



Fuelling the future of mobility: Moon-produced space propellants

Go Beyond

The forthcoming decade is expected to witness a wave of missions to the Moon and Mars, and fuel supply is a major challenge to make these travels economically sustainable. The difference in the required energy to launch from Earth and from the Moon is causing people to reconsider refuelling point positions (e.g. NHRO, Near Halo Rectilinear Orbit) and contemplate using space-produced propellants. A whole production and transport value chain would have to be established on the Moon. Initial investments are sizeable (~\$7B) but an economic opportunity for space propellants should exist if launch costs from Earth do not fall too much below current SpaceX standards. Capex optimization and increased scale should further improve the competitiveness of space propellants. Positive outcomes for 'terrestrial' applications are also expected to be significant. ➔

The Case for Moon-Produced Propellants

The next decade is expected to witness a boom in Lunar and Mars exploration.

After the space race of the 60s, there has been an unprecedented resurgence of unmanned Lunar and Mars missions since the end of the 90s, as well as the spread of space programs to various countries. (e.g. Chinese rovers on the moon, UAE mission to Mars, etc...). The next decade is expected to witness further Lunar and Mars exploration.

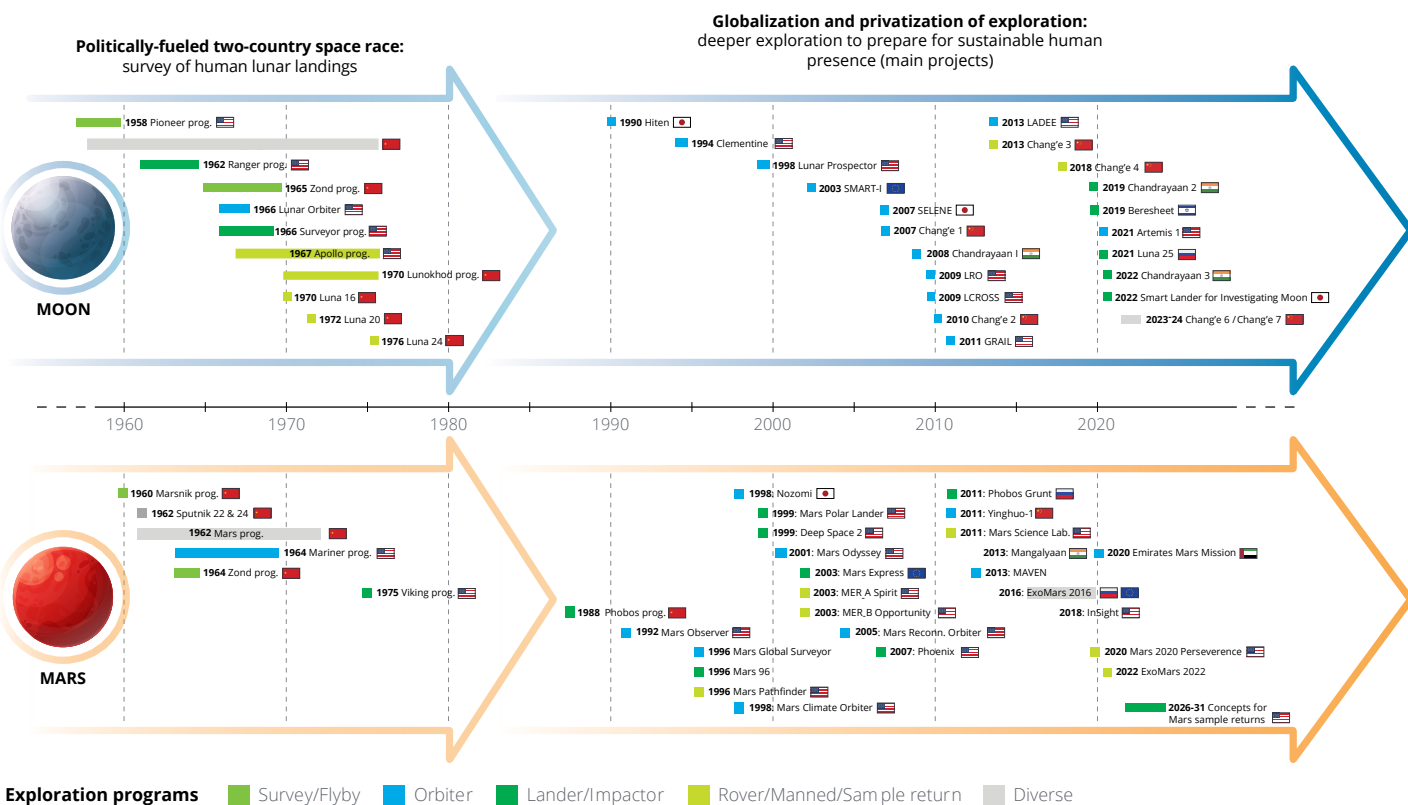
Although historically dominated by governmental players, space exploration will increasingly attract private operators, bringing about major technical and business model disruptions. Indeed, at the beginning of April 2021, Elon Musk's SpaceX won the NASA \$2.9B contract to build a Moon lander, besting Jeff Bezos' Blue Origin and others (who are, however, still relevant competitors for further missions) in the contest to carry American astronauts to the lunar surface¹. A first landing on the Moon is scheduled for 2024, and Elon Musk recently reiterated his ambition to land manned spaceships on Mars before 2030².

After 2024, NASA expects to set up a base camp on the moon ('Artemis Base Camp') to be a long-term foothold for lunar exploration, as well as a Moon-orbiting station ('Gateway') on the NHRO (Near Rectilinear Halo Orbit) being a site for developing the knowledge and experience necessary to venture beyond the Moon and into deep space (e.g. Mars-analog missions). The fuel supply will then be a major challenge in making cis-lunar traveling economically sustainable.

Furthermore, space-exploration-driven technologies often have beneficial impacts on 'terrestrial' applications. Safran, Airbus and Ariane Group launched the 'Hyperion' project, to leverage space-launcher technologies to cryogenic systems for hydrogen powered aircraft. Technical advances driven by this new wave of space exploration are also to be expected.

Space-exploration-driven technologies also have very beneficial impacts on 'terrestrial' applications.

Figure 1
Chronology of major Lunar and Mars exploration programs



Source: Country space agencies, Corporations, Monitor Deloitte analysis

Space-produced propellants can be a major catalyst for space exploration.

The energy required to sustain space programs is clearly stated by the Tsiolkovsky rocket equation stating the amount of necessary propellants in terms of the difference between the initial (m_0) and the final (m_f) masses of the vehicle being proportional to an exponential of ΔV (the maximum change of velocity of the vehicle), v_e being the effective ship exhaust velocity.

$$m_0 - m_f = m_f (e^{\Delta V/v_e} - 1)$$

A much larger ΔV (9.5 km/s to LEO) is needed to escape Earth gravity than to travel across cislunar space, therefore requiring a huge amount of propellants. This difference in the required energy to launch from Earth and from the Moon is pushing industrial players to consider refuelling points (e.g. EML-1, NRHO) in space with an energy source (e.g. focus on LH_2 and LOx in our document, CH_4 being also a feasible option) that will be mined and processed on the Moon.

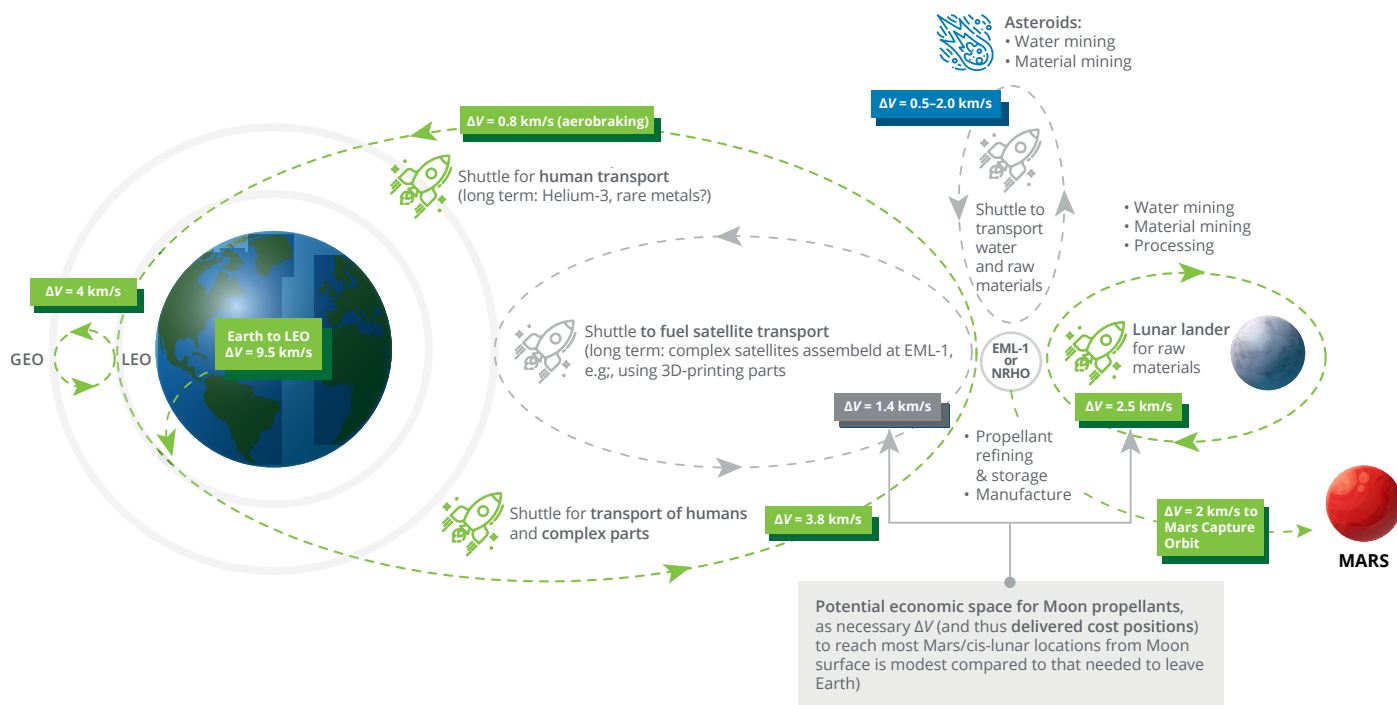
There is no doubt that developing viable LH_2 (hydrogen) and LOx (oxygen) production on the Moon will drive major technical breakthroughs also benefiting Earth-based technologies.

The major parameters influencing the success of such an initiative will be:

- the development of a stable and sizeable market for space propellants (with a regular schedule of manned and unmanned missions on the Moon and to Mars);
- the ability of players (both public and private) to position themselves on the different space propellants, value stages to develop a coordinated, technically consistent and economically viable solution;
- the cost competitiveness of space launchers, as their falling costs – currently mainly driven by SpaceX – may jeopardize Moon-produced propellant prices which would be highly dependent on 'Next Best Offers' from Earth.

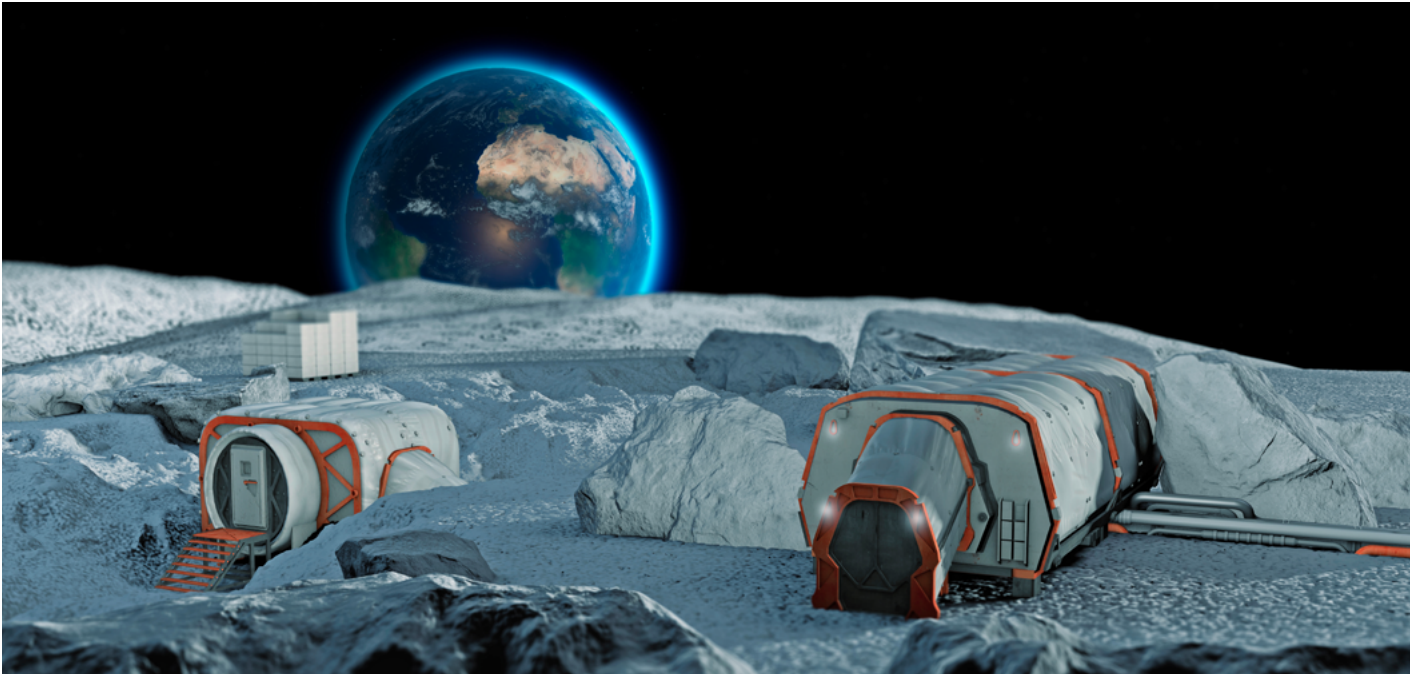
The difference in the required energy to launch from Earth and from the Moon is pushing industrial players to consider refuelling points in space using an energy from the Moon.

Figure 2 Major routes in cis-lunar space (and associated ΔV)



GEO: Geostationary Earth Orbit - **LEO:** Low Earth Orbit - **EML:** Earth Moon Lagrange Point
 — Potential trade routes

Source: Study of Lunar Propellant Production (2018), United Launch Alliance

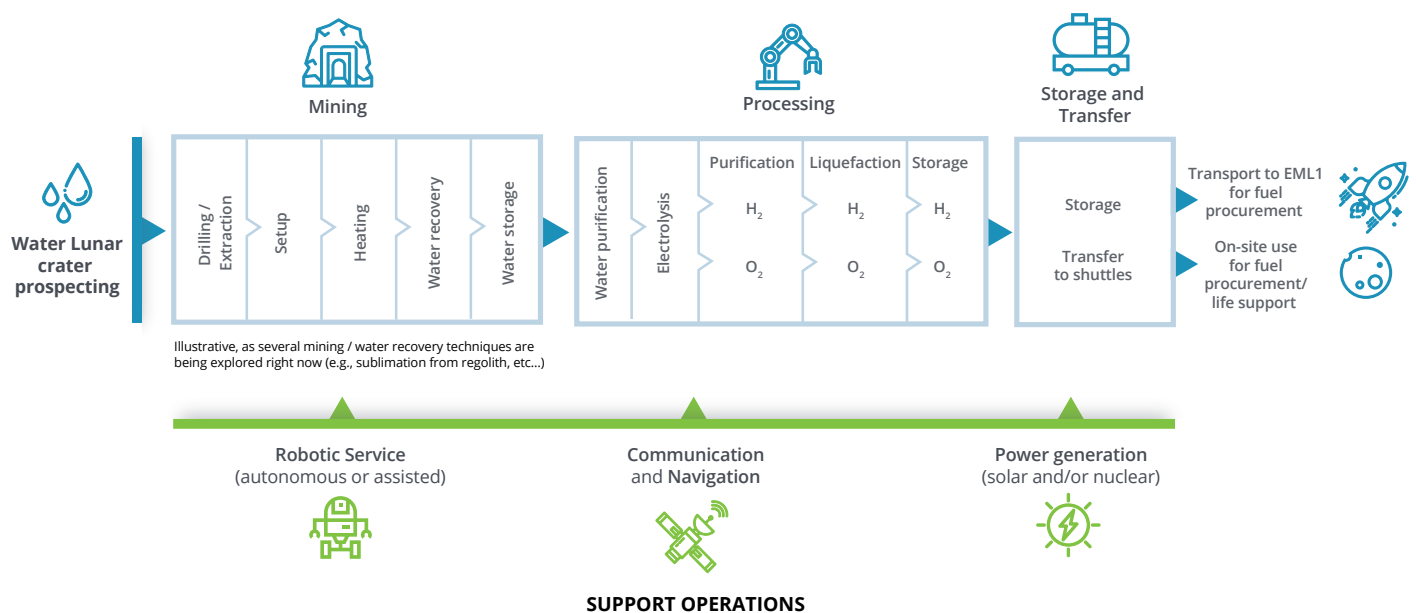


Practical Matters: The Space Propellant Value Chain

In order to produce space propellants on the Moon, a whole value chain must be developed, from mining ice from its source in Permanently Shadowed Regions (PSR) on the Moon, through processing, and all the way to the end user as propellant. The full infrastructure will involve major systems: the lunar mine, propellant processing, power, robotic services, communication/navigation and propellant handling and logistics (in-space and on the lunar surface).³

To be competitive, all construction and operations are expected to be performed by robotic systems, the need for manned missions being limited to a few exceptional maintenance or repair operations in case of major damage.

Figure 3
A possible Moon propellant production value-chain



Source: Study of Lunar Propellant Production (2018), United Launch Alliance, Corporate websites, Monitor Deloitte analysis

Currently, even if the economic viability of propellant production on the moon is a question mark, all technologies necessary to perform propellants production on the Moon are **either in development or have already been developed:**

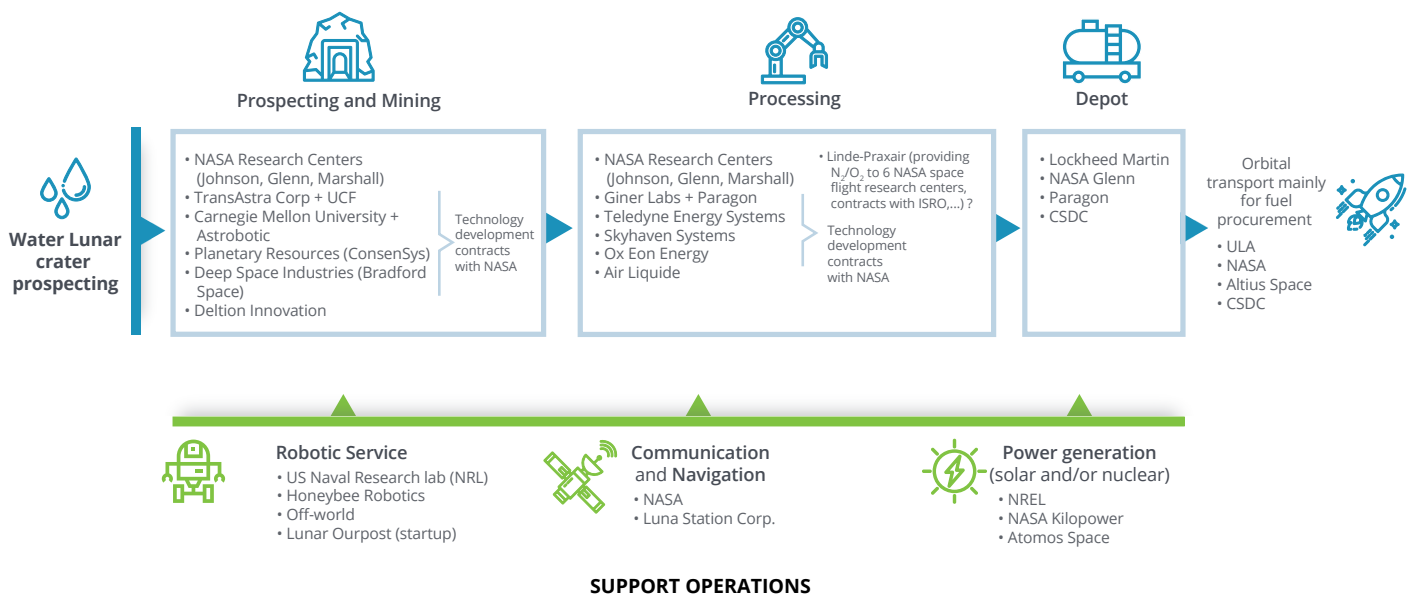
- **Mining:** There are uncertainties about the physical forms of lunar water, which could include blocky ice deposits, adsorbed molecules and hydrated minerals in PSR areas. Extraction of the water should therefore be performed by direct sublimation so that moving large amounts of regolith can be avoided.
- **Processing:** Water will be broken down into hydrogen and oxygen in an electrolyzer, which will then be liquefied for storage. Low temperatures within craters will be a challenge for all robotic operations, but will make storage easier, keeping LH₂ and LOx cold, reducing power needs.

- **Power generation:** Two means of generating power are being contemplated. Solar power is a well-known technology in space but would need to be located outside the PSR in a sunlit area, therefore specific (and costly) power transmission infrastructure. Nuclear power plants can function within a PSR.

As of today, many future space-propellants ecosystems stakeholders can be identified, but many uncertainties remain, such as their level of ambition for these activities and their ability to deliver effective and viable technologies.

To produce space propellants on the Moon, a whole value chain must be developed, from mining ice from in permanently shadowed regions, through processing and all the way to the end user.

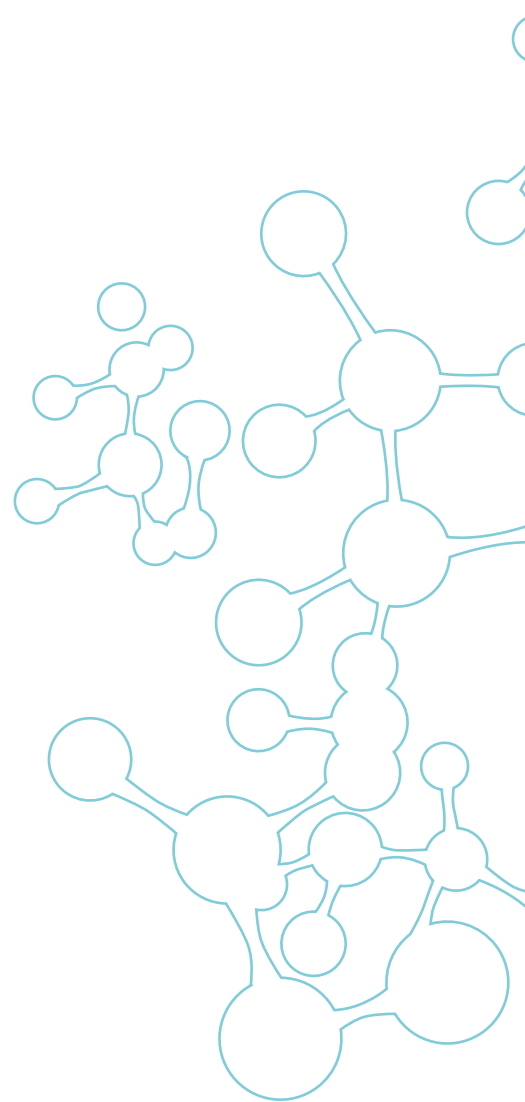
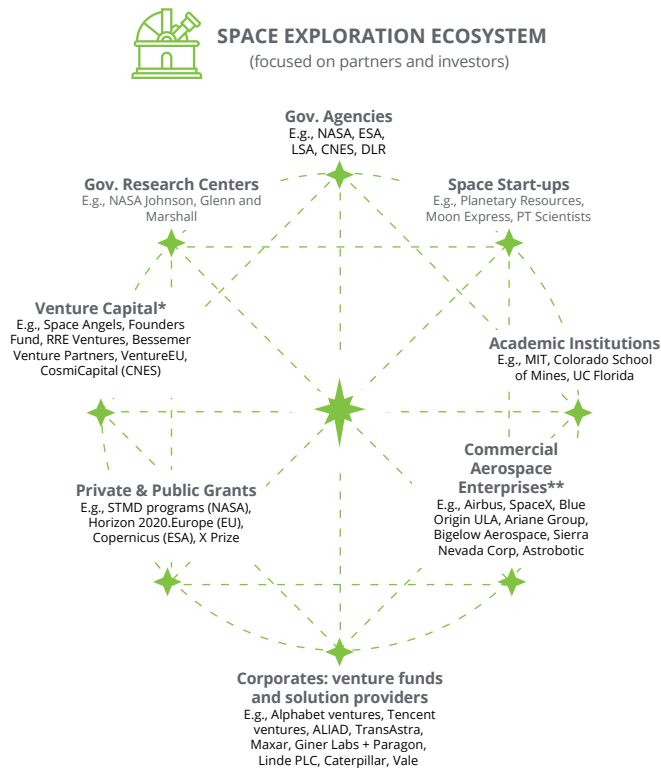
Figure 4
Players currently developing technologies for the moon-produced propellants value chain



Isolated initiatives are unlikely to deliver tangible medium-term results, so entering a consortium with space agencies and/or private operators (SpaceX, Blue Origin) will be a key factor in achieving goals, including direct integration into major programs,

increased funding efforts, compatible technologies and scale in infrastructure.

Figure 5
Typical ecosystems to be developed in order to develop and fund a moon-produced propellant enterprise



Benefits of partnership

Potential partners & investors	Funds	Expertise	Co-create	Operationalize
Grants			Explore short-term funding: equity or grants	
Venture capital*				Explore R&D partnerships
Corporate venture funds				Explore acquisitions and joint ventures
Academic Institutions				
Gov. research Centers				
Start-ups	Explore long-term strategic partnerships			
Corporate suppliers				
Gov. agencies				
Commercial aerospace**				

*Includes angel investors, government venture funds and space-related accelerator/incubator support

**Refers to aerospace enterprises operating or providing solutions beyond Earth-launch/rocket technology

The Business Case: Propellants may be produced on the moon by 2030

The addressable propellant market in the cis-lunar area by 2030

Moon-produced propellants can be used for various routes within cislunar space, fuelling a broad range of vehicles (launch vehicles, satellites/orbiters, space stations, spacecraft, landers/ascent modules) and extra-terrestrial camps. They can be used both for propulsion and life support for manned missions.

For simplicity's sake, we will assume that by 2030, with SpaceX and NASA successfully reaching their objectives, Moon and Mars missions will be regularly performed, yet still at a nascent stage.

- Moon:** Two manned missions per year (with the lander requiring 25 t of propellants⁴ for each journey between the Gateway station and moon surface, consistent with a 13 t dry weight lander), plus one heavier cargo mission, requiring 50 mt of propellants – which is comparable to the pace of the Apollo program.

- Mars:** one manned mission every two years (when the Earth and Mars have optimal relative positions, allowing spacecrafts to enter the Hohmann transfer orbit), requiring 280 t of fuel at the Gateway station⁵ each trip.

The total resulting demand at EML-1 or NRHO would then be for 240 t of propellants/year, corresponding to a fuel production of ~520 t on the Moon (taking into account fuel necessary to power the cargo vehicle transporting propellants from the lunar surface to Gateway) Of course, the demand could be much higher if several space agencies launch simultaneously coordinated Moon or Mars missions relying on the same fuel standards. But from a conservative standpoint, we consider this very unlikely.

Moon-produced propellants can be used for various routes within cis-lunar space, fuelling a broad range of vehicles and extra-terrestrial camps. They can be used both for propulsion and manned-mission life support.

Figure 6
Field of market possibilities for Moon-produced propellants

Customers	Space routes					
	LEO/GTO	GEO	EML or NRHO	LLO	Moon	Beyond (e.g., Mars)
Launch vehicles	Fuel ■■		Fuel ■			
Satellites / orbiters	Fuel ■■■■	Fuel ■■■■		Fuel ■■■■		Fuel ■■■■
Space stations	Fuel ■■■■ Life support ■■■■		Fuel ■■ Life support ■■	Fuel ■■■■ Life support ■■■■		Fuel ■■■■ Life support ■■■■
Spacecrafts			Fuel ■■ Life support ■■	Fuel ■■■■ Life support ■■■■		Fuel ■■■■ Life support ■■■■
Lander & ascent modules				Fuel ■■■■ Life support ■■■■	Fuel ■■■■ Life support ■■■■	Fuel ■■■■ Life support ■■■■
Extra-terrestrial surface camps & operations					Fuel ■■ Life support ■■	Fuel ■■ Life support ■■

Typical applications

- Space activities mainly concentrated on Earth orbits
- Manned exploration and colonization of Moon
- Unmanned exploration of Deep Space
- Manned exploration and colonization of Deep Space

Pricing of moon-produced propellants

The backstop for Moon-produced propellant prices will be set by terrestrial competition. To be attractive on the market, space-produced propellants must be sold at EML-1 cheaper than the cost of transporting them from Earth, with a discount (e.g., 10%) necessary to cover the risks of switching from one technology to another.

Currently, 'best offers' from Earth are driven by Space-X costs, and are **in the range of \$12k/t up to EML-1/NHRO**, extrapolated from costs to LEO of \$4 k/t (e.g. Falcon 9 launches of 15.6 tonnes to LEO for \$62M, typically for Starlink launches) and to GEO of 8k\$/t (e.g. Falcon Heavy launch of Arabsat-6A satellites in April 2019: 6.46 tonnes for \$90 M).

Costs have plummeted in recent years, and SpaceX claims to be able to propose costs lower than ~20-30% soon (e.g. increasing Falcon 9 payload up to 16.8 tonnes, while decreasing costs down to \$52M).

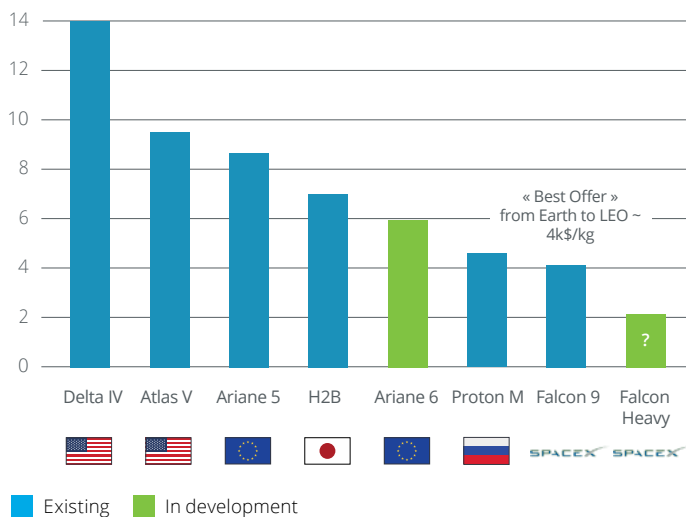
However, these costs are subject to controversies, as Roscosmos head Dmitry Rogozin claims that SpaceX is dumping prices on commercial launches⁶ to force Russia out of the market, while charging NASA as much as four times more for government launches to make up the difference (e.g. the \$316M contract awarded by the Department of the Air Force for the National Security Space Launch (NSSL) Phase 2 contract⁷)

As launch costs drop, the value of propellant at the lunar surface will fall. Therefore, a further sizeable reduction of launchers costs is the major threat for Moon-produced propellants, economic viability.

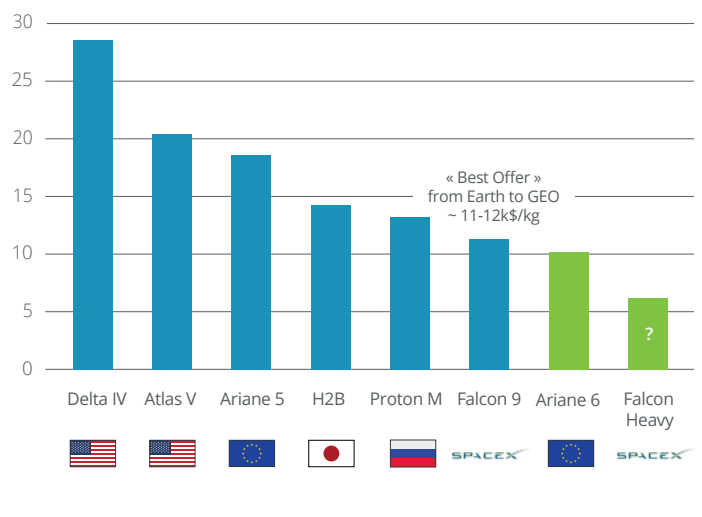
The backstop for Moon-produced propellant prices will be set by terrestrial competition, as they will have to be sold at EML-1/NHRO cheaper than the cost of transporting them from Earth

Figure 7
Evolution of launching costs up to LEO and GEO (\$/kg)

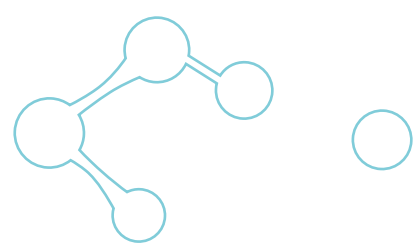
Cost of heavy launchers to LEO and GEO



Cost of heavy launchers to GEO



Source: Study of Lunar Propellant Production (2018), United Launch Alliance, Corporate websites, Monitor Deloitte analysis



Estimates of costs to build-up and operate the propellant production infrastructure on the Moon

CAPEX estimates

Several academic research works have investigated potential costs of Moon propellants production infrastructures over the last decades (e.g., Blair (2002)⁸; Charania (2007)⁹; Lavoie (2016)¹⁰, ...). However, reference studies show significant variations in estimates of performance. Differences also exist in the preferred power plant assumptions, Blair and Charania assuming a small nuclear reactor, while Lavoie relies rather on solar PV panels.

On average, reference studies establish infrastructure costs at ~\$200k/kg of equipment:

- This is to be compared with most advanced equipment sent to space, such as recent Mars missions (Curiosity: total mass of 3.8 tonnes for \$2.5B and Perseverance: total mass of 3.65 tonnes for \$2.2B, i.e. \$600–650k/kg) or advanced GEO weather satellites such as GOES-U (\$1.4B for a total mass of 2.8 tonnes i.e. \$500k/kg).
- A military telco satellite such as Syracuse 4 / 5, built by Thales and Airbus cost in the ~€450M–500M range for 3.5 tonne equipment (i.e. \$150k/kg)

- Finally, Starlink satellites, produced in huge quantity have costs down to \$2–4k/kg.

In this document, we will conservatively use an average of these 3 reference studies, adjusted for inflation (i.e., formulated in 2020 USD) as a central scenario, scaling plant size according to necessary propellants production (i.e. 520 t / year on the Moon surface):

- Development costs are assumed as fixed
- Manufacturing costs are variable with the total mass of the facilities (43.1 tonnes)
- The whole system is being delivered to the Moon, at costs of \$36k/kg
- Propellants between lunar surface and EML-1/NHRO are assumed to be performed by 2 Cargo vessels costing \$300M each (analogy with price paid by NASA to Lockheed Martin for 3 first Orion spacecraft). **Total CAPEX is therefore expected to amount \$6.85B**

Given the uncertainties on expected CAPEX levels, a sensitivity measurement (on a +/-50% CAPEX range) is also performed.

Figure 8
Summary of CAPEX estimates for Moon-propellants production

			Blair (2002)		Charania (2007)		Lavoie (2016)		Average (Assumptions)	
			Dev.	Manuf.	Dev.	Manuf.	Dev.	Manuf.		
Production	Total	t propellant/y	245		57.6		140		148	
	Mass	kg	630		2,600		4,000			
Mining	Costs	\$M	69	49	206	69	384	274		
	Mass	kg	7,134		5,910		5,000			
Processing	Costs	\$M	1,127	80	755	251	1,096	274		
	Mass	kg	3,421		5,400		1,900			
Power Plant	Costs	\$M	811	499	254	85	0	860		
	Mass	t	11.2		13.9		10.9		12.0	
Total	Costs	\$M	2,008	627	1,214	405	1,480	1,408	1,567	813
	Cost / Mass		179	56	87	29	136	129	131	68
Key Ratios	Cost / Production	\$k/kg	8.2	2.6	21.1	7.0	10.6	10.1	10.6	5.5
	Production / Mass	\$k/kg.y	21.9		4.1		12.8		12.3	

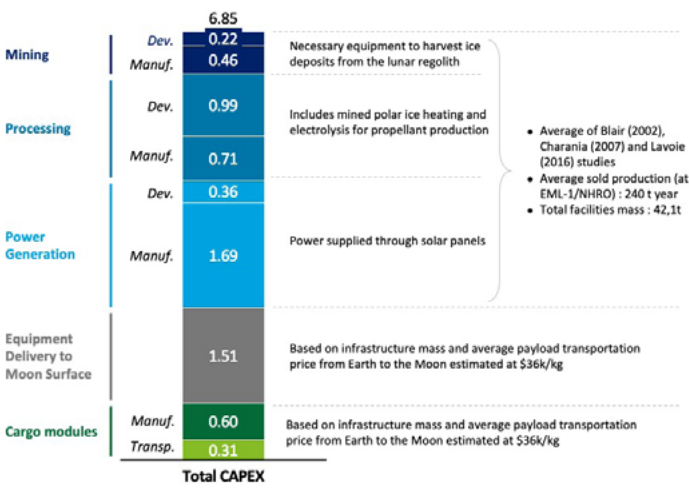
OPEX estimates

To remain competitive, O&M are performed a completely robotic way. Extrapolating from existing studies³, we assume that all the hardware has a 10-year lifespan, and that annual costs include \$28M of operating costs, and imately 1.1 tonnes of spare parts (proportionately with the ISS)¹¹.

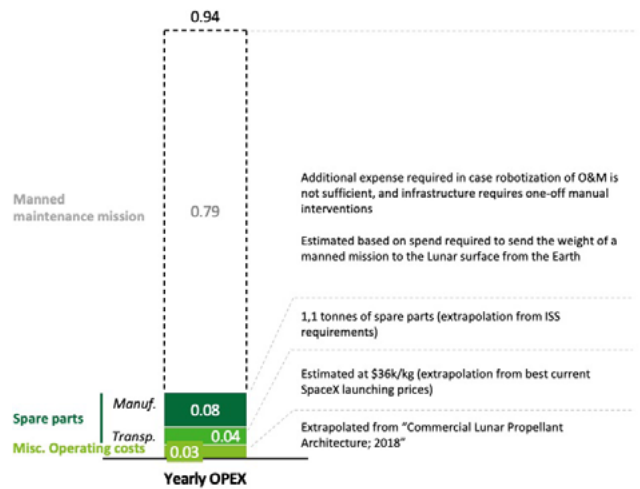
Most significant costs would occur if manned missions are mandatory to manage major damages or failures in the lunar hardware. We estimate the cost of a manned mission at a 'marginal' \$800M in a run-rate mode (i.e. excluding development costs).

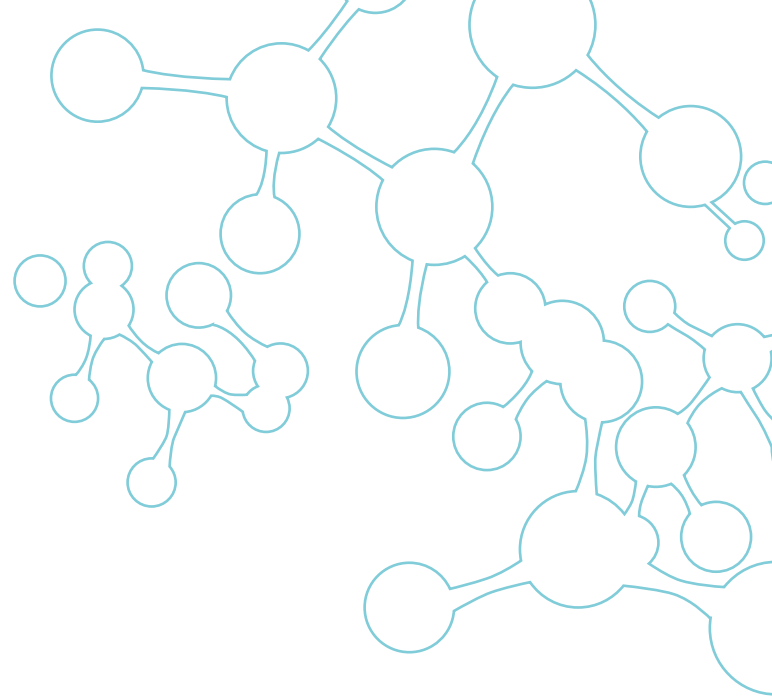
Figure 9
CAPEX and OPEX estimates for Moon-propellants production

Necessary CAPEX for lunar propellants production & logistics (240 t/y at EML-1; amortization over 10 years; \$B)



Necessary yearly OPEX for lunar propellants production & logistics (240 t/y at EML-1; \$B)



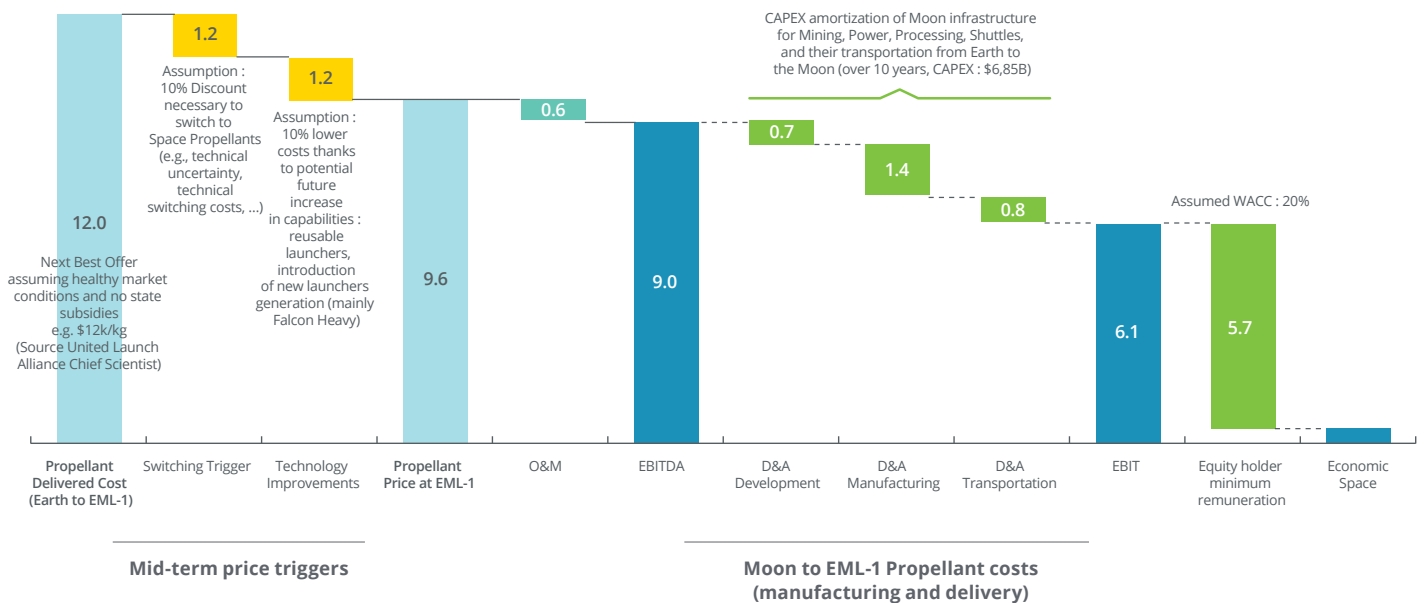


Closing the business case

To be viable, a lunar-produced propellants project should yield a 20%+ return on capital employed for its investors (i.e. the high-end cost-of-equity levels for cutting-edge innovation start-ups).

Initial estimates show that, with limited discounts on propellant prices at EML-1 vs. the current situation (e.g. 10% less as a switching trigger than Earth produced propellants and 10% less again as a cost reduction than launching costs from Earth), **there should be an economic space for such projects.**

Figure 10
Economic space for Moon-produced propellants at EML-1 / NHRO



Initial estimates show that, with limited discounts on propellants price at EML-1 vs. the current situation, there should be an economic space for such projects

We also looked at the IRR of a lunar propellants production project, assuming a development and construction phase of 5 years, followed by 10 years at a rate sales at EML1-NHRO of 240 tonnes per year, with sensitivity measurements on CAPEX levels, space launch costs evolution and need for manned missions to perform O&M tasks.

Figure 11
IRR of a lunar propellants production project

		CAPEX variations (%)		Space Launch Cost Evolution vs. 2021 (%)					
		0	-10	-20	-30	-40	-50		
Fully Robotic	50	17.6	15.6	13.5	11.1	8.4	5.2		
	25	20.8	18.8	16.5	14.0	11.3	8.0		
	0	24.8	22.7	20.3	17.8	14.9	11.5		
	-25	30.0	27.8	25.4	22.7	19.6	16.1		
	-50	37.6	35.2	32.6	29.7	26.5	22.7		
Intermediate (2 manned missions during lifetime)	50	15.7	13.9	11.8	9.5	6.9	3.9		
	25	18.7	16.8	14.7	12.4	9.7	6.6		
	0	22.4	20.5	18.3	15.9	13.1	10.0		
	-25	27.3	25.3	23.0	20.5	17.6	14.3		
	-50	34.3	32.1	29.7	27.0	24.0	20.5		
Manual (5 manned missions during lifetime)	50	12.9	11.2	9.3	7.2	4.8	2.0		
	25	15.6	13.9	12.0	9.8	7.4	4.5		
	0	19.0	17.2	15.2	13.0	10.5	7.6		
	-25	23.3	21.5	19.4	17.2	14.6	11.6		
	-50	29.3	27.4	25.3	23.0	20.3	17.1		

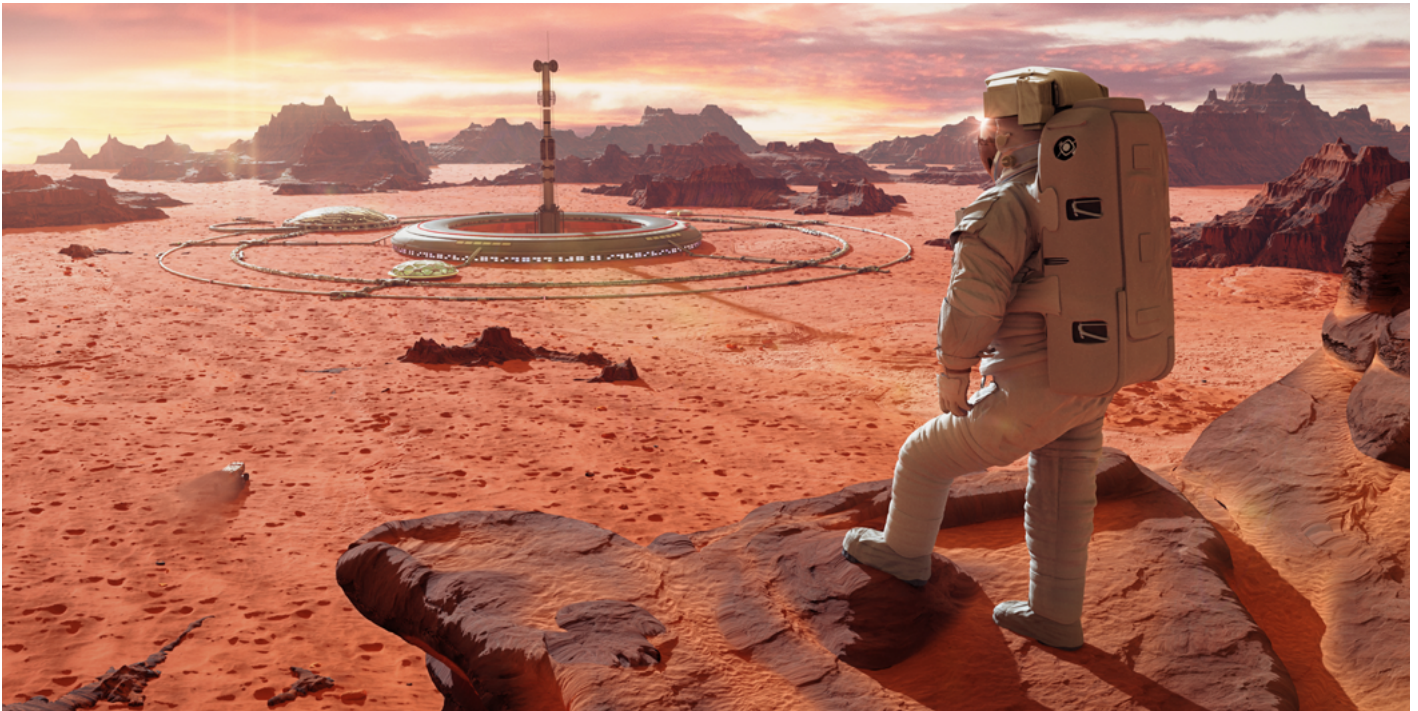
Several scenarios appear to be economically consistent:

- Acceptable (>20%) IRR levels can be achieved under the assumption of constrained CAPEX (max. 25% above central assumptions, and more likely with costs improvements) and space launch costs evolution limited to ~20%.
- In the case of stronger space launch cost reductions, CAPEX should be strongly optimized (down to 50% less than current central assumptions).

- Manned missions during the project lifespan have a rather limited impact (each mission accounting for less ~1.5 pt. of IRR).

At LEO, however, the economic equation looks drastically different, as limited prices of Earth launches (~\$4k/kg) and additional fuel costs to travel from EML-1/NHRO to LEO undermine any opportunity to create value.

Conclusion



The next decade is expected to witness further Lunar and Mars exploration. Indeed, NASA awarded SpaceX a \$2.9B contract to build a Moon lander by 2024, with Elon Musk recently also recently reiterating his ambition to land manned spacecraft on Mars before 2030.

The huge difference in the energy required to launch from Earth and from the Moon is pushing industrial players to consider refuelling points (e.g. EML-1, NRHO) in cis-lunar space with an energy source that will be mined and processed on the Moon.

To produce space propellants on the Moon, a whole value-chain must be created: mining, processing, logistics and transportation, robotic operations, communication systems and power plants, the required technologies having been currently developed or currently in development.

Several players are now addressing this nascent value chain in a rather scattered way, but an integrated approach today is fundamental as isolated initiatives are unlikely to deliver tangible medium-term results.

As of 2030, if the current ambition is realized, a ~240-tonne-per-year propellant market could emerge at the future Gateway station (NHRO), with a foreseen economic viability if space launch prices from Earth do not plummet significantly.

Mastery of CAPEX levels and also scale (to absorb major one-shot development costs, through the development of complementary uses such as rovers and human life support) will therefore be the key drivers of competitiveness at NHRO.

Closer refuelling locations (e.g. LEO), however, do not appear as credible markets, with launch costs from Earth already reaching levels below \$4k/kg.

However, technological advances performed for space propellants production should also have very positive consequences on the development of hydrogen powered 'terrestrial' technologies. Today, projects such as Hyperion, driven by Airbus, Safran and Ariane Group leverage space technologies to develop cryogenic systems for future hydrogen-powered aircrafts.

Mastery of CAPEX levels and also scale will be the key drivers for the competitiveness of space-produced propellants at NHRO. Closer refuelling locations (e.g. LEO) do not appear as credible markets, with launch costs from Earth already reaching levels below \$4k/kg.

Glossary

CAPEX: Capital expenditure

CH₄: Methane

EML-1: Earth-Moon Lagrangian Points #1

GEO: Geostationary Earth Orbit

LEO: Low Earth Orbit

LH₂: Liquid Hydrogen

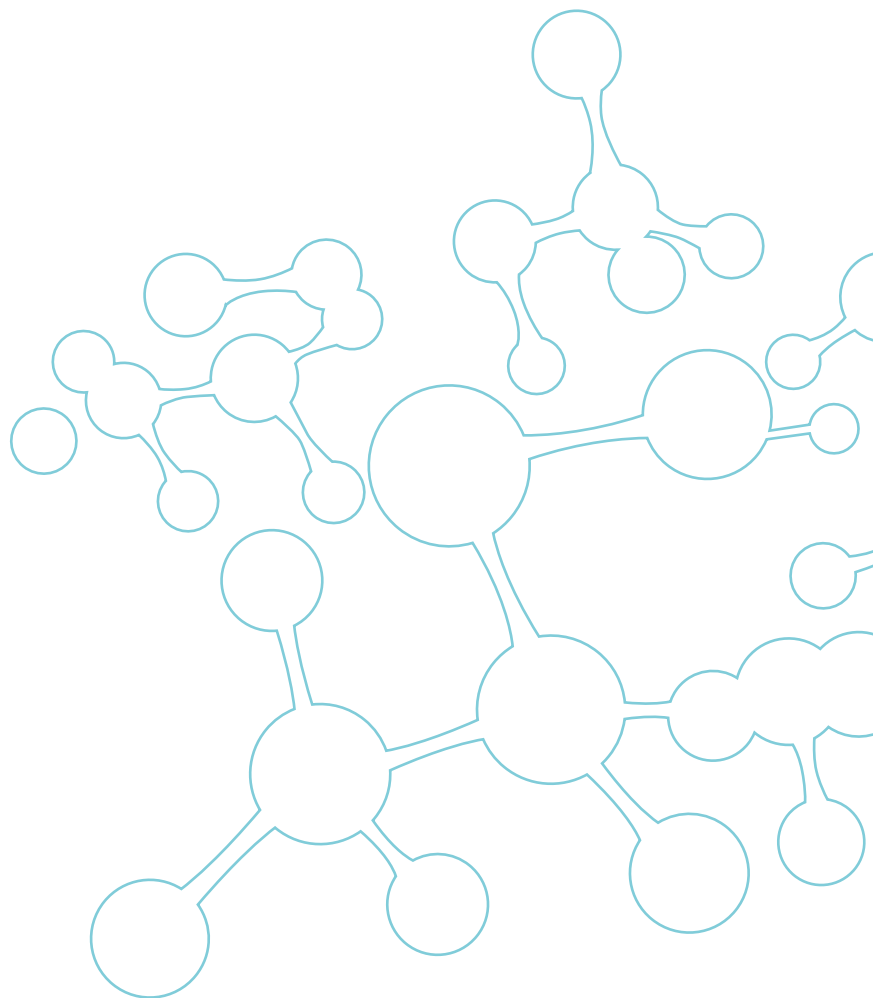
LOx: Liquid Oxygen

NRHO: Near Rectilinear Halo Orbit

O&M: Operations and Maintenance

OPEX: Operating expenditure

PSR: Permanently Shadowed Regions
(on the Moon)



Future of Mobility Contacts



Olivier Perrin
Partner
Energy, Resources & Industrials
Monitor Deloitte
France
operrin@deloitte.fr



Alexandre Kuzmanovic
Director
Energy, Resources & Industrials
Monitor Deloitte
France
akuzmanovic@deloitte.fr



Harsha Eashwer Singhraj
Manager
Energy, Resources & Industrials
Monitor Deloitte
France
heashwersinghraj@deloitte.fr



Aksel Deghmani
Manager
Energy, Resources & Industrials
Monitor Deloitte
France
adeghmani@deloitte.fr



Pascal Lim
Senior Consultant
Energy, Resources & Industrials
Monitor Deloitte
France
plim@deloitte.fr



Kamil Mokrane
Senior Consultant
Energy, Resources & Industrials
Monitor Deloitte
France
hmokrane@deloitte.fr

References

1. <https://www.nasa.gov/press-release/as-artemis-moves-forward-nasa-picks-spacex-to-land-next-americans-on-moon>
2. https://twitter.com/elonmusk/status/1374284021379731457?ref_src=twsrc%5Etfw
3. <https://www.sciencedirect.com/science/article/abs/pii/S2352309318300099>
4. <https://www.fbo.gov/utills/view?id=c520facdb1ffa46f8e5981eb14b33bd1>
5. <https://www.liebertpub.com/doi/full/10.1089/space.2017.0037>
6. <https://phys.org/news/2020-04-russia-space-chief-spars-elon.html>
7. <https://www.defense.gov/Newsroom/Contracts/Contract/Article/2305454/>
8. https://www.researchgate.net/publication/260387318_Space_Resource_Economic_Analysis_Toolkit_The_Case_for_Commercial_Lunar_Ice_Mining/download
9. <http://www.sei.aero/archive/IAC-07-A5.1.03.pdf>
10. <https://arc.aiaa.org/doi/pdf/10.2514/6.2016-5526>
11. <https://oig.nasa.gov/docs/IG-14-031.pdf>

Monitor **Deloitte.**

Deloitte refers to one or more of Deloitte Touche Tohmatsu Limited ('DTTL'), its global network of member firms, and their related entities. DTTL (also referred to as 'Deloitte Global') and each of its member firms are legally separate and independent entities. DTTL does not provide services to clients. Please see www.deloitte.com/about to learn more. In France, Deloitte SAS is the member firm of Deloitte Touche Tohmatsu Limited, and professional services are rendered by its subsidiaries and affiliates.

Deloitte is a leading global provider of audit & assurance, consulting, financial advisory, risk advisory and tax & legal services. With 312,000 professionals in 150 countries, Deloitte has gained the trust of its clients through its service quality for over 150 years, setting it apart from its competitors. Deloitte serves four out of five Fortune Global 500® companies.

Deloitte France brings together diverse expertise to meet the challenges of clients of all sizes from all industries. Backed by the skills of its 6,900 employees and partners and a multidisciplinary offering, Deloitte France is a leading player. Committed to making an impact that matters on our society, Deloitte has set up an ambitious sustainable development and civic commitment action plan.

Deloitte
6, place de la Pyramide – 92908 Paris-La Défense Cedex

© 2021 Deloitte Monitor. A Deloitte network entity

