The Case for Mining Platinum Group Metals on the Moon

EXTERRA SPACE

Contents

Introduction

Sustainable deep-space exploration needs an economic driver.

The proof of this statement is found in near-Earth orbits. Satellites for communication, navigation, and remote sensing, all provide positive returns on investment, ensuring the development of an economy based on these assets. However, no application that would enable the same kind of economic development in deep space has yet been deployed on the Moon or beyond. Based on decades of scientific studies, it is well-known that the Moon hosts a variety of minerals that have uses on Earth. If these minerals can be mined, refined, and brought back to Earth profitably, lunar exploration will become routine, which will, in turn, lead humanity deeper into the Solar System.

The advantages of lunar mining are not limited to a utopian vision of a techno-progressive future. Moving mining off Earth will benefit our planet's environment. The mining industry is estimated to contribute 5% of global greenhouse gas emissions[1], in addition to contributing to other environmental problems such as habitat destruction and groundwater depletion. Secondly, lunar mining will enable resource-poor countries with a space program to become independent of mineral imports. Lastly, just as the oil and mining industries on Earth require geologists, the lunar mining industry will require planetary scientists. Planetary science will, therefore, enjoy a golden age of funding and discoveries.

> 'Sustainable deep-space exploration needs an economic driver.'

While mining in space opens a Pandora's box of technological challenges, the biggest challenges are, in fact, economic in nature. Today, assuming a cost of $500,000 to bring back a kilogram of mass from the lunar surface, any resource we return will need to be valued at more than $500,000/kg for profitability. Once the total costs of a mining mission are taken into account it becomes clear that the resource must also have a large addressable market and potential for future growth.

Exterra Space is pioneering lunar mining of platinum group metals (PGMs) and their return. In this white paper, we discuss why we picked the Moon, as opposed to other Solar System bodies, why we chose to mine PGMs, and the economic factors that our endeavour will crucially depend upon.

Target Selection

Asteroids are perhaps the first celestial bodies that come to mind when thinking of space mining. Depending on their classification, they contain various kinds of resources. For example, M-type, or metallic asteroids, are known to contain significant amounts of PGMs[2]. C-type, or carbonaceous, asteroids contain hydrated minerals and water ice[3]. Because near-Earth asteroids (NEAs) contain both M-type and C-type bodies and many (though not most) require less energy than the Moon to return material to Earth, they have become the main focus of space-mining discussions.

The Moon, however, offers several key advantages over NEAs as a source of asteroid-derived resources. Over the 4.5 billion years of its existence, the Moon has been bombarded by asteroids, as evidenced by the millions of craters on its surface. In many of these impacts, the remnants of the impactor survive on or near the surface, in the form of meteorites or melt sheets. It is estimated that there may be up to 6500 craters that contain PGM-bearing asteroidal remnants[4], with a cumulative value of several trillion dollars.

Furthermore, we know for certain that the Moon contains PGM-bearing asteroidal material. This confidence comes from direct evidence: Apollo samples include meteoritic fragments enriched in PGMs. Additionally, we know that the same classes of asteroid that have struck Earth, many of them PGM-rich, have also impacted the Moon. By contrast, NEAs are difficult to detect and characterise. Many are observed only briefly, their sizes, shapes, and compositions are poorly constrained, and remote measurements provide only broad taxonomic classifications. As a result, an asteroid that appears promising from Earth-based observations may ultimately prove to be low-value silicate rubble or carbonaceous material, which makes target selection for asteroid-mining missions highly uncertain.

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Statistically speaking, there are only about 400 NEAs that are ore-bearing (i.e. containing commercially profitable material), out of which only about 10 are accessible today[5]. With the advent of SpaceX’s Starship, about 100 ore-bearing NEAs would become accessible. It is estimated that prospecting NEAs for PGMs will require as many as 40 space probes[6], whereas a single lunar orbiter and a handful of lunar rovers will be able to prospect and explore the Moon.

To make matters worse for asteroid mining, despite their name, near-Earth asteroids are not necessarily ‘near Earth’. They are merely objects whose orbits come within 0.3 astronomical units of the Earth’s orbit, whereas the Moon is about a hundred times closer than that. Large Earth-asteroid distances have several consequences, the most important of which is that the communication delay between Earth and the mining mission would be on the order of minutes.

	MOON	ASTEROIDS
ACCESSIBILITY AND PHYSICAL CHARACTERISTICS		
Distance	Travel time: ~Days Communication delay: 3 s Remote ops possible	Travel time: ~Months Communication delay: ~Minutes Remote ops impossible
Delta-v constraints	100% of surface accessible	2.5% accessible now[5]; 68% with Starship
Detection and characterisation	1 orbiter, < 5 in-situ assay rovers	High-resolution telescope, > 40 in-situ assay probes[6]
Rotational stability	Stable	Tumbles, making operations fuel-inefficient
Surface stability	Stable	Highly unstable rubble pile
Surface gravity for mining and processing	0.17 g No fuel required to stay on the surface	~0 g Fuel required for station-keeping (landing impossible)
Surface gravity for return	More fuel for escape	Less fuel for escape
RESOURCES		
Resources	Titanium, uranium, thorium, helium-3, rare Earth elements, hydrated minerals, water ice, all asteroidal resources, including PGMs	PGMs, hydrated minerals, water ice
PGM ore-bearing targets	Up to 6500 craters, other sites[4]	~10 accessible now[5]; ~100 with Starship
Concentration of asteroidal resources	Less than that of asteroids, on average, due to mixing with regolith	-
EXPLORATION INTEREST		
High-productivity human presence	In the next 5-6 years	In 20+ years
Worldwide interest	30 missions from 11 countries in the next 5 years[7]	5 missions from 5 countries in the next 5 years[8]
APPLICATIONS		
Enabled Use Cases	Resources for Earth, lunar scientific and commercial exploration, lunar infrastructure, lunar fuel production, staging area for Solar System exploration, astrophysics from the Moon, lunar tourism	Resources for Earth, fuel for Solar System exploration and cis-lunar satellites (the latter will require the asteroid to be moved to an orbit around the Earth)

Table 1: A comparison of mining on the Moon vs. mining on asteroids. It is clear from this table that the Moon is the optimal choice for humanity's first forays into space resource exploitation.

This rules out teleoperation, and will necessitate fully autonomous mining and refining, compounding the already formidable challenge of performing these activities in near-zero gravity and without liquid water. In addition to the lack of gravity, asteroid surfaces are also unstable, so mining spacecraft would not be able to land on the body, and thus, would have to expend fuel for station-keeping.

To summarise, due to its proximity and the relative ease of prospecting and exploration, the Moon presents an unrivalled opportunity to mine the resources it harbours. Moreover, the fact that over 30 missions from 11 countries are slated to visit the Moon just in the next 5 years[7] is a testament to the increasing commercial and strategic importance of our closest celestial neighbour. Unlike asteroids, the Moon also contains elements such as titanium, uranium, helium-3, etc., which will play a role in its future colonisation.

Table 1 shows the relative advantages and disadvantages of mining the Moon versus mining asteroids.

Resource Selection

The Moon contains a variety of resources. However, when it comes to extraction and return, not all are created equal. Profitable resource extraction on the Moon requires a material with high value and a large market. Value per unit mass matters because the expense of returning material from the Moon is critically dependent on launch costs, i.e., economic viability is limited to resources whose value per kilogram exceeds the transportation cost per kilogram. Market size is important because lunar mining is an expensive proposition. Its total costs would be on the order of billions of dollars, so unless the total addressable market of the resource being mined is greater than the cost, profitability would not be achievable.

Very few lunar resources check both boxes. For example, titanium has a $30B market, but costs only $8/kg for titanium alloy ingots, its most expensive form. We are unlikely to see lunar return costs fall

RESOURCE	PRICE/KG ($)	MARKET SIZE ($M)	CAGR
Platinum group metals	60,000*	40,000	4%
Titanium	8	30,000	6%
Helium-3	20,000,000	200	10%**
Rare earth elements	2,000***	6,000	10%
Uranium	150	10,000	5%
Thorium	50	500	6%

* Demand-weighted average
** The outlook range is high, so we have picked an average value.
*** Average

Table 2: Prices and market sizes of a few lunar resources.

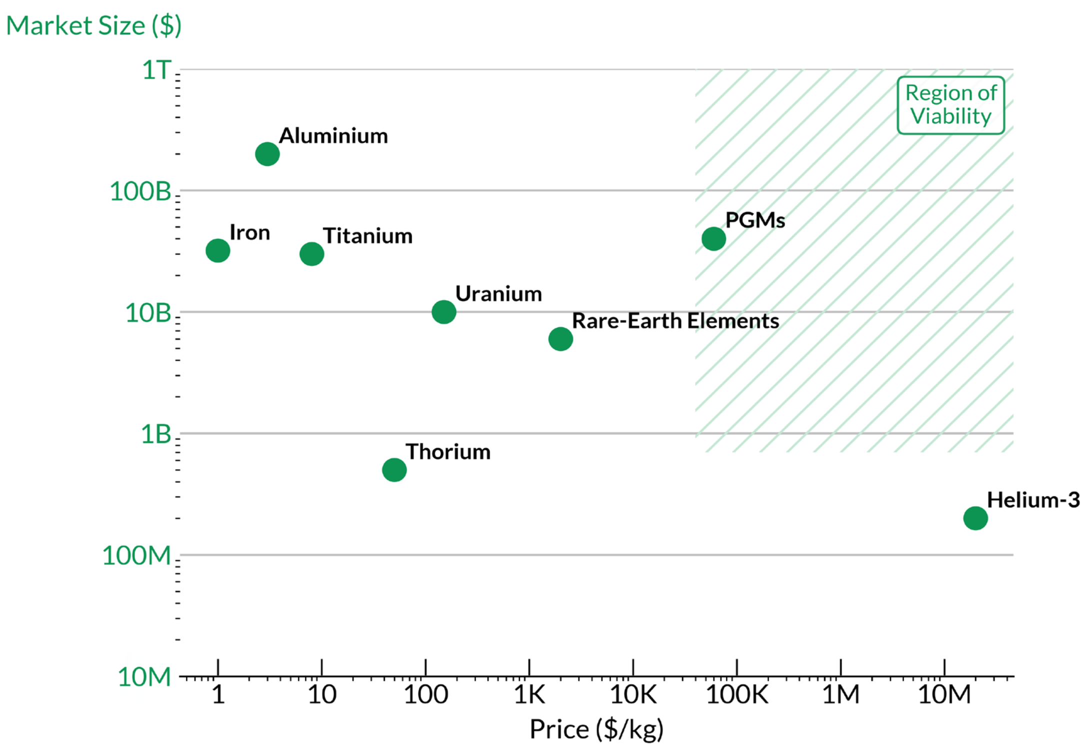

Figure 1: The lunar resource profitability landscape. The shaded region denotes economic viability under anticipated return costs, assuming present-day prices and market sizes. PGMs fall within this region, while helium-3 would require significant market growth to become viable.

below $8/kg this century, so, assuming the price of titanium does not increase dramatically, it is safe to conclude that we will not be mining it from the Moon and returning it to Earth in the foreseeable future. At the other end of the scale, helium-3 has a reported price of $20M/kg, but has a market of less than $200M. Lunar mining program costs will likely be in the billions of dollars, so any resource whose market — even at 100% market share — is smaller than program costs will be unprofitable, unless one appeals to the future growth of the market. PGMs are the *only* resource that is valuable enough and has a market that is large enough to make space mining economically feasible today.

Table 2 summarises the prices and market sizes of a few lunar resources. Figure 1 illustrates the lunar resource profitability landscape, showing current price per kilogram and market size for selected resources. The shaded region denotes the combinations of price and market size that would be economically viable under anticipated lunar return costs at the time of material return.

Platinum Group Metals

PGMs are remarkable metals whose catalytic properties make them suitable for a variety of applications. In fact, 'they are the only viable option in a number of technologies, because of their performance and durability in extreme environments'[9]. Today, by far, the largest application of PGMs — about 65% of total PGM use — is in autocatalysts. The remaining uses include clean energy, chemical manufacturing, jewellery, and other industrial applications. Within clean energy, PGMs are used in hydrogen fuel cells, the market of which is $6B, and growing at 16% compound annual growth rate (CAGR). If the hydrogen economy comes to fruition and hydrogen becomes the dominant fuel of the future, PGMs will play a central role in it.

PGMs cost $60M/tonne on average, and its total market is $40B, growing at 4% CAGR. The largest producers are South Africa (60% by weight) and Russia (23%). The former has significant systemic issues, including labour-related concerns, and the latter is geopolitically risky. Therefore, supply risk is generally considered to be high for PGMs. Currently, PGMs are in a deficit due to constrained supply, exacerbated by a 'sustained lack of investment in mine production'[10]. PGM prices have shown a sustained long-term upward trend — for example, the price of palladium is now 15 times what it was in 1990 — and this trend is expected to continue. Additionally, PGMs exhibit extreme short-term volatility. For instance, the price of Rhodium increased from $25M/tonne in 2019 to almost $1B/tonne in 2021 before decreasing to pre-pandemic levels. Price swings of this nature impose significant pressure on consumers, who have to deploy drastic risk-management measures, e.g., purchasing PGMs in excess to mitigate future risk. To make matters worse, PGM mining is capital-intensive. New mines cost significantly more than a billion dollars to commission[11], a cost that is comparable to that of space missions[12,13].

Their placement in the price-market size space, together with their critical nature, supply and pricing risks, and production costs, make PGMs the ideal resource for lunar mining. Unlike production on Earth, mining on the Moon would alleviate geopolitical risks, rely on large-scale automation that precludes dangerous manual work, decreases costs in the long term, and provides an abundant and reliable source of PGMs, significantly reducing price volatility that hampers business.

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Economics

In this section, we dive deeper into the question of economic feasibility. Several factors affect profitability when it comes to space resource mining: program research and development (R&D) budget, launch cost per unit mass, mass of the mining equipment, resource price and its expected change, resource market size and its CAGR, the amount of material brought back to Earth, and other operating costs. In the following analysis, we roll the cost of operations, excluding launch costs, into the R&D budget for the sake of simplicity, since non-launch operating expenses are expected to be only a small fraction of the total cost. The aforementioned variables combine non-intuitively, so we have built a simulator to evaluate various scenarios (see the screenshot in Figure 2).

In the default scenario of our simulator, with $1B in R&D spending, 50 tonnes of mining equipment, a factor of 100 decrease in launch costs over the next 10 years[14], a 5% annual increase in PGM prices, and 15 tonnes of refined product returned annually, a fully-funded lunar PGM mining program that begins R&D in 2026 would be profitable by 2036. The assumed 5% annual increase in PGM prices is intentionally conservative compared to recent market trends. PGMs are in a deficit market, which has led to their prices skyrocketing. Platinum prices rose almost 60% between May and December 2025, and palladium prices increased by 50%. If this trend continues, profitability would be achieved sooner. On the other hand, cost overruns could delay profitability. Nevertheless, our simulations demonstrate the suitability of PGMs for space mining. Everything else being equal, for helium-3 mining to be profitable within a reasonable time frame, a large increase in market size is necessary. Assuming no radical progress in quantum computing that could result in a larger market, a helium-3 mining venture would remain unprofitable for 20 years. Ultimately, PGMs are the *only* resource that is valuable enough and has a market that is large enough to make space mining economically feasible *today*.

The largest contributor to overall cost is the mass of the extraction equipment, given today's launch costs, which highlights the importance of designing lightweight, modular systems. Our modelling shows that keeping equipment mass near 50 tonnes enables profitability as early as 2036, while even a ten-fold increase to

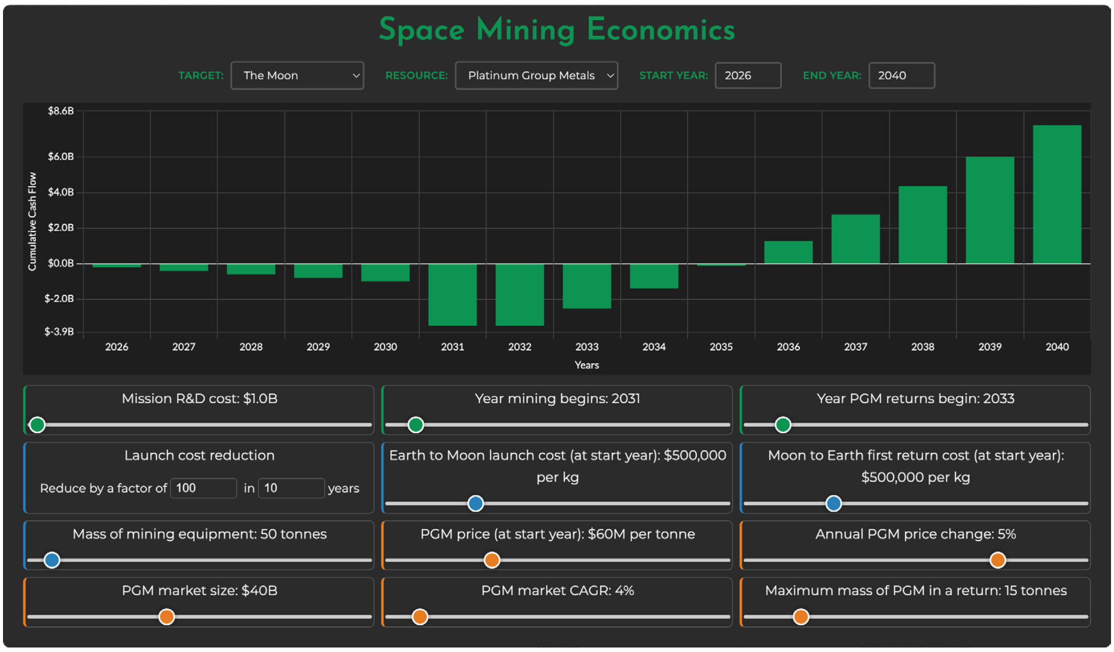

Figure 2: Our space mining economics simulator, publicly available at https://exterra.space/economics.

500 tonnes only shifts this to 2044. Launch cost per unit mass is the next biggest factor. Launch costs are already in free fall, driven by the rapid progress of reusable heavy-lift systems such as SpaceX's Starship and Blue Origin's New Glenn[15]. Starship, for instance, is expected to decrease the cost per kilogram to low-Earth orbit by a factor of 100 in the short term. The cost per kilogram to the lunar surface is expected to experience a factor of 10 decrease in the short term, and more in the longer term[16]. A hundred-fold decrease over the coming decade would accelerate profitability significantly, while even a ten-fold drop delays the break-even year only to 2041. Mission R&D is the third-largest factor. Even increasing development costs from the default scenario of $1B to $10B shifts the break-even point only slightly, from the baseline of 2036 to 2041. A drop in PGM prices has an even smaller effect. If PGM prices remain at today's levels, rather than following the expected upward trend, profitability is postponed just one year, moving from 2036 to 2037. Together, these results show that Exterra's model remains robust across a wide range of assumptions, with further gains expected as extraction technologies mature and launch costs continue to fall.

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Although launch cost strongly influences economic viability, it is an external factor beyond our control, as Exterra is not a launch provider. Within this context, the two most important variables we can control are mining equipment mass and the mission R&D cost. Optimising both is crucial for any viable space-resource venture. Reducing equipment mass appears at first glance to be a daunting engineering challenge, since conventional terrestrial mining systems are enormous. For example, the Komatsu 980E-SSE haul truck has an operating mass of 635 tonnes[17], and Earth-based mining and refining plants are effectively factory-scale. Recovering asteroid-derived resources on the Moon, however, is fundamentally different from terrestrial mining; it is not a matter of deep excavation, but of surface extraction. When asteroids strike the Moon, they spread fragments and molten material from both the impactor and the lunar surface, producing ejecta blankets that hold this debris mostly within the shallow regolith. Because the Moon lacks an atmosphere or active geology to erode or bury this material, it remains accessible for billions of years. While subsequent impacts can mix and scatter the debris, this so-called 'lunar gardening' is not expected to bury meteoritic material to significant depths. Apollo samples confirm that meteoritic material remains mixed into shallow surface deposits[18]. This scientific context points to the possibility of deploying compact, modular systems that are only a fraction of the mass of terrestrial equipment, making lunar resource extraction economically feasible.

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Policy, Legal, and Regulatory Considerations

The 1967 *Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies*, commonly known as the *Outer Space Treaty*, is the cornerstone of international space law[19]. It establishes that outer space is a global commons that cannot be claimed as sovereign territory by any nation, and that its exploration and use must be carried out for peaceful purposes and for the benefit of all mankind. Importantly, while the treaty restricts territorial claims, it does not prohibit the extraction and ownership of space resources once they have been recovered.

Building on this framework, national and international initiatives have begun to clarify how commercial space resource activities can proceed. The *Luxembourg Space Resources Law* of 2017[20] formally recognises the right of companies to own and trade materials they extract in space, providing one of the first clear legal regimes to support commercial operations. The *Artemis Accords*[21] extend this approach at the international level, affirming that resource utilisation is consistent with the Outer Space Treaty and encouraging cooperation among partner nations. Taken together, these measures confirm that while celestial bodies themselves cannot be appropriated, there is a legal pathway for companies to extract and own the resources they recover.

Exterra Space is committed to adhering to these legal frameworks while promoting sustainable space resource extraction. As a pioneer of this new industry, Exterra will collaborate with regulatory bodies in formulating practical and balanced space laws, ensuring lunar mining aligns with global interests and responsible industry standards.

Conclusion

PGMs occupy a uniquely important role in modern industry, yet their terrestrial production faces significant challenges. Combined with the sharply decreasing cost of access to space, this makes them the ideal candidate for space-mining ventures. The Moon, our nearest celestial neighbour, is an abundant and accessible source of these critical metals, further strengthening the case for lunar PGM extraction. Exterra's mission is therefore not only economically viable and represents a major step towards sustainable, commercially-driven activity in deep space, but also will change the very nature of space exploration, and will extend humanity's reach into the cosmos.

References

1. https://www.mckinsey.com/capabilities/sustainability/our-insights/climate-risk-and-decarbonization-what-every-mining-ceo-needs-to-know
2. Kargel, 'Metalliferous asteroids as potential sources of precious metals', JGR Planets, 1994
3. Rivkin, 'The fraction of hydrated C-complex asteroids in the asteroid belt from SDSS data', *Icarus*, 2012
4. Chennamangalam, Brook, Elvis, Peterson, 'On ore-bearing asteroid remnants in lunar craters', *Planetary and Space Science*, 2025
5. Elvis, 'How many ore-bearing asteroids?', *Planetary and Space Science*, 2014
6. Elvis and Esty, 'How many assay probes to find one ore-bearing asteroid?', *Acta Astronautica*, 2014
7. https://en.wikipedia.org/wiki/List_of_missions_to_the_Moon#Future_missions
8. https://en.wikipedia.org/wiki/List_of_missions_to_minor_planets#Future_missions
9. 'The PGM Opportunity', Johnson Matthey, 2024
10. 'Platinum Group Metals Focus 2025', Metals Focus
11. https://energycapitalpower.com/south-africa-platinum-group-metals-to-raise-1-8b-for-waterberg-project
12. https://www.sciencefocus.com/space/top-10-what-are-the-top-10-most-expensive-space-missions
13. https://astronautical.org/sites/default/files/vonbraun/2009/Von_Braun_Symposium_2009-10-20_4a_Tooley.pdf
14. https://x.com/elonmusk/status/1313858597428826120
15. https://www.citigroup.com/global/insights/space_20220509
16. https://www.spacex.com/vehicles/starship
17. https://www.komatsu.com/en-us/products/equipment/trucks/electric-drive-mining-trucks/980e-5se
18. 'Lunar Sourcebook: A User's Guide to the Moon', edited by Heiken, Vaniman, and French, Cambridge University Press, 1991
19. https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/outerspacetreaty.html
20. https://space-agency.public.lu/en/agency/legal-framework/law_space_resources_english_translation.html
21. https://www.nasa.gov/artemis-accords/

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