries to the Moon in the 2030s. Argonaut will be launched on Ariane 6, and as this launcher’s capability evolves, so the capacity for payload (including any payload support systems such as power systems and robotics) would increase from around 1500kg to more than 2000kg. The Argonaut lander will include precision landing and hazard avoidance systems, building on the past developments related to PILOT and on the outcomes and operational experience of the flight of LandCam-X (covered in E3P Period 2).

Argonaut would primarily deliver equipment, cargo and logistics to the Moon in support of NASA’s Artemis architecture. Deliveries could also include self-standing ESA-driven robotic missions.

Examples of potential missions for Argonaut at Phase 0 level have been studied extensively during E3P Period 2. Deliveries could include pressurised cargo, unpressurised cargo, robotic systems and infrastructure elements. The development of this lander is the primary activity for Cornerstone 3 in Period 3. Phase A/B1 studies for the first Argonaut mission will be conducted in parallel under ExPeRT (see EUB/W54-03). Discussions with NASA on the first mission in support of Artemis in 2030 are ongoing. The Transportation pathway is driven by the development of this capability and preparations for its evolutions in the 2030s.

In order to prepare and de-risk the Argonaut lander development and its evolutions, the early flight to the Moon of small-class technology payloads may be considered, particularly in the GNC area.

Communications and Navigation Pathway

This pathway is also well advanced, thanks to various already on-going initiatives. Lunar Communications and Navigation are at the heart of operations and data return, which are key to realise and maximise the benefits of lunar exploration. Advanced capabilities in this area paves the way for complex surface activities with multiple elements. These capabilities are particularly instrumental for areas of the Moon of particular interest for exploration, like the South Pole region, which presents very specific combinations of illumination and Earth visibility conditions.

The end objective on the Communications and Navigation pathway is to establish a European infrastructure for communications and navigation services by the end of this decade. Its primary element is the Moonlight constellation that was approved as a multi-directorate activity at CM22. An intermediate step on this pathway is Lunar Pathfinder, a first communications and navigation service led by SSTL (UK) as a commercial initiative and to be delivered in lunar orbit by Firefly as part of a NASA CLPS Task Order. ESA is also providing the HALO Lunar Communications System (HLCS) as its first delivery as part of the Gateway international projects within Artemis.

Lunar surface communications are also on the Communications and Navigation pathway, for data exchanges between surface assets and/or astronauts. Technology maturation activities are ongoing under ExPeRT (and TDE), e.g. WiFi/LTE infrastructure for lunar local network; a communication, task management and operation assistant device for the astronaut called Electronic Field Book.

Finally, the communications and navigation European architecture include the Earth ground infrastructures and services offered by ESOC, who has now a long record of supporting lunar missions of international partners, but also recently of private players (i.e. ispace), as well as those offered by Goonhilly.

Energy Management Pathway

Energy management is the next most critical and technologically challenging capability for lunar exploration after transportation. It is the driving factor for long duration surface activities on the Moon. Without advanced capabilities in this area, only a few Earth days of operations are possible, limiting the return on investment. The primary challenge is surviving the lunar night (in the order of 10 to 14 Earth days depending on the landing site excluding permanently shadowed regions), during which energy is needed for survival in the extreme cold, and for operations. Energy management able to deal with the very large spectrum of illumination and thermal conditions during the lunar day and night requires either large energy storage solutions based on batteries or fuel cells coupled with solar generation, or nuclear power sources. These provide an energy capability that underpins all of the other lunar pathways.

The pathway for ESA includes a combination of solutions addressing different aspects of the energy management needs of future missions, including power generation, energy storage and thermal properties / thermal control systems for extremely low / high temperature environments. Key technologies to be developed are rechargeable fuel cell systems (RFCS), deployable vertical solar arrays and radioisotope power systems (RPS). These are to be developed towards the establishment of two major products to be available in the 2030s:

- Radioisotope power sources (RPS), initially radioisotope heating units (RHUs), providing thermal energy for different applications including self-standing elements such as deployed payloads, rovers and cargo. This was proposed in the frame of a multi-directorate project as the “Endure” component of the GSTP programme at the 2022 Ministerial Council
- A surface charging station based on solar generation and storage using batteries and rechargeable fuel cells, providing kW of power to equipment and facilities (two parallel pre-Phase A studies are on-going under ExPeRT) in the perspective of a longer term global and sustainable scenario

Implementation in flight of some intermediate steps should be considered in order to demonstrate the new technologies, their integration and operations in an overall energy management system, and to establish them as reliable solutions ahead of the development of a complete charging station as a critical element in a future surface infrastructure.

The first application of ESA energy solutions at the lunar surface may be to support the long duration operations of a scientific payload at the surface. Such a platform would most likely be based on mature technologies; solar power and batteries, to provide a timely first capability to enable early science.

A subsequent step would be the development of more substantial energy solutions enabling long term activities of larger or more payloads or to support larger surface systems. Such a charging station would be based on a combination of solar power, battery technology, RFCS and possibly RPS.

In Situ Resource Utilisation Pathway

ISRU would be a game-changer for long term activities in space, with strong synergies with terrestrial challenges. This is an area that will grow in importance in the next decade and beyond.

The end objective on this pathway may be an ISRU plant of an appropriate scale to support a more global, sustainable exploration scenario on the Moon in the long term, minimising the need to send new consumables.

Whatever the retained process for producing usable products from local resources, major uncertainties about the characteristics of local resources still need to be addressed through ground based and surface activities and the maturity both at technology level and at integrated level of such a complex robotic system still need to be advanced, as described in PB-HME(2019)12, rev.1 - the ESA Space Resources Strategy, and in EUB/W55-09 - In-Situ Resources Utilisation (ISRU) Campaign Technology Roadmap – Update and in ESA/PB-HME(2023)14 - ESRIC Implementation Plan for E3P Period 3 2023-2025.

There are two primary parallel possible paths for In Situ Resource Utilisation (ISRU) on the Moon. The first is the use of cold trapped polar volatiles as a source of water, oxygen, hydrogen, and other volatile species. The second is the reduction of minerals in lunar regolith to provide oxygen and metallic alloys. Other ISRU approaches include the use of regolith to produce materials for construction and radiation shielding. The overall approach to ISRU is described in the Space Resources Strategy (ESA/PB-HME(2019)12, rev.1).

The use of cold trapped water ice requires as a first step that ice resources are mapped and quantified so that their potential as useful resources can be confirmed. While the presence of water ice at the lunar poles is confirmed, the abundance, distribution, sources, sinks and utility of resources needs to be better understood. Achieving this requires surface measurements across the polar regions in locations with different conditions to ground truth orbital data and to test models of where volatiles might be found and in what quantities. This first stage must then be followed by comprehensive mapping, at the surface, of volatiles in areas where reserves are expected to reside.

The first stage of this polar prospecting campaign has already started, as an international effort involving missions from multiple agencies. ESA's main contribution to this effort today is PROSPECT, with EMS-LUPEX as a second smaller contribution. PROSPECT on CLPS 2.2. and EMS-LUPEX are among a number of early polar missions including PRIME-1 and VIPER from the USA and Chang'e 6 and 7 from China.

The other pathway for ISRU is the reduction of minerals to produce oxygen. Such processes can, depending on the selected process, be applicable at any lunar location. ESA has worked during E3 Period 1 and 2 to assess different possible approaches and is focusing on electrochemical reduction in molten salt as the preferred way forward. Such a process, developed for terrestrial metal production, can be applied to any mineral and can, in principle, remove all oxygen from the oxides in those minerals given enough time and energy.

To advance this ISRU capability technology development activities are required across the process chain from excavation to reduction to the handling of both solid and gaseous products. Most of this work is best performed on Earth. For this reason, dedicated research is being undertaken and investments are being made in establishing facilities to support this work (see ESA/PB-HME(2020)40 - European Space Resources Innovation Centre (ESRIC) – Updated Implementation Plan). An in-situ demonstration on the Moon can be used to validate work performed in terrestrial laboratories in the true lunar environment and would provide an important step towards demonstrating feasibility and creating operational experience.

Such an ISRU demonstrator (ISRU DM) has been studied in E3P Period 2. The concept is based on a molten salt electrolysis process. The ISRU DM would build on the first ISRU process demonstration on the Moon by PROSPECT, which uses a simpler but inefficient hydrogen reduction process to perform reduction. The present activities in ExPeRT advance the ISRU DM concept towards SRR, and a number of key technologies. SRR is expected in Q1 2024. Technology activities are expected to conclude at the beginning of 2025. Key building blocks of the ISRU-DM might be interesting candidates for a contribution to a potential NASA ISRU-related mission in the 2030+ timeframe. Such a type of end-to-end demonstrator may be considered for an Argonaut mission as primary or complementary payload, or for HLS.

Surface Mobility Pathway

This is a key capability to truly explore once landed and to reach different locations on the surface of the Moon. It links with several other pathways:

- **Science**: many scientific investigations listed in the Science Pathway would benefit tremendously from, sometimes even require, mobility, allowing to establish a map of measurement points rather than a limited local series if located on a fixed surface element; mobility is also a key asset to select samples to be analysed or returned
- **In Situ Resource Utilisation**: the capability to characterise different sites from a resource perspective is essential
- **Other pathways:** on the long term, it could support the logistics and the deployment of large systems and infrastructures
- **Energy Path**: a mobility of a certain size will need to be able to operate for a long time to be meaningful, which will ask for an energy management solution (e.g. via charging)

There are numerous possible lunar mobility systems, with various functions including autonomous innovative GNC techniques, different types of mobility, a broad range of payload capability, robotic or crewed. Numerous projects by different actors are on-going in Europe, both from a HW and SW perspective. Unique development experience including preparation of the operations for the Rosalind Franklin rover on Mars exists in Europe.

A large-size mobility does not seem affordable in the short term. Further, Canada has decided to contribute a robotic utility rover as its principle contribution to Artemis surface utilisation and Japan plans to contribute large pressurised human rover for regional exploration. Still, it might be envisaged for a later ESA-led Argonaut mission or HLS. A smaller-size rover could be considered as a small-class opportunity payload, as a small lunar mission or as a European complementary payload on Argonaut#1. The possibility to use commercial rover services being developed by several private European entities needs to be taken into account as well.

Crew and Habitation Pathway

With the crucial importance in the programme of the European Astronaut Corps and of human spaceflight to the three destinations, building on the heritage of the ESA habitation modules for the ISS and Gateway, and on the various technologies and systems in the field of life support systems developed for many years in Europe, the possibility to invest in the long term in a large infrastructure that will sustain the presence of astronauts is relevant. It is noted that ASI is cooperating bilaterally with NASA on the possible provision of surface habitation.

There are also links with the Energy Path since certain technologies can be common between life support systems and energy storage (e.g. electrolyser) and that the various loops of consumables and waste are linked and need to be optimised as a whole.

In addition, this Pathway also encompasses tools and equipment (scientific, logistics) supporting directly the crew in their operational activities during surface exploration campaigns.

Robotics Pathway

Robotic manipulation capabilities onboard static or mobile elements on the surface are a must for any activities using lunar soil over the end-to-end handling chain, from extraction, analysis and processing to disposal. This applies to early characterisation activities, to resources prospection investigations and later to large-scale exploitation, as well as to sampling for return to the Earth (ISRU and Science pathways). They are also key for logistics activities like deployment and assembly of infrastructures. They are as such enablers of complex activities involving multiple systems and elements, also the astronaut in the loop. Those robots can be of different types: drillers, robotic arms, cranes, scoops, distribution systems etc. and involve innovative control algorithms in order to improve their performance and their autonomy.

Europe presents unique competences in this area through various space projects (e.g. ExoMars drill, PROSPECT drill, MSR STA, sample handling chain for ExoMars, sample handling chain for PROSPECT etc.).