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A prospective market & business perspective on Lunar ISRU for propellant applications

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Abstract
Lunar resources are increasingly being considered as a key element of future exploration missions. By reducing the need for incoming material fluxes, In-situ resources utilization (ISRU) might act as an enabler to long-term, sustainable human presence on the Moon, and facilitate the use of the Moon as a starting point for further exploration of the Solar system. While it is crucial, the economic sustainability of lunar ISRU currently remains a subject of research [1,2].
Our study identifies the resources available up to date on the Moon, that can be categorized into two main types: material resources, and immaterial resources. In terms of demand, the activities on the Moon that could create needs for propellant can actually be classified into 5 main "end-goals" : scientific exploration, resource utilization, manufacturing, construction and tourism. The future of these activities will strongly depend on three macro-drivers: availability of lunar energy, human presence on the Moon, and quantity of available resources. From these macro-drivers, we envision five potential archetype scenarios for the future. To estimate the market size of O_2 propellant for each, we identify 16 potential vehicles and then focus on those using cryogenic chemical propellants: unmanned and manned launchers, manned spacecraft, space cargo, point-to-point rockets, and landers. These assumptions allow to derive a preliminary estimate of O_2 propellant demand between almost zero to almost 40 kt/year, mostly driven by trips to Earth.

1. Introduction and purpose of the present study

1.1. Context

In-Situ Resource Utilization (ISRU) involves the extraction and utilization of resources found on celestial bodies such as the Moon, to support human activities and missions in space. The history of ISRU studies on the Moon is marked by ongoing exploration and technological advancements. For instance, NASA's Lunar Surface Innovation Initiative is aims at developing and demonstrating technologies that utilize the Moon's resources for various purposes [3,4,5]. These technologies could be used to produce water, fuel, and other essential supplies while enabling excavation and construction on the lunar surface.
Through chemical reactions, propellants produce high-pressure gases that are expelled at high velocities, creating the reactive force known as thrust. Typically, propellants consist of a fuel component responsible for energy release during combustion, and an oxidizer component that supplies the necessary oxygen for the fuel to burn efficiently. By expelling propellant gases, vehicles can achieve the necessary propulsion.
By harnessing local resources, such as regolith (silicon oxides, with more than 40% O_2 in mass) for oxygen, and possibly water (if confirmed in large quantities), ISRU can potentially reduce the reliance on Earth for propellant resupply. This can significantly enhance the sustainability and cost-effectiveness of space missions, as well as enable long-duration space exploration and sustainable presence in space. ISRU will allow to take advantage of the lower gravity of the Moon, and to reach other orbits with less energy than from Earth. ISRU has the potential to reinvent the way space missions are thought and the transportation in space, even in Earth orbit.

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Defining what could be the market and the value chain around the ISRU business supposes at least to identify all the available resources but it supposes also to define what could be the applications on the Moon and how they will use propellants that will be based on these lunar resources.

1.2. Purpose of the present study

The purpose of this preliminary study is to lay the groundwork for a comprehensive evaluation of the lunar propellant demand from a bottom-up perspective, while characterizing the main sources of uncertainties of such a long-term perspective. This method involves characterizing all peaceful use cases of propellant on the Moon while remaining as agnostic as possible to technological choices. Because our market sizing is based upon plausible use cases, utilizing different vehicles, it will also allow to identify potential value chain structures and help stakeholders envision their role in the lunar ISRU ecosystem and focus their efforts on the most promising use cases.

1.3. Methodology

In order to estimate the demand for lunar-derived O_2 propellant, we used the following approach :

1- Summarize the available resources on the Moon (“supply” side).
2- Identify the various vehicles for transportation on the Moon (“demand” side) and highlight those who are compatible with an in-situ propellant use.
3- Highlight the macro-drivers of each end-goal that are the most impactful and the most uncertain. Conduct a prospective design of the potential future scenarios on space exploration projections based on the combinatory of the prioritized macro-drivers, e.g. on how the applications on the Moon could evolve.
4- Estimate the impact on propellants demand based on these scenarios; each scenario is qualified in terms of impact on propellant consumption. Then, prioritize the vehicles that are common to the most impactful scenarios.
5- Derive individual demand equations to estimate the quantity of O_2 propellant required by each scenario.

2. The Supply Side: Qualification of available resources on the Moon

The Moon is rich in resources that hold great potential for lunar permanent settlement and commercial utilization. These resources can be categorized into two main types: material mining resources, and immaterial sustainable resources.
Mining resources include valuable elements such as solar wind implanted volatiles (Helium-3, Hydrogen, Methane, Carbon, Nitrogen), water, Oxygen, and metals [3,4,5]. These resources offer opportunities for energy generation, fuel production, water supply, or construction materials (regolith itself can be used as construction material) [6,7,8]. The Table 1 presents a state-of-the-art estimation of the elements available on the Moon that can be used as propellant.
In addition, the Moon possesses various immaterial resources that can support long-term habitation and industrial activities [7]. Solar energy is intermittent but abundant on the lunar surface and can be harnessed for electricity generation with PV panels and Lunar Night survival systems (e.g. : regenerative fuel cell systems). The microgravity environment provides also unique opportunities for scientific research, while the lunar landscape offers ample land for infrastructure development. The hard vacuum and low temperatures present favorable conditions for manufacturing processes. Waste will also be considered as a resource on the Moon, towards a circular and sustainable economy. Furthermore, utilizing lunar resources promotes carbon-free and safer industrial practices.

Overall, the presence of material resources and immaterial resources on the Moon presents a wealth of opportunities for future exploration, sustainable settlement, and commercial ventures. Understanding and effectively harnessing these resources will be crucial for realizing the full potential of lunar activities and advancing human presence in space. Also, space resources' scarcity will most likely push for the development of circular and sustainable processes, for the benefit of Space and Earth on the long term (spin offs).

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Component	Formula	Percentage of mass in regolith samples (%wt)	Associated propellant example
Oxygen	**O**	40% lunar average [8]	Cryogenic O_2
Iron	**Fe**	15% in sample [7]	Iron particles
Aluminum	**Al**	14% in sample [7]	Aluminum powder
Water	**H_2O**	5.5 (±2.9)% in sample [6]	Cryogenic H_2/O_2-Water/Aluminum hybrid
Hydrogen	**H_2**	1.4% in sample [6]	Cryogenic H_2
Carbon monoxide	**CO**	0.7% in sample [6]	Oxygen and carbon monoxide
Magnesium	**Mg**	0.4% in sample [6]	Magnesium and carbon dioxide
Carbone dioxide	**CO_2**	0.32% in sample [6]	Cold gas
Ammonia	**NH_3**	0.31% in sample [6]	Ammonium Perchlorate
Mercury	**Hg**	0.24% in sample [6]	Mercury for ionic thruster
Methanol	**CH_3OH**	0.15% in sample [6]	Decomposition in hydrogen and carbon monoxide
Methane	**CH_4**	0.03% in sample [6]	Cryogenic Methane
Carbon	**C**	0.0124 (± 0.0045)% lunar average[8]	Precursor to hydrocarbons
Nitrogen	**N**	0.0081 (± 0.0037)% lunar average[8]	Cold gas thruster
Fluor	**F**	0.007 (± 0.0047)% lunar average[8]	Fluor as a pure or mixed oxidizer (FlOx)
3-Helium	**^3He**	0.0042% lunar average[8]	Cold gas thruster
Chlorine	**Cl**	0.003 (± 0.002)% lunar average[8]	Chlorine pentafluorine
4-Helium	**^4He**	0.0014 (± 0.0011)% lunar average[8]	Cold gas thruster
Neon	**Ne**	1.23e-7 (±0.8e-7)% lunar average[8]	Electric thruster
Argon	**Ar**	0.55e-7 (±0.21e-7)% lunar average[8]	Electric thruster
Krypton	**Kr**	0.54e-10 (0.21e-10)% lunar average[8]	Electric thruster
Xenon	**Xe**	0.14e-10 (0.05e-10)% lunar average[8]	Electric thruster

Table 1 – Mass concentration and composition of certain lunar samples components in lunar regolith that can be use as propellant [6,7,8] %wt represents "percentage by weight." It is a unit of measurement that expresses the proportion of the particular component in regolith, relative to the total weight of the compound. Uncertainty on figures may be important according to the low number of return samples studied.

Euro2Moon would like to alert the reader that these data are estimations based on a limited number of samples collected from missions such as Apollo, Clementine or the Lunar CRater Observation and Sensing Satellite (LCROSS) thus significant uncertainties exist.

1. The Demand Side : End goals, Demand drivers and Scenarios

1.1. Taxonomy of lunar activities

In order to get an exhaustive view on the applications in Moon (what we call “end-goals”), we built a tree to explore all the possibilities. The activities on the Moon can actually be classified in 5 main “end-goals” : **scientific exploration**, **resource utilization**, **manufacturing**, **construction** and **tourism**. By segmenting lunar activities into these distinct categories, we can better identify and prioritize the objectives, resources, and strategies associated with each goal, leading to a more comprehensive and structured approach to lunar exploration and in-situ utilization.

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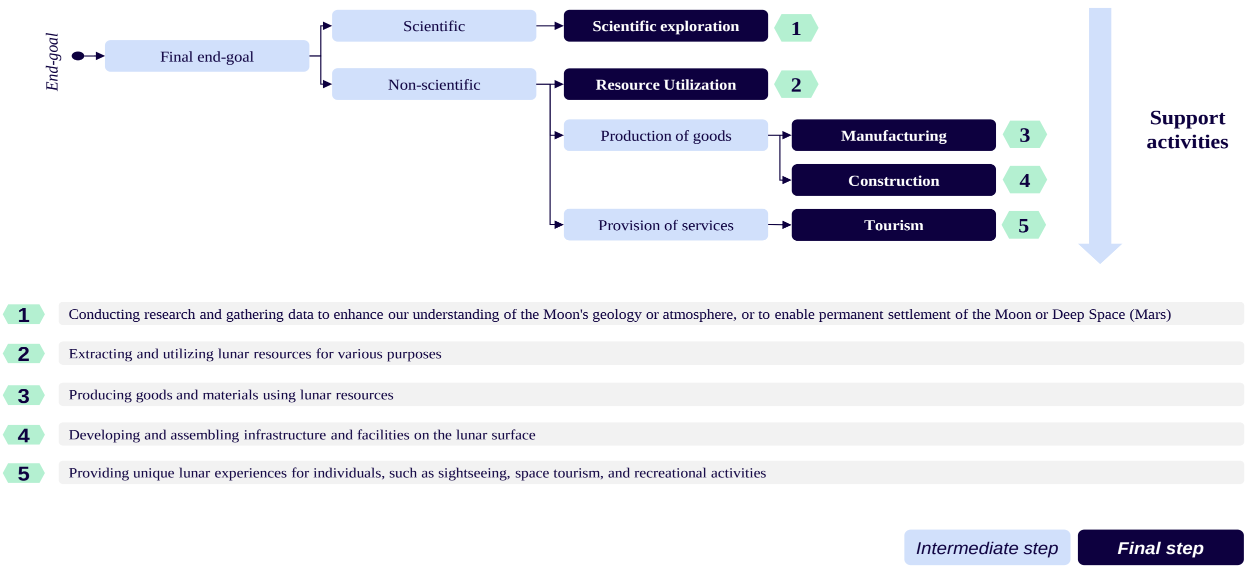

Figure 1 - Mapping of Lunar activities

All these end-goals are possible thanks to support activities that are needed to operate on or around the Moon. The table below gives an extent of these supports.

Support activities	Description
Transportation	Transportation is a vital support activity for lunar operations, enabling the movement of resources, equipment, and personnel to, from, and on the Moon.
Positioning, Navigating, Timing	PNT systems enable precise positioning and navigation for vehicles on surface, communication or other support for lunar activities.
Observation / Data gathering	Observation capabilities provide essential data for monitoring lunar conditions and conducting scientific research.
Cislunar orbit activities	The unique characteristics of low lunar gravity and delta-V enable efficient delivery of propellants to cis-lunar orbits, facilitating in-orbit servicing and refueling operations.
Security	Ensuring the protection of assets, infrastructure, and personnel against potential risks and threats in the lunar environment.

Table 2- Description of support activities

Security shall not be investigated in this paper which first focuses on civilian/commercial usages of ISRU.

1.2. Identification of demand drivers

The objective of identifying the drivers for each end-goal is to understand the factors that influence positively or negatively its development in the future. By identifying these factors (also called “key drivers” or “drivers”), they allow to better size the O_2 propellant demand, even if there could be an remaining uncertainty associated with each end-goal, which refers to the variability or unpredictability of its achievement. This uncertainty will impact the value of these key drivers but the list of these drivers would remain the same whatever the future is. To identify the drivers, we constructed underlying driver trees based on the demand equation for each end-goal and extract the macro-drivers. As an example, we have highlighted the macro-drivers by color-coding them in blue in the figure below for the end goal “Resource Utilization”.

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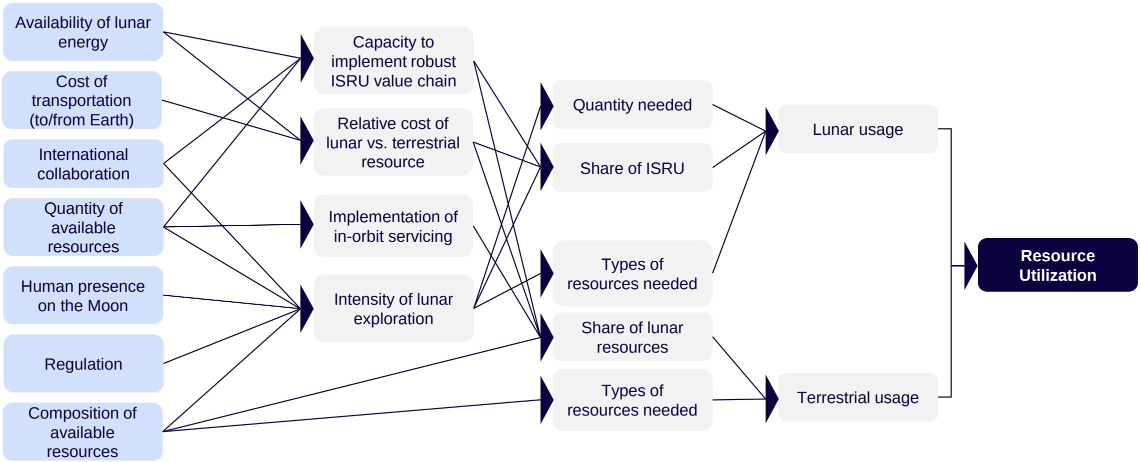

Figure 2 - Tree of underlying demand drivers by end-goal. Example for lunar resource utilization end-goal.

The figure outlines key factors influencing resource utilization. Differentiating between resources for terrestrial and lunar use, volume, types, and ISRU share are considered. Macro-drivers at the left include:

- *Regulation*: Policies impacting lunar resource utilization shape viability and business opportunities.
- *Human presence on the Moon*: Long-term presence may drive increased resource utilization to support various needs.
- *Availability of lunar energy*: Abundant, reliable energy is crucial for mining and material processing.
- *Cost of transportation (to/from Earth)* : Higher costs hinder exploration, while affordable methods enable new opportunities of exploration.
- *Quantity of available resources*: Accurate estimation guides economic potential and reduces Earth dependence.
- *International collaboration*: Shared resources, expertise, standardization and advancements promote efficient and responsible utilization. International collaboration is key for Moon development. Its impact could be further analyzed in the future papers, and its certainty is not absolute, which must encourage actors to enhance logistics and interoperability or others. Euro2Moon is an example of collaboration that goes in this way.
- *Composition of available resources* : Chemical composition, purity, and physical properties impact feasibility and commercial value.

By analyzing these macro-drivers, we can better understand the challenges, opportunities, and priorities in the field of lunar resource utilization. We did this exercise for each end goal to extract their key and macro-drivers, leading to identify a group of macro-drivers that will impact all or most of the end goals.

1.3. Definition of key future scenarios

As explained above, the macro-drivers will influence the future development of Moon activities. However, their impact will not be the same. Therefore, in order to prioritize and analyze the potentialities for lunar development, we qualify each macro-driver along two dimensions : its uncertainty and its level of impact on the propellant value chain. This qualification helps to define the key trades of the potential scenarios :

- Low Impact macro-drivers will not be considered on the scenario definition, even if they are certain or not
- High Impact and Certain macro-drivers will be consider on all scenarios : they will impact the future in all cases
- High Impact and Uncertain macro-drivers will condition the generation of scenarios, according their possible output. A scenario could then be defined as the value of each High Impact & Uncertain macro-driver.

Our methodology assigns a score to each macro-driver based on its level of uncertainty and impact, ranging from low to high. These factors have been evaluated qualitatively with experts interviews from Euro2Moon. By plotting these scores on the matrix, we can visually identify the macro-drivers that have the highest potential impact and the greatest degree of uncertainty.

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Macro-driver	Imp.	Rationale	Inc.	Rationale
Science budget	**4**	Adequate funding will enable scientific missions, advancements in knowledge, and the potential for groundbreaking discoveries on the Moon that can enable industrial or service development.	**B**	There is a pretty clear forecast on the future science budget [2].
Cost of transportation (to/from Earth)	**4**	The cost of transportation will play a pivotal role in determining whether missions are launched, emphasizing its critical impact.	**A**	We can have a clear forecast of the transportation expenses in the coming years. [2]
Quality of lunar manufactured goods	**2**	The impact on propellant consumption is not significant, as manufacturing on the Moon does not appear to be economically viable at 2050 horizon [2]	**A**	The intrinsic qualities of lunar manufactured goods, such as low gravity and the vacuum environment, are well-established and certain.
Composition of available resources	**3**	The composition of lunar resources have a significant impact as they enable self-sufficiency and reduce reliance on Earth.	**C**	The certainty surrounding these qualities is relatively low due to the limited number of samples available for analysis.
Human presence on the Moon	**4**	The presence of humans on the Moon is considered crucial for enabling a wide range of lunar activities as it will enable tourism, manned scientific exploration or maintenance for industrial ecosystems.	**C**	It is also characterized by a high level of uncertainty. Factors such as funding, technological advancements, and international collaborations can influence the timeline and extent of human presence on the Moon.
Regulation	**4**	Regulation plays a crucial role in determining the permissibility and oversight of activities on the Moon. It serves as a key factor in allowing and governing various lunar endeavors.	**B**	The certainty surrounding regulations is relatively high, given that efforts to establish a legal framework for space activities began as early as 1967 with the Outer Space Treaty.
Availability of lunar energy	**4**	The availability of lunar energy holds significant potential for enabling a wide range of lunar activities without reliance on terrestrial energy sources.	**D**	The impact of lunar energy is uncertain due to the current level of maturity of technologies for efficiently harnessing and utilizing this energy.
Quantity of available resources	**3**	The lunar resources hold immense potential as raw materials for achieving independence from Earth and supporting various lunar activities.	**D**	The certainty surrounding the reserves is currently limited due to the relatively small number of samples collected thus far. Moreover, technologies to collect them are at a low maturity [1]
International collaboration	**4**	International collaboration will have a significant impact as it will structure the geography of the value chain, reduce the mission costs with economies of scale and it will enhance commerce	**B**	For the moment, there are many space agencies that can let hope for a collaboration between countries in a future sustainable settlement on the Moon.

Table 3 - Characterization of macro-drivers on impact and certitude. Imp. : Impact. Inc. : Incertitude. For impact: 1=low impact 4=high impact. For incertitude: A= certain D=uncertain

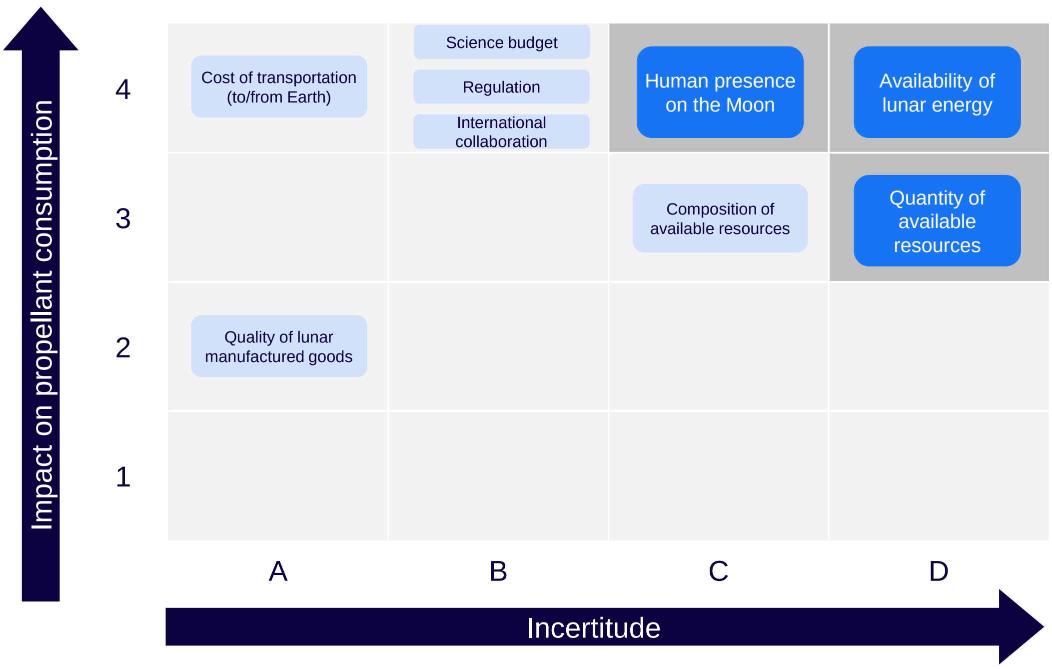

Figure 3 - Prioritization of macro-drivers. from 1=low impact to 4=high impact. From A=highly certain to D=highly uncertain

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The key macro-drivers, namely "Availability of lunar energy", "Human presence on the moon," and "Quantity of available resources," are critical and uncertain factors for the future. Here's a concise description of each:
Availability of lunar energy: The presence of abundant and renewable energy sources on the moon, such as sunlight and nuclear power, is crucial for sustainable lunar activities. However, the maturity of energy utilization technologies and the extent of available energy remain uncertain.
Human presence on the moon: The level of human presence on the moon significantly impacts the scale and scope of lunar activities. It expands the potential for scientific research, resource utilization, and infrastructure development. However, the timeline, required investment, and international cooperation for establishing a sustained human presence on the moon are uncertain.
Quantity of available resources: The presence of valuable resources on the moon, including water, metals, and minerals, enables long-term exploration and utilization. These resources can support life, fuel production, construction, and manufacturing. However, the distribution, quality, and accessibility of these resources are uncertain, pending further prospecting, technological advancements, and sample collection.

1.4. Characterization of stretched archetype scenarios

The analysis output above provide us with a comprehensive understanding of the macro-drivers that possess significant impact and high levels of uncertainty. This knowledge will serve as a guide in formulating diverse scenarios for lunar development, incorporating different combinations of these macro-drivers. Based on the three primary macro-drivers identified, we construct an option space to generate eight archetype scenarios, encompassing a spectrum from low to high divergence points. It is important to note that while the scale is continuous, the extreme divergence points allow us to consider the diverse actors and activities that may manifest within each scenario. It is more than possible that the future will not be precisely one of these scenarios. However, these scenarios define the range of possibilities and it is important for each player of the value chain to determine the best scenario for him, and to identify and detect the weak signals associated with one or several archetype scenario. These scenarios have been designed in the 2050 horizon.

Macro-driver	Possible points of divergence	
Human presence on the Moon	None	High
Availability of lunar energy	Scarce	Abundant
Quantity of available resources	Low	High

Table 4 - Scenario option space

Each of these three macro-drivers was assigned a level, either High or Low, to capture the range of possibilities. Within each scenario, we identified and categorized the corresponding end-goals that could potentially be realized, as described in the

		Macro-drivers			**End-goals**					
N	**Name of the scenario**	Availability of lunar energy	Human presence on the Moon	Quantity of available resources	**Scientific exploration**	**Resource utilization**	**Tourism**	**Construction**	**Manufacturing**	**Impact on propellant consumption**
1	*The Prosperous Frontier*				✓	✓	✓	✓	✓	
2	*Thriving Amidst Scarcity*				✓	x	✓	✓	✓	
3	*The Vast Energy Frontier*									
4	*Resource Rich Wilderness*				✓	✓	x	✓	✓	
5	*Resource Dominion*									
6	*Eclipse: Struggle for Survival*									
7	*The Dawn of Lunar Energy*				✓	x	x	x	x	
8	*Desolate Horizon*				✓	x	x	x	x	
		Legend	High	Middle	Low	Unrealistic				

Table 5 - Classification of scenarios according to their impact on the propellant consumption

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Certain scenarios among the eight identified are considered unrealistic due to constraints and considerations. For example, Scenario 5 and Scenario 6 are not feasible due to their heavy reliance on lunar energy for sustaining large-scale human space settlement. The availability of energy on the Moon is crucial for human presence and reducing dependence on Earth for life support and logistics. Likewise, Scenario 3, which involves a fully automated lunar economy, is unlikely as human intervention is necessary for the successful implementation and operation of such a complex system.

Scenario	The Prosperous Frontier	Thriving Amidst Scarcity	Resource Rich Wilderness	The Dawn of Lunar Energy	Desolate Horizon
Drivers	Human presence ☑ / Lunar energy ☑ / Resources ☑	Human presence ☑ / Lunar energy ☑ / Resources ☒	Human presence ☒ / Lunar energy ☒ / Resources ☑	Human presence ☒ / Lunar energy ☑ / Resources ☒	Human presence ☒ / Lunar energy ☒ / Resources ☒
Associated activities	• Abundant energy can be leveraged for resource utilization, manufacturing, construction for sustainable settlement • Energy supports in situ needs and commercial transportation. • Thriving lunar tourism industry. • The abundance of resources makes the Moon a refueling station for deep space exploration and reduce dependance from Earth.	• Abundant energy can be leveraged for life-support, manufacturing or construction with terrestrial resources. • Science exploration and tourism in a life base. • Supercomputing or storage and electricity refuel of vehicles or for life-support.	• Limited resource utilization as there is no energy to extract it. • Limited automated manufacturing or construction activities. • Few scientific missions with no habitation. • Utilization of rare or intrinsic quality resources.	• Supercomputing or storage and electricity refuel of vehicles or for life-support. • Limited automated construction for in-situ needs with terrestrial resources. • Limited scientific missions with no habitation.	• Business as usual • Only a few scientific missions with no long term habitation occur.

Human presence on the Moon — *Availability of lunar energy* — *Quantity of available resources*

Figure 4 : Associated activities and description for each feasible scenarios

For example, what could then be the future of *Prosperous Frontier* archetype scenario in 2050? Abundant energy available on the Moon provides opportunities for various activities, including resource utilization, long-term habitation, and commercial trips between the Moon and Earth. With the availability of lunar energy, major actors can engage in resource extraction, which can be utilized for both local purposes and commercial ventures. The construction of bases and infrastructure is also facilitated by the abundance of energy and resources. Furthermore, the development of lunar tourism has gained significant traction, while scientific exploration extends not only to the lunar surface but also to deeper space, leveraging the Moon as a refueling station. Overall, the abundance of energy and resources on the Moon shapes a range of activities in space exploration and utilization. Also, abundance of lunar propellants, allow to reinvent the architecture of cis lunar operations, with the development of propellant depots at different orbits. Eventually, international collaboration will be key in this scenario as it will reduce logistics footprint and costs, and it will enable further progress with synergies and interoperability.

2. Identification of priority use cases

Each archetype scenario will have an impact on the propellant value chain and especially its market size. Depending on each, the type of vehicle and the sizing of the utilization will vary for each of these potential futures. In the following pages, we therefore identify all the possible use cases for using propellant.

2.1. Screening of use cases

We narrow our focus to the specific use cases which directly fits with vehicle that can be employed for lunar or space exploration. These vehicles are distinguished by five key dimensions: origin of the ride, destination, distance travelled, payload, and the ultimate end-goal.

Origin	Earth	Moon	Mars	Space	
Destination	Earth	Moon	Mars	Space	
Distance	Short (<10km)	Middle (10-1,000km)	Long (>1,000km)		
Payload	Freight	Passengers	Unmanned payload		
End-goal	Exploration	Resource exploitation	Manufacturing	Construction	Tourism

Figure 5 – Moon transportation & logistics use case option space. Space travels are considered long-distance as the indicative

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ranges are only relevant on the Lunar surface

Unmanned payload is a payload that realizes the mission during the trip while freight is only payload that is transported between two locations. Sixteen distinct lunar systems referred to as “vehicles” emerged out of 144 possible combinations of the first 4 dimensions. This approach allows us to explore and evaluate a wide range of vehicle configurations, enabling us to make informed decisions regarding their suitability for various missions and objectives.

	Origin				Destination				Distance			Payload			Example
	Earth	Moon	Mars	Space	Earth	Moon	Mars	Space	Short	Middle	Long	Unmanned payload	Freight	Passengers	
Exploration rover		✓				✓			✓			✓			Rashid rover (Rashid Space Center)
Transport rover		✓				✓			✓				✓	✓	Lunar Roving Vehicle (NASA)
Lander				✓		✓					✓	✓	✓	✓	M1 (ISpace) / Argonaut (ESA)
Railway		✓				✓			✓			✓	✓	✓	FLOAT (NASA)
Unmanned launcher		✓						✓			✓		✓		Ariane 5 (ESA)
Manned launcher		✓						✓			✓			✓	SLS (NASA)
Manned spacecraft				✓	✓		✓	✓			✓			✓	Orion capsule (Lockheed Martin)
Space cargo				✓	✓		✓	✓			✓		✓		Nyx (The Exploration Company)
Point-to-point rocket		✓				✓					✓		✓	✓	Starship (SpaceX)
Astonaut propulsion unit				✓				✓	✓					✓	Manned Maneuvering unit (NASA)
Probe				✓				✓			✓	✓			Rosetta (ESA)
Hopper		✓				✓			✓			✓	✓		Micronova (NASA)
Orbital station				✓				✓			✓	✓	✓	✓	ISS (NASA/ESA/Roscomos/JAXA/CSA)
In orbit propellant depot				✓				✓			✓		✓		Tanker 001 Tenzing (OrbitFab)
Servicer				✓				✓			✓		✓		Mission Extension Vehicle (Alliant Techsystems)
Satellite				✓				✓			✓	✓			Moonlight constellation (ESA)

Table 6 - Moon transportation vehicles [7,11,12] Space travels are considered long-distance as the indicative ranges are only relevant on the Lunar surface. Vehicles with Earth or Mars origin are not considered.

2.2. ISRU potential of the use cases and prioritization

For every vehicle, ISRU propellant use is primarily influenced by the distance from Earth where the vehicle is used [12], so ISRU propellant could be interesting for every of the 16 identified vehicles. However, some vehicles have no interest to use propellant (ISRU or not). In order to segment the vehicles and identify those for which propellant usage is beneficial, we have developed an analysis based on the duration of use and the power requirements of each vehicle. The results of our analysis and literature review are in the matrix below, and allow us to evaluate the potential benefits associated with propellant utilization across the 16 different vehicle types.[1]

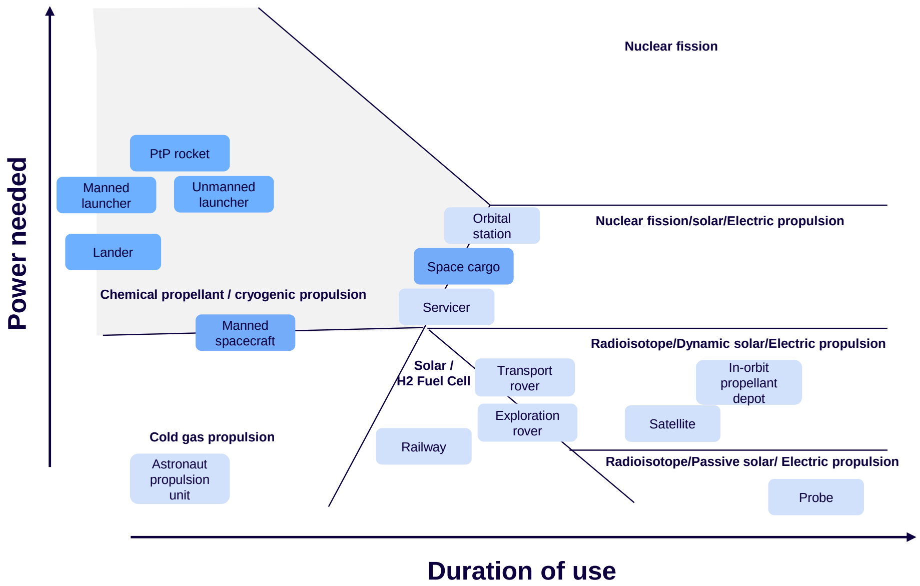

Figure 6 – Matching of use cases and preferred propulsion technology based on required power and duration of use (refers to the length of time it can effectively operate and fulfil its intended mission objectives in space) [1,13,14]

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According to the material resources, the most abundant and available resource is O_2 (Table 1) that is used for chemical propellants. Moreover, to lead a first approximation of the O_2 propellant demand, we decided to focus on the most chemical propellant intensive vehicles that are structuring for the total demand. Thus, we narrow the calculation to: **unmanned launcher, space cargo**, **manned launcher, manned spacecraft, point-to-point rocket,** and **lander**. Servicer and orbital station will only need propellant to maintain a position, which is assumed to be low propellant intensive.

2.3. Prioritized vehicles

A **manned launcher** is a type of rocket specifically designed to transport astronauts from Moon to space (lunar orbit) on middle and long distances. The demand equation for manned launcher can be defined as the number of passengers to be transported within a specific timeframe from Moon to lunar orbit. It can be, in fact, a lander that returns from Moon surface to orbit.
A **manned spacecraft** is a specialized vehicle designed to transport astronauts from space (orbit) to Earth, Mars or farther. The demand equation for manned spacecraft can be defined as the number of astronauts to be transported within a specific timeframe from lunar orbit to the Mars, Earth, or other celestial bodies. Similar to manned launchers, high capacity launchers are required to route spacecraft from Earth to orbit.
An **unmanned launcher** is a type of space vehicle designed to deliver payloads into space from Moon without the presence of human operators or crew onboard. It is used primarily for satellite deployment, scientific missions, and commercial applications. It can be, in fact, a lander that returns from Moon surface to orbit. The demand equation for unmanned launchers involves factors such as the number of launches required, payload mass and dimensions, desired orbit or destination, and launch window constraints.
Space cargo refers to the transportation of goods and supplies from space (orbit) to Earth, Mars or farther space. The demand equation for space cargo can be defined as the volume and weight of cargo to be transported within a specific timeframe. Similar to manned launchers, high capacity launchers are required to route cargos from Earth to orbit.
A **space lander** is a spacecraft designed to transport passengers or payloads from orbit to surface , such as scientific instruments, rovers, or habitats. Space landers play a crucial role in exploration and surface missions, enabling the deployment of scientific experiments, commercial use, and preparing for future human missions. The demand equation for space landers encompasses factors such as payload mass, mission objectives, and surface conditions.
A **point-to-point rocket** for lunar applications is a cutting-edge vehicle designed to transport passengers or payloads efficiently and rapidly between different locations on the Moon's surface. The demand equation for point-to-point encompasses factors such as payload mass to transport on surface and on long distances, landing accuracy requirements, mission objectives, and surface conditions.
The macro-metrics that will be needed to evaluate the scenarios needs in O_2 propellant will be the number and tonnage of manned and unmanned missions from/to/on the Moon. It will be detailed by end-goal (knowing that manufacturing will not be economically viable in 2050 [2]). There is also a need of high capacity launchers to route the launchers, the cargos, the spacecrafts or the rockets, to the Moon, and landing facilities and dust barriers if the launchers are reusable.

3. Use case value chain structure and demand equation

3.1. Value chain

According to the identified chemical propulsion, we have chosen in this paper to focus on the liquid **oxygen** propellant, as it seems a good proxy to get a first view on market sizing.
Based on this key chemical transformation process, the value chain of propellant production on the Moon encompasses several key stages as described in the figure below.

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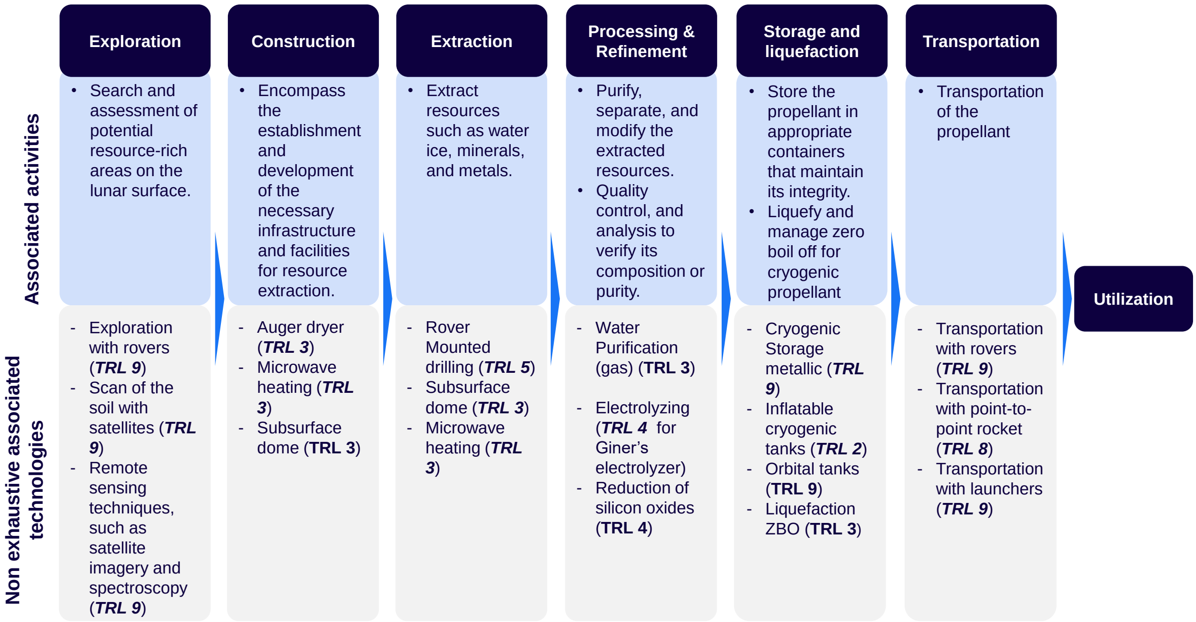

Figure 7 - Key points of the value chain for lunar-derived propellant production [1,15,16]

3.2. Demand equation

In order to estimate the volume of O_2 propellant needed for each scenario, we estimate the number of vehicles needed for the lunar exploration, we can consider the following demand equation :

$$\text{Total quantity of lunar propellant demand} = \text{Number of missions} \times \frac{\text{consumption}}{\text{mission}} \quad \textbf{(1)}$$

$$= \frac{\text{Total quantity of goods/number of passengers to transport (from} - \text{to} - \text{on) Moon}}{\frac{\text{capacity}}{\text{mission}}} \times \frac{\text{consumption}}{\text{mission}}$$

3.3. Total quantity of goods/number of passengers to transport (from-to-on) the Moon

The total mass of O_2 propellant can be detailed for each activities on or around the Moon :

$$\begin{aligned} m_p = {} & m_{p-rocks} + m_{p-satellite} + m_{p-Mars} + m_{p-construction} + m_{p-passengers-landers} \\ & + m_{p-passengers-return-surface} + m_{p-passengers-return-orbit} + m_{p-support} \\ & + m_{p-refuel-orbit} + m_{point-to-point-passengers} + m_{point-to-point-resources} \\ & + \text{other potential sources of propellant demand} \end{aligned} \quad \textbf{(2)}$$

With:

- m_p the total mass of propellant to produce,
- $m_{p-rocks}$ the mass driven by non-propellant rocks with terrestrial use, using a launcher and a manned spacecraft, considered as Starship for both roles,
- $m_{p-satellite}$ the mass driven by the launch of satellites from the Moon,
- m_{p-Mars} the mass driven by the Mars missions,
- $m_{p-construction}$ the mass driven by the construction of habitats for tourism or science exploration,
- $m_{p-passengers-landers}$ the mass driven by the transportation of passengers from orbit to surface
- $m_{p-passengers-return-surface}$ the mass driven by the transportation of passengers from surface to Earth, using a launcher and a manned spacecraft.
- $m_{p-passengers-return-orbit}$ the mass driven by the transportation of passengers from orbit to Earth.
- $m_{p-support}$ the mass driven by the transportation of support activities such as life-support or maintenance

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- $m_{p-refuel-orbit}$ the mass driven by the transportation of propellant to orbit for refueling other spacecrafts,
- $m_{point-to-point-passengers}$ the mass driven by the transportation on surface over long distances of passengers.
- $m_{point-to-point-resources}$ the mass driven by the transportation of resources in the value chain, on surface and over long distances.

There may be other activities (potential sources of propellant demand), this list is not exhaustive but gives a good first example of the methodology. All the scenarios have been sized by using key values for each sizing factor linked with a macro-driver. Each scenario will used these key values from 0% to 100%.

Sizing factor for propellant	Unit	Value	Reference	Justification
Satellites to launch from the Moon	#/yr	20		Assumptions for the needs of positioning, timing, navigating and data gathering, based on a parametric analogy of the 1500 satellites launched from the Earth every year
Non-propellant resources to Earth (samples)	t/yr	2	[2]	Economically viable market according the source. Non propellant resources will be transported to Earth only once there is robust, refuelable, reusable and sustainable transportation
Tourists for flyby	#/yr	20	[2]	Economically viable market according the source
Mars missions	#/yr	0.5	[17]	Mars missions can be launched once every 26 months, we assume it will be the mature frequency of mission to Mars
Passengers to surface of the Moon	#/yr	10	[2]	According to the future science budget by the source. Assumption of one mission per year with 10 passengers. Not considering passengers that are living permanently on the Moon
Number of habitats/decade	#/dc	3	[2]	According to the needs of inhabitants according the source
Support to surface	t/yr	10		Sized according to the actual life-support to ISS (1.5t/person/year) and for assumed maintenance. Not considering mining facilities construction as they should be deployed in 2050.
Spread of bases	ratio	1		It signifies whether the bases or infrastructures (dedicated to passengers) are more compact and centralized (closer to 0) or spread out over a wider area (closer to 1). A higher value indicates that a portion passengers will need to travel using point-to-point rocket systems.
Spread of value chain	ratio	1		It signifies whether the bases or infrastructures (dedicated to mining and resources) are more compact and centralized (closer to 0) or spread out over a wider area (closer to 1). A higher value indicates that a portion of resources will need to travel using point-to-point rocket systems.

The values for other 4 scenarios derived from the first one. But we, as Euro2Moon, will be able to update these data in the next steps of our study. This only leads to a first case study of our methodology.

Vehicle concerned	Sizing factor for propellant	Unit	End-goal	*Prosperous Frontier*	*Thriving Amidst Scarcity*	*The Dawn of Lunar Energy*	*Resource Rich Wilderness*	*Desolate Horizon*
Unmanned launcher / space cargo	Satellites to launch from the Moon	#/yr	All end-goals	**20**	**20**	**20**	**10**	**0**
	Non-propellant resources to Earth (samples)[1]	t/yr	Resource utilization / Scientific exploration	**2**	**0**	**0**	**1**	**0**
	Mars missions	#/yr	Scientific exploration	**0.5**	**0**	**0**	**0.5**	**0**
	Tourists for flyby	#/yr	Tourism	**20**	**20**	**0**	**0**	**0**
Manned launcher / manned spacecraft	Passengers to surface[2]	#/yr	Scientific exploration	**10**	**10**	**0**	**0**	**0**
	Tourists for flyby	#/yr	Tourism	**20**	**20**	**0**	**0**	**0**
Point-to-point rocket	Passengers to surface[2]	#/yr	Scientific exploration	**10**	**10**	**0**	**0**	**0**
	Spread of bases	ratio	Tourism / Scientific exploration	**1**	**0.5**	**0**	**0**	**0**
	Spread of value chain	ratio	Resource utilization	**1**	**0**	**0**	**1**	**0**
	Non-propellant resources to Earth[2]	t/yr	Resource utilization	**2**	**0**	**0**	**1**	**0**
Lander	Passengers to surface[2]	#/yr	Scientific exploration	**10**	**10**	**0**	**0**	**0**
	Number of habitats/decade	#/dc	Construction	**3**	**3**	**0**	**0**	**0**
	Support to surface	t/yr	All end-goals	**10**	**10**	**10**	**10**	**10**

Table 7 – Sizing factors for propellants in the application markets with the vehicle concerned in the horizon 2050 [2,17] yr: year dc: decade.

Tourists for flyby, with their return trip to Earth, are conditioning the mass of propellant that will be need to be transported to orbit tanks thanks to a manned launcher.

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3.4. Capacity per mission

Table 8 summarizes our capacity assumptions needed to illustrate the application of our methodology. Future Euro2Moon studies will bring deeper insights on potential realistic values for these parameters.

Category	Metric	Value	Unit
Mass	Satellite mass	0.5	t
Mass	Astronaut mass + equipment	0.1	t
Mass	Launcher dry mass	180	t
Mass	Lander dry mass	11	t
Mass	Units of habitat mass	10	t
Mass	Assumed mass payload for Mars mission	100	t
Mass	Capacity for launcher	100	t
Crew	Crew capacity of lander	2	people
Crew	Launcher capacity	10	people

Table 8- Examples of assumptions for the calculation of the total O_2 propellant demand

We based our calculations on characteristics of SpaceX spacecrafts and engines, an hydrogen rocket having a more important dry mass. Assumed masses payload are hypothesis from Euro2Moon.

3.5. Consumption per mission

Category	Metric	Value	Unit
Delta-V	Delta-V from Moon surface to lunar orbit	2,400	m/s
Delta-V	Delta-V from Moon surface to Earth	13,600	m/s
Delta-V	Delta-V from Moon orbit to Mars	6,400	m/s
V_e	Average ejection velocity for LOX-LH2 and LOX-CH4 engine in vacuum	4,000	m/s

Table 9 – Examples of assumptions for the calculation of the total propellant demand

Delta-V is estimated by taking a elliptic trajectory from the origin that intercepts the destination. We focus on the total quantity of goods to transport from the Moon to Space, or from the lunar orbit to the Moon surface. We exclude the use of lunar-derived propellant on Earth, assuming it is not economically interesting [12]. For point-to-point rocket, we assumed that the trip goes to LLO orbit, in order to launch with a high angle to avoid geometry constraints of the Moon. So for the consumption per mission, it deals with the Tsiolkovsky equation [24]:

$$m_p = (N \times m_{dry-mass} + \mathrm{m}_{payload}) \left(e^{\left(\frac{\Delta V}{V_e}\right)} - 1 \right) \quad \textbf{(3)}$$

With m_p the mass of propellant, ΔV is the difference of speed that the spacecraft needs to be in, or to go out, orbit. V_e refers to the specific impulse of the propulsion system used by the rocket or spacecraft, $m_{dry\text{-}mass}$ and $m_{payload}$ are the dry mass of the vehicle and the total mass of payload, N is the number of missions.
The number of missions N is calculated as follow:

$$N = \left\lceil \left(\frac{Total\ tonnage\ to\ transport}{\frac{capacity}{mission}} \right) \right\rceil \quad \textbf{(4)}$$

Where $\lceil x \rceil$ refers to the ceiling function and returns the smallest integer that is greater than or equal to x. The number of missions vary also with the international collaboration, the needs in terms of timeline, or logistics. For the number of manned missions, we can estimate it with:

$$N_{scientific-manned-missions} = \sum_{\mathrm{US,China,EU,private}} \left(\frac{\#\ \text{of scientifics} \times \text{rotation/yr}}{\#\ \text{of scientifics per rotation}} \right) \quad \textbf{(5)}$$

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3.6. Case study – an example of application

Applying this methodology leads to a first estimation of the total produced mass of lunar-derived propellant (O_2) at **41 kilotons** (metric) per year in the 2050 horizon, in the "Prosperous Frontier" scenario.

For the scenario *Dawn of Lunar Energy*, only scientific exploration is allowed, leading to a O_2 propellant mass equal to the mass for support (rovers, instruments…) and the refuel in orbit of these landers. By applying the same approach than above, we estimate to **0.2 kt** per year of O_2 propellant to be produced. However, as there could be no or low available reserves to produce propellant, it could not be produced on the Moon.

Table 6 below provides a more detailed estimation of propellant mass by scenario. Three main uses cases size the demand :

- The return trip of non-propellant resources to Earth
- The return trip of passengers to Earth from orbit, or from surface
- The refuel in orbit to reduce the launch cost from Earth, or to go to Mars

	Propellant demand (kt/year)				
Mass of propellant for	**Prosperous Frontier**	**Thriving Amidst Scarcity**	**Resource Rich Wilderness**	**The Dawn of Lunar Energy**	**Desolate Horizon**
Satellite	0.6	0.6	0.6	0.6	-
Non-propellant resources to Earth (samples)	11.5	-	11.4	-	-
Construction in landers	0.0	0.0	-	-	-
Mars trip	0.6	-	-	-	-
Passengers in landers	0.0	0.0	-	-	-
Passengers return trip from orbit to Earth	6.0	6.0	-	-	-
Passengers return trip from surface to Earth	22.9	22.9	-	-	-
Support in landers	0.0	0.0	0.0	0.0	0.0
Refuel in orbit	6.1	5.6	0.7	0.2	0.2
Point-to-point rocket for resources	0.4	-	0.4	-	-
Point-to-point rocket for passengers	0.9	0.9	-	-	-
	-	-		-	-
Total mass of O2 (t)	**41.2**	**30.3**	**11.6**	**0.7**	**0.2**

Table 10 : Calculations of propellant quantity per scenario (kt/year in 2050). ✓ : associated macro-driver, x : non-associated macro-driver. Considering that O_2 is in average 84% of the mass of propellant in a LOX/CH4 or LOX/LH2 engine

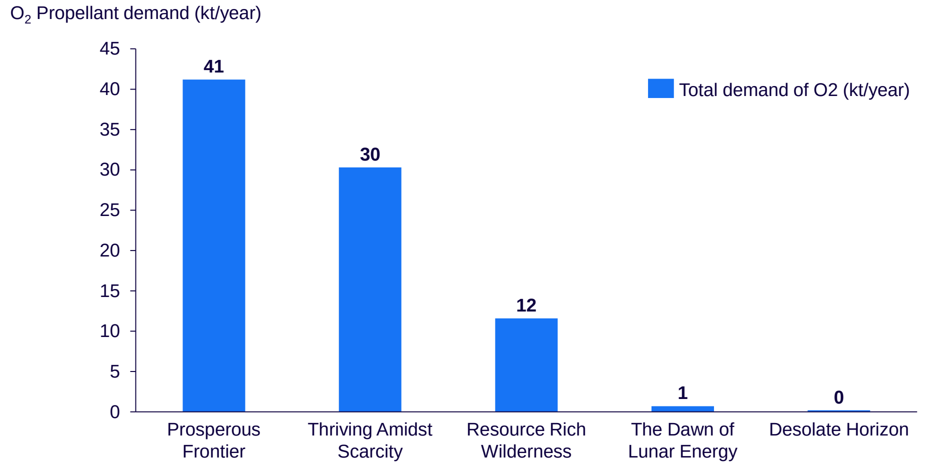

Figure 8 – Total consumption of O_2 propellant (kilotons per year) for considered scenarios in 2050

As O_2 will be produced from Moon regolith (SiO_2), containing up to 40% O_2 in mass, if we consider the uppermost meter of regolith with a homogenous concentration and density (1660 km/m^3 [7]) of regolith on the total superficy of the Moon, we can estimate the total mass of O_2 by 31 billion of tons. Thus this demand seems accessible if the extraction and transformation technologies are under maturation.

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4. Conclusions and perspectives

In this paper, we have developed a generic methodology laying the ground for a bottom-up assessment of the market demand for ISRU-based propellants on the Moon, which will ultimately help guide decision-making and strategic planning for the sustainable development of lunar activities.
This methodology relies on identifying lunar activities and the underlying demand drivers, among which we identified several divergence points. These divergence points allow us to construct several archetype scenarios. We then analyze the individual demand of each of the main use cases, which then allows us to calculate the aggregated demand for each scenario. The usefulness of such a scenario-based approach is illustrated in the strong variability of the results of our case study. In fact, the added-value of such a methodology resides as much in its ability to display and anticipate uncertainties than in its ability to produce numerical estimates of a total demand.
As preliminary as our first results are, their variability suggests that the development of lunar ISRU should require bold business decisions and support from public space agencies, as well as strong international collaboration, in order to improve the sustainability of the business case of lunar ISRU.
Further steps in this research will take a deeper look into the detailed demand equations for each use case, and will aim at providing updated values for the assumptions required to calculate the associated demand. The scope of the study shall then be enlarged, both in terms of use cases considered for propellant demand, and would be expanded beyond the sole demand for propellants only, covering all possible lunar ISRU applications.

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