

# Mineral Exploration Beyond Our Planet Earth and Advances in Mining

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## ABSTRACT

Mineral exploration beyond Earth has emerged as a critical frontier for sustainable resource acquisition and space exploration advancement. As terrestrial deposits of essential minerals face depletion and environmental concerns mount, mineral exploration from asteroids, the Moon, Mars etc offers alternative sources. Current research indicates that asteroids contain platinum-group metals at concentrations 10,000-30,000 times higher than Earth's crust, with M-type asteroids particularly rich in iron, nickel, cobalt, and precious metals. Just asteroid 16 Psyche alone is estimated to contain metallic resources worth approximately \$10,000 quadrillion, demonstrating the extraordinary economic potential of space exploration and mining. The article examines technological advances enabling space mining, environmental and economic considerations, current challenges and future outlook among others.

**Keywords:** Advances in Mining; Asteroids; Environmental Considerations; Mineral Exploration; Space Mining.

## INTRODUCTION

Mineral exploration off-Earth is driven by growing concern over terrestrial resource depletion and the environmental impacts of mining. Asteroids, the Moon, and Mars hold vast untapped resources that could augment Earth's supplies and support space exploration. For example, many asteroids contain iron, nickel, cobalt and platinum-group metals (PGMs) at much higher grades than Earth ores. Meteorite studies find PGMs in some asteroid fragments at tens to hundreds of parts per million (ppm), roughly 10–20× higher than typical Earth crust values. In particular, M-type asteroids (metallic, likely remnants of planetary cores) are extremely metal-rich. NASA notes that the asteroid 16 Psyche (an M-type in the main belt) could consist largely of iron and nickel, and estimates its metals' value at on the order of \$10,000 quadrillion [1], [2]. These “space mines” also contain valuable water and volatiles (especially carbonaceous C-type asteroids) that can be split into hydrogen and oxygen for rocket fuel. Mineral exploration has long been a cornerstone of human progress, underpinning advancements in technology, infrastructure, and energy systems. Traditionally, mineral exploration refers to the process of locating, identifying, and assessing mineral deposits on Earth. This process involves extensive geological surveys, sampling, drilling, and sophisticated analytical techniques to determine the size, quality, and economic potential of mineral resources [3], [4]. The extraction of these resources has fuelled industrial development, urbanization, and modern technology for centuries. In recent years, however, the global demand for minerals has surged dramatically. This growth is largely driven by the rapid expansion of the technology sector, renewable energy systems, and electric mobility. Critical minerals such as lithium, cobalt, rare earth elements, and nickel are essential for batteries, wind turbines, solar panels, and advanced electronics [5], [6]. Meeting the needs of a growing population and transitioning to low-carbon economies are placing unprecedented pressure on terrestrial mineral reserves. Many of these resources are geographically concentrated, environmentally costly to extract, and vulnerable to geopolitical risks, intensifying the urgency for alternative solutions. Space-based mineral exploration is emerging as a compelling response to these challenges. The concept involves identifying and extracting valuable resources from celestial bodies such as the Moon, Mars, and asteroids. Unlike Earth, many of these bodies possess abundant, untapped reserves of precious metals, industrial minerals, and even water ice that could support both space exploration and terrestrial industries [7],

[8]. By harnessing extra-terrestrial resources, humanity could reduce the strain on Earth’s ecosystems, secure critical supply chains, and enable sustained human presence in space. As technological advancements in robotics, remote sensing, and propulsion systems continue, mineral exploration beyond our planet is shifting from a distant vision to a near-term reality. Understanding the evolution of traditional mineral exploration, the rising demand for critical minerals, and the necessity of expanding beyond Earth sets the foundation for exploring this transformative frontier.

**A. Method**

The study employs a comprehensive review of mineral exploration off-earth as a methodology detailing the rationale for extra-terrestrial mineral exploration, potential sources of extra-terrestrial minerals, advances in space mining technology, key players and on-going projects, economic and strategic considerations, challenges in extra-terrestrial mining and future outlook, among others.

**B. The Rationale for Extraterrestrial Mineral Exploration**

Although new discoveries, technological improvements, substitution, and recycling have historically expanded accessible reserves, terrestrial minerals remain finite and increasingly constrained by land-use competition, environmental limits, long lead times, and uneven geographic distribution. The National Academies emphasize that mining inherently depletes finite stocks and that sustaining supply depends on continual reserve additions, improved extraction/processing, and recycling—factors that face growing scientific, economic, and policy challenges [9]. At the same time, clean-energy transitions are shifting demand toward “energy transition minerals” (e.g., lithium, nickel, cobalt, graphite, rare earth elements, copper). The IEA finds that clean-energy technologies require substantially more mineral inputs than fossil-based systems and that demand for these minerals is rising rapidly; supply today is concentrated and investment plans risk falling short, creating vulnerabilities and potential cost inflation for batteries, grids, and renewables as provided **Fig.1**. [5].

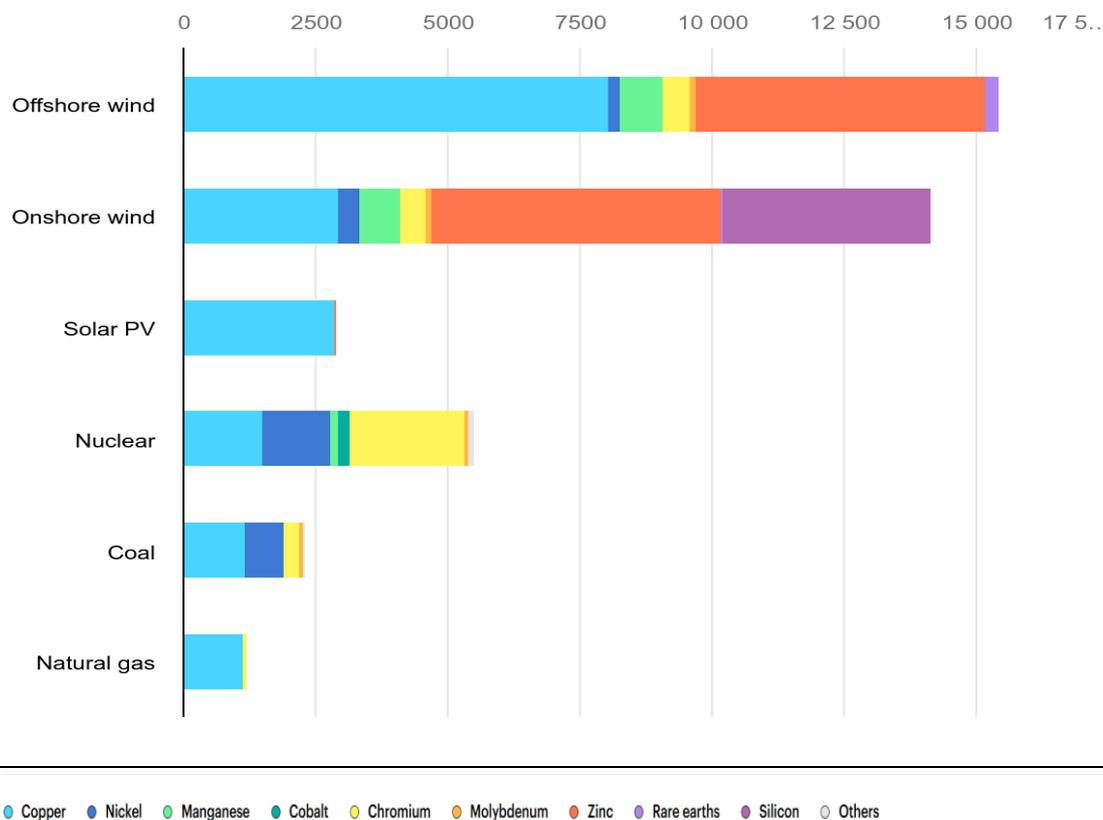


Fig. 1. Minerals used in clean energy technologies compared to other power generation sources [5].

From an energy-systems perspective, electrification and decarbonization are powerful economic drivers. The IEA’s special report and subsequent outlooks identify surging requirements for batteries, wind turbines, solar PV, and electricity networks, with raw materials now a larger share of technology costs (e.g., lithium and nickel

price spikes can materially raise battery pack costs). This, coupled with highly concentrated mining and refining (top producers dominate output; processing is especially concentrated), strengthens the case for diversifying supply, including considering non-terrestrial sources—while also accelerating recycling and material efficiency [10]. More recently, the IEA’s global outlooks as illustrated in **Fig. 2** underline the same trend: demand for copper, lithium, nickel, cobalt, graphite, and rare earths continues to expand under decarbonization scenarios, prompting calls for diversified supply chains and risk management across mining, refining, and manufacturing.

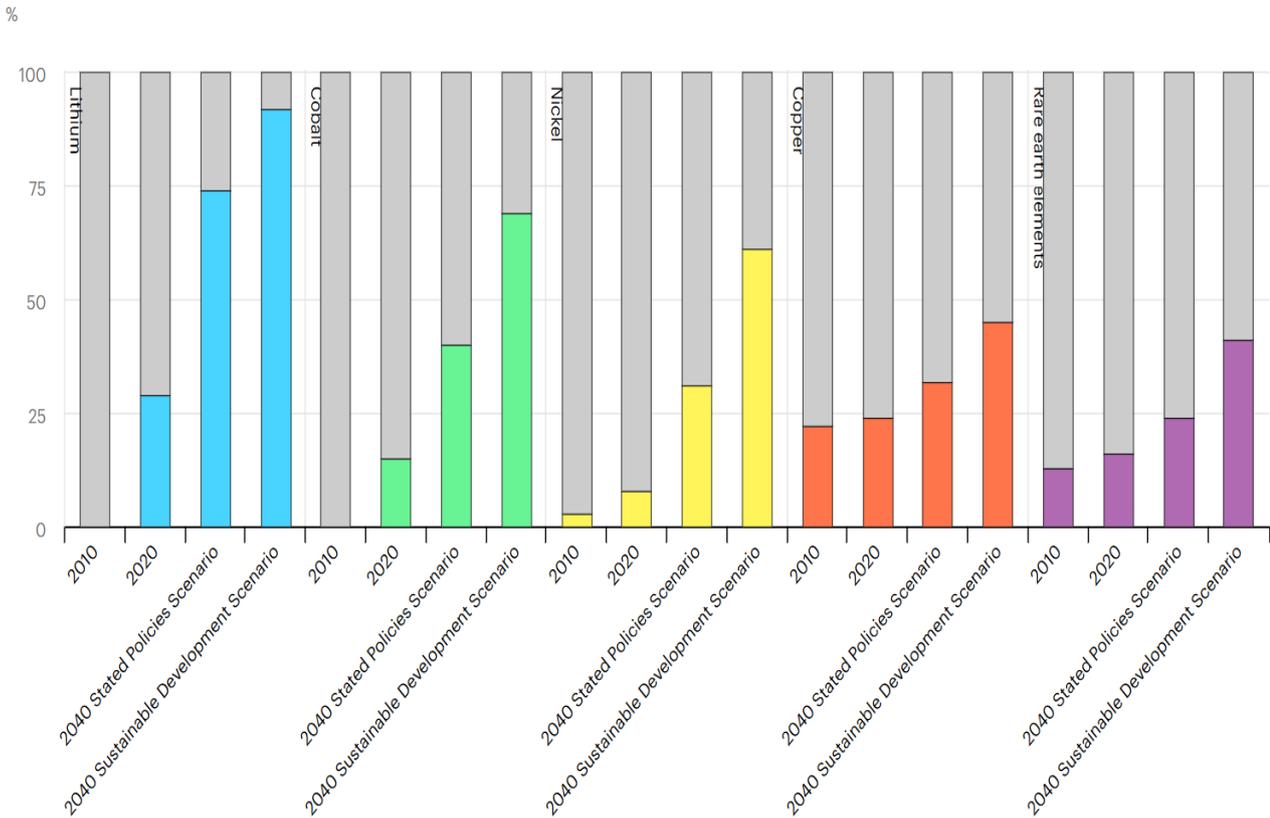


Fig. 2. Share of clean energy technologies in total demand for selected minerals by scenario, 2010-2040 [10]

Complementing energy drivers, policy and industry analyses (IEA/OECD) frame critical minerals as a new frontier for energy security, where supply reliability, market transparency, sustainability standards, and strategic stockpiles will shape technology deployment costs and timelines [11]. Beyond economics, exploration is propelled by human curiosity and the pursuit of knowledge. Space exploration advances our understanding of the solar system and enables us to harness the unique attributes of the space environment for human benefit, foundational motivations that now intersect with practical interest in resources on the Moon, asteroids, and Mars. These scientific and utilitarian goals have long been recognized as core elements of space exploration’s purpose.

### C. Potential Sources of Extra-Terrestrial Minerals

The pursuit of mineral exploration beyond Earth involves identifying celestial bodies rich in resources that can support human activities both in space and on Earth. Among the most promising targets are the Moon, asteroids, Mars, and the icy moons of the outer planets. Each of these bodies presents unique opportunities and challenges for mineral extraction.

**1) The Moon:** The Moon has long been recognized as a prime candidate for extraterrestrial mining. One of its most valuable resources is Helium-3, a rare isotope virtually absent on Earth but potentially abundant on the lunar surface due to billions of years of solar wind exposure. Helium-3 could one day serve as a fuel for nuclear fusion, offering a cleaner and more efficient energy source [12]. In addition to Helium-3, the Moon’s regolith contains significant concentrations of rare earth elements (REEs), titanium, and aluminum, all critical for modern electronics, renewable energy technologies, and aerospace applications. Lunar polar regions also harbor large

deposits of water ice, which could be processed into drinking water, breathable oxygen, and rocket fuel, making the Moon a vital refueling station for deeper space exploration. The combination of these resources has fueled a growing “lunar gold rush,” with major powers and private companies investing heavily in robotic and crewed missions aimed at developing sustainable mining operations.

**2) Asteroids:** They are often referred to as “floating treasure troves” because of their dense concentrations of metals and volatiles. Many near Earth asteroids (NEAs) are rich in platinum-group metals (PGMs), nickel, iron, and cobalt, making them highly attractive for mining ventures [13]. A single metallic asteroid could contain more metals than have ever been mined in human history, offering unprecedented opportunities for resource diversification.

In addition to metals, certain carbonaceous asteroids contain water-bearing minerals, which could be converted into liquid oxygen and hydrogen propellant for spacecraft. The ability to refuel in space using asteroid-derived water would significantly reduce the cost of interplanetary missions and enable a permanent human presence beyond Earth.

**3) Mars:** Mars presents another rich source of extraterrestrial minerals. Remote sensing and rover missions have identified large deposits of iron oxides, responsible for the planet’s characteristic red color. Sulfur compounds and silicate minerals are also abundant, and certain regions may contain deposits of rare elements such as lithium and thorium [14]. The Martian polar ice caps hold vast reserves of water ice, essential for sustaining life and producing fuel. Developing in-situ resource utilization (ISRU) technologies on Mars would reduce the need for costly resupply missions from Earth and form the basis for permanent settlements [12].

**4) Other Celestial Bodies:** Beyond the Moon, asteroids, and Mars, the icy moons of Jupiter and Saturn, such as Europa, Ganymede, Enceladus, and Titan, represent promising long-term targets for mineral exploration. These bodies are believed to harbor subsurface oceans, water ice, and potentially organic compounds that could support future space economies and scientific research [15]. While mining these distant moons poses significant technological and logistical challenges, their resource potential could be transformative. For instance, water ice extracted from these bodies could be converted into propellant, creating refueling hubs that extend human reach deeper into the solar system.

**5) Comparative Resource Abundance:** Comparative assessments indicate that several extraterrestrial bodies contain resource concentrations that in many cases exceed those of terrestrial deposits. Metallic and stony-iron asteroids, for example, have been shown to contain platinum-group metals (PGMs) at tens to hundreds of parts per million (ppm), potentially far above the 3–10 ppm typically observed in Earth’s highest-grade PGM ores [13]. Similarly, carbonaceous asteroids may contain several weight per cent water ice, whereas water on Earth, although abundant, is rarely present as an ore-grade deposit in a mining context. Lunar regolith has also been confirmed to contain trace helium-3 accumulated through solar wind implantation over geologic timescales, offering a possible long-term fusion fuel if extraction and energy technologies become viable [12]. Table 1 summarizes several key resource types, comparing indicative spatial grades or abundances with typical terrestrial values.

**TABLE 1. Indicative Resource Abundances In Selected Extraterrestrial Targets Compared to Terrestrial Values**

Resource	Extraterrestrial grade/abundance	Terrestrial grade/abundance
<b>Platinum-group metals (PGMs)</b>	Up to ~100 ppm in some metallic asteroids (iron meteorites range roughly ~6–230 ppm total PGMs, with a median ~40–50 ppm).	Typically, ~5–10 ppm in high-grade Earth PGM ores, with median values often around ~3–7 ppm in producing mines.
<b>Water ice</b>	Approximately ~5–10 wt% in some hydrated carbonaceous (C-type) asteroids; ~1–5 wt% in mixed ice–regolith deposits at lunar poles.	Abundant within Earth’s hydrosphere, but generally not present as a concentrated “ore” body in the mining sense.
<b>Helium-3 (He<sup>3</sup>)</b>	Trace concentrations in lunar regolith,	Essentially absent as a naturally exploitable resource

	<p>on the order of ~10–20 ppb by mass in Apollo samples, accumulated via solar wind implantation. Total lunar He-3 inventory has been estimated at around <math>\sim 1 \times 10^6</math> tonnes in the upper few metres of soil.</p>	<p>on Earth (only very small quantities are available). Large-scale use would require breeding in reactors or sourcing from off-Earth environments.</p>
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Although these indicative grades are scientifically significant, resource abundance alone does not determine economic viability. Extraction and beneficiation in microgravity environments pose substantial operational challenges, and the cost of accessing, processing and transporting materials remains high relative to present terrestrial alternatives. As a result, resource concentration mainly strengthens the rationale for in-situ resource utilisation (ISRU), particularly for water-derived propellant, life-support consumables and longer-term infrastructure, rather than for direct export of materials to Earth [12], [13].

#### D. Advances in Space Mining Technology

The development of advanced technologies is central to making extraterrestrial mineral exploration and mining feasible. Innovations in robotics, artificial intelligence (AI), autonomous spacecraft, additive manufacturing, and remote sensing are revolutionizing how we locate, extract, and utilize resources in space.

- 1) **Robotics and AI in Exploration and Extraction:** Robotics and AI are essential for performing complex operations in the harsh and remote environments of space. Modern robotic systems are being designed to operate autonomously, perform sample collection, drill into planetary surfaces, and process raw materials with minimal human intervention. AI-driven algorithms enable these robots to adapt to unpredictable conditions, optimize mining strategies, and reduce communication delays with Earth-based operators. For example, robotic arms equipped with advanced sensors and computer vision systems can identify and extract valuable minerals from asteroid surfaces [16]. Swarm robotics, where multiple smaller robots work collaboratively, is also being explored as a way to maximize efficiency and reduce mission risks.
- 2) **Autonomous Spacecraft for Asteroid Prospecting:** Autonomous spacecraft play a crucial role in the initial stages of space mining by surveying and prospecting asteroids and other celestial bodies. These spacecraft are equipped with advanced navigation systems, AI-based decision-making capabilities, and high-resolution imaging instruments that allow them to identify mineral-rich targets without direct human control. Notable missions such as NASA’s OSIRIS-REx and JAXA’s Hayabusa2 have demonstrated the feasibility of autonomous rendezvous, sample collection, and return from near-Earth asteroids [17, 18]. Future spacecraft will be capable of conducting detailed mineralogical assessments, mapping surface compositions, and even deploying robotic miners directly onto promising targets.
- 3) **3D Printing and In-Situ Resource Utilization (ISRU):** In-situ resource utilization (ISRU) is the practice of using locally available materials to support space missions, thereby reducing the need to transport supplies from Earth [19]. Additive manufacturing (3D printing) is a critical component of ISRU, enabling the construction of tools, spare parts, and even entire habitats using extraterrestrial regolith and other mined materials [20]. Experiments have shown that lunar and Martian soil simulants can be processed into building materials using heat, microwaves, or binding agents. This approach could drastically lower mission costs and support long-term space settlements by providing structural materials, oxygen, and fuel directly on-site.
- 4) **Advances in Remote Sensing and Spectroscopy for Mineral Identification:** Remote sensing technologies allow scientists to detect and characterize mineral deposits on celestial bodies from orbit. Instruments such as multispectral and hyperspectral imagers, ground-penetrating radar, and laser altimeters can reveal the composition, texture, and structure of planetary surfaces [21]. Recent advances in spectroscopy, particularly infrared and gamma-ray spectroscopy, have improved the ability to identify specific mineral signatures at great distances. AI-enhanced data analysis is further increasing the accuracy and speed of resource assessments, enabling mining companies and space agencies to prioritize targets with the highest economic potential.

5) **Engineering Feasibility and Processing Approaches:** Although technological advances are making extraterrestrial resource utilization more realistic, large-scale mining operations must operate under conditions that differ fundamentally from terrestrial environments. Very low gravity, vacuum, extreme temperature variation and communication delays limit the applicability of conventional earth-based mining equipment and require autonomous systems able to anchor, excavate, and handle loose regolith. Sample-return missions such as Hayabusa2 and OSIRIS-REx have demonstrated surface interaction, rendezvous and sample acquisition on small bodies, providing important insight into asteroid mechanical properties and regolith behavior in microgravity [17], [18].

Extraction concepts under investigation include mechanical excavation, thermal extraction of volatiles, and electromagnetic or electrostatic separation designed to concentrate metal-rich particles. Microgravity beneficiation may also utilize centrifugal separation and thermal processing to release water or volatiles from hydrated materials. Such approaches are essential for producing propellant, structural materials or oxygen as part of in-situ resource utilization (ISRU) frameworks, which aim to reduce dependence on terrestrial supply chains and lower mission mass [19].

Despite recent progress, most processing flowsheets remain conceptual and have not been demonstrated at operational scale. Energy availability, anchoring reliability and autonomous control of excavation and processing systems remain significant engineering challenges. Consequently, early feasibility largely depends on pilot-scale demonstrations that validate extraction steps under representative environmental conditions, particularly on the Moon and near-Earth asteroids [17], [19].

## E. Key Players and On-going Projects

A combination of national space agencies, private companies, and international collaborations is driving the push toward extraterrestrial mineral exploration and space mining. Each player brings unique expertise, resources, and strategic objectives, collectively accelerating the race to harness resources beyond Earth.

### 1) Space Agencies:

**NASA (United States):** NASA has been at the forefront of space exploration and is heavily involved in resource-focused missions. Programs like the Artemis Program aim to establish a sustainable human presence on the Moon, with lunar resources such as water ice playing a critical role in supporting future missions. The OSIRIS-REx mission, which successfully collected samples from asteroid Bennu, demonstrates NASA's capability in asteroid prospecting, a precursor to future mining operations.

**ESA (European Space Agency):** ESA collaborates widely with international partners and private companies to develop lunar exploration and resource utilization strategies. Initiatives like Prospect and the Moon Village concept are aimed at developing technologies for extracting and using lunar water and other materials.

**JAXA (Japan):** Japan's space agency has made significant contributions through missions like Hayabusa and Hayabusa2, which successfully returned asteroid samples to Earth. These missions provide valuable insights into the composition of asteroids and the potential for mining their resources.

**ISRO (India):** The Indian Space Research Organization is expanding its lunar and planetary exploration programs. Missions such as Chandrayaan-2 and Chandrayaan-3 focus on mapping lunar surface resources, with a particular emphasis on water ice deposits at the Moon's poles.

**CNSA (China National Space Administration):** China has made rapid progress through its Chang'e lunar missions, which include sample return missions and plans for long-term lunar bases. CNSA is also exploring the potential of extracting resources like helium-3 from the Moon's regolith and establishing infrastructure for sustained human activity.

### 2) Private Companies:

**SpaceX:** While not directly focused on mining, SpaceX plays a pivotal role in reducing the cost of access to

space through its reusable launch vehicles. Its Starship program is envisioned as a critical transportation system for future Moon and Mars missions, indirectly enabling space resource utilization.

**Planetary Resources (now acquired by ConsenSys):** This pioneering company was established with the vision of prospecting and eventually mining asteroids for valuable metals and volatiles. While it no longer operates independently, its legacy helped advance the concept of commercial asteroid mining.

**Moon Express:** Moon Express is developing robotic landers capable of delivering payloads to the lunar surface. The company's long-term objective is to extract and utilize lunar resources such as water and precious metals.

**ispace (Japan):** ispace is a leading commercial lunar exploration company working on missions to transport equipment and mining technologies to the Moon. Its HAKUTO-R program includes lunar landers and rovers designed to prospect and map lunar resources.

**3) International Collaborations and Commercial Ventures:** International collaboration is essential for the future of space mining, given the scale and cost of operations. Agreements such as the Artemis Accords promote shared principles for space exploration and resource utilization among participating nations. Commercial ventures are also increasingly working alongside governments. Partnerships between agencies like NASA and private companies under the Commercial Lunar Payload Services (CLPS) program are accelerating the deployment of resource-prospecting missions to the Moon. Moreover, joint initiatives between spacefaring nations, such as ESA's cooperation with JAXA and NASA, and CNSA's partnerships with Russia—are pooling resources and expertise to build sustainable infrastructure for off-Earth resource extraction.

**4) Techno-Economic Context for Extraterrestrial Mining:** While resource concentrations in space can exceed terrestrial deposits, techno-economic studies emphasize that cost, mass and mission architecture are the primary determinants of feasibility. Early analyses of asteroid mining highlighted that profitability depends less on total metal value and more on launch mass, operational cost, and achievable throughput over time [22]. In most near-term scenarios, transporting refined metals back to Earth is unlikely to be economically competitive without significant reductions in launch costs or major increases in in-space demand.

A recurring finding is that water-based ISRU (for propellant and life support) is among the most promising early applications because in-orbit fuel production directly reduces launch mass and enables multi-mission architectures. This contrasts with platinum-group metals, which face terrestrial market saturation risks and require complex return-to-Earth logistics [13]. As a result, techno-economic modelling generally supports stepwise development, beginning with in-space utilization, followed by infrastructure growth and only longer-term commercial extraction for terrestrial markets where viable [22].

Overall, techno-economic frameworks suggest that value will initially arise from enabling new mission capabilities (e.g., propulsion, life-support consumables, in-orbit construction), rather than immediate bulk material return to Earth. Consequently, economic viability depends strongly on launch cost trends, ISRU efficiency, system autonomy and evolving market demand within the broader space economy [13], [22].

## F. Economic and Strategic Considerations

The economics of space mining are complex and debated. On one hand, we can say the raw value of resources is immense: asteroids could carry more metals than the entire global economy. However, the costs of getting mining equipment to space, operating it, and returning product are tremendous. A classic analysis notes that launch costs (\$12/g). This implies that simply hauling ore to Earth is not immediately profitable without new markets or vastly lower launch costs. For example, retrieving a small 20-meter asteroid ( $\approx 1$  million kg) might cost on the order of \$1–2 billion, and at present prices of recovered materials (fuel and metals) might only generate  $\sim$ \$100 billion of value, a large gap given technological uncertainty [22]. This demo calculation figures illustrate the challenge. As shown conceptually in Fig. 3, lower launch costs dramatically reduce the minimum payload mass or resource value required for a mission to break even, narrowing the gap between technical feasibility and a viable business case [22].

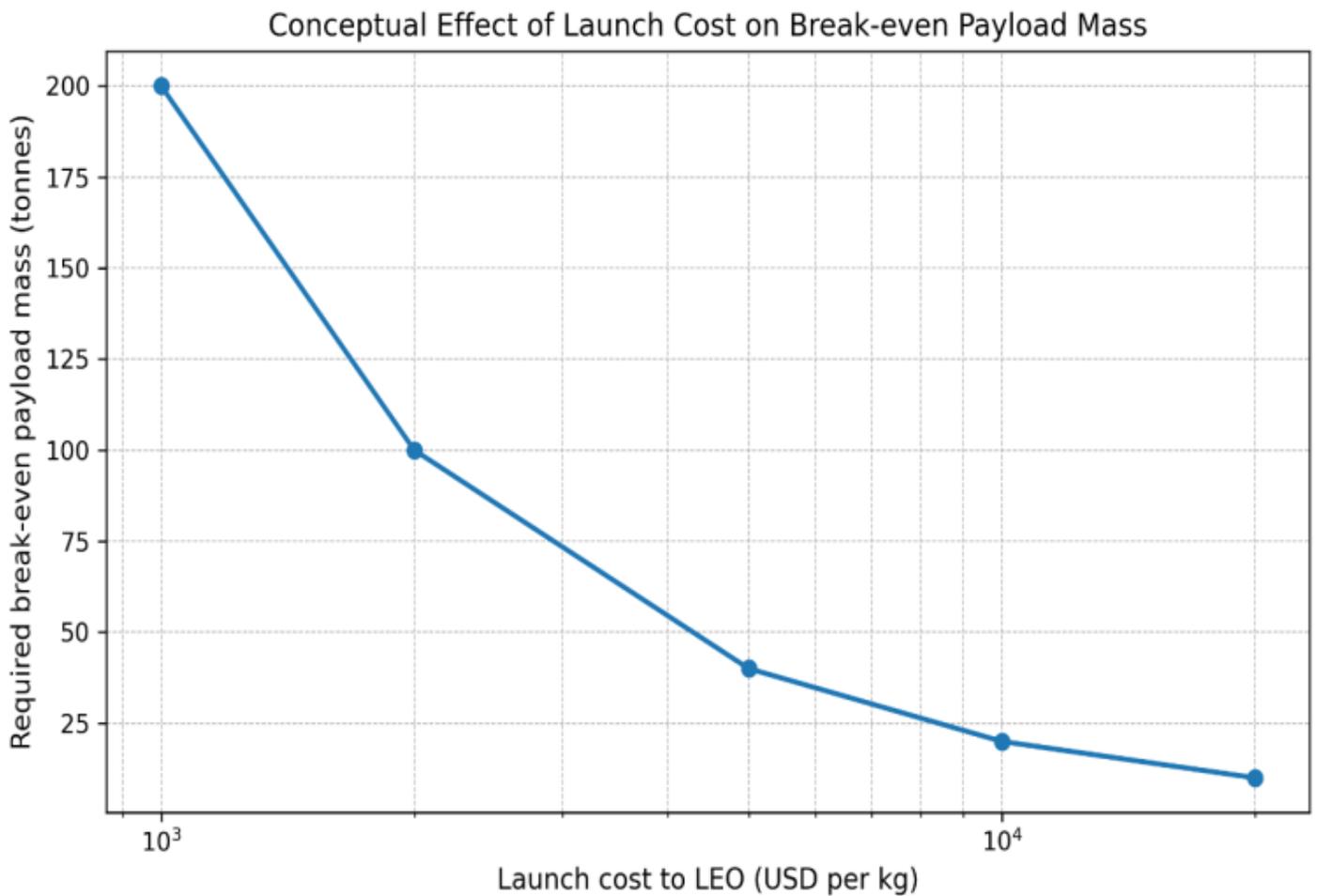


Fig. 3: Conceptual effect of launch cost on required break-even payload mass.

NASA’s OSIRIS-REx cost about \$1.3 billion to return just 0.1 kg from Bennu. This sample return was science-driven, not profit-driven, but it underscores the expense of small harvests. By contrast, forecasts of Psyche’s worth (\$10,000 quadrillion) assume bringing all its metal mass to Earth, an operation far beyond current capability. Financially, oversupplying Earth with platinum and rare metals could crash prices, making the venture even less attractive. Thus most experts agree that initial markets are in space, not on Earth. Water and propellant are top priorities: extracting water for rocket fuel at in-space depots would directly reduce launch mass from Earth, offsetting costs. Metals could be used for on-orbit manufacturing (e.g. building satellites and stations from asteroid metal). In these scenarios, value comes from enabled capabilities (more missions, larger structures) rather than commodity sales. Colorado Mines professor Kevin Cannon notes that exporting materials to Earth remains “economically dubious”, but that providing propellant and in-space materials could justify asteroid mining. Another economic factor is regulatory incentives. Governments have begun underwriting space mining R&D. NASA paid startups for lunar resource demonstrations (in some cases \$1 contracts) to establish legal and business norms. Private investors have also poured millions into space-mining ventures; for instance, several asteroid companies have raised tens of millions in VC to date. These investments reflect a long-term bet: that future demand (especially in a burgeoning space economy) will outstrip supply, and that first movers will reap the benefits. At the same time, there are strategic and economic downsides. Large-scale asteroid mining could destabilize commodity markets on Earth. Artificial scarcity or gluts could ensue. Environmental costs shift from Earth to space: we must consider the risks of operating heavy industry off-planet (space junk, contamination of celestial bodies, etc.). There are also opportunity costs: trillions could be spent developing space infrastructure while Earth’s issues (renewables, recycling, deep-sea mining) remain pressing. A balanced view notes that space mining is not a panacea but a long-term complement to terrestrial efforts as satellite launch market grows. According to Fortune Business Insights on Space Technologies, the satellite launch market is projected to grow from USD 442.33 billion in 2025 to USD 571.83 billion by 2032, exhibiting a CAGR of 3.7% [23]. Fig. 4 as captured by fortune business insights summarizes trends, drivers among others.

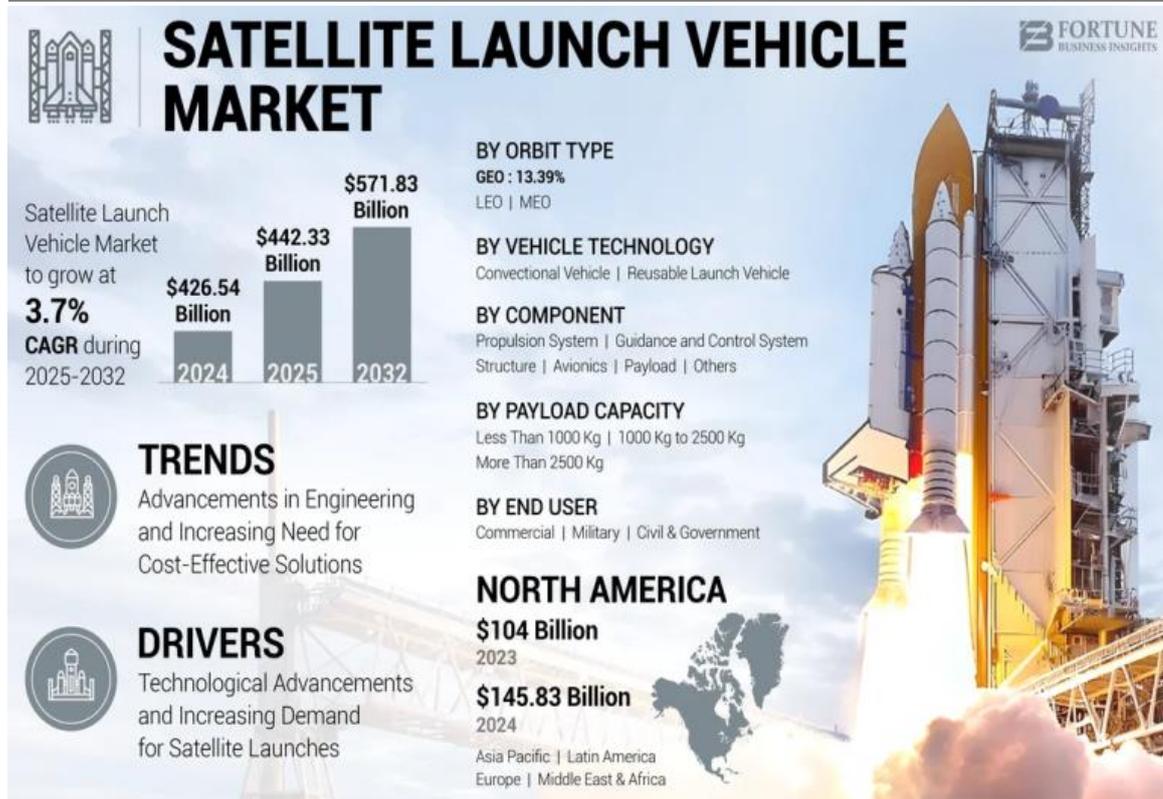


Fig. 4: Satellite Launch Vehicle Market Projection, Trends, Drivers etc. [23].

1) **Strategic and Risk–Benefit Overview:** Strategic assessments distinguish between mission profiles that prioritize in-space utilization and those proposed for eventual terrestrial supply. Near-term applications, notably water extraction for propellant and lunar oxygen for ISRU, directly support exploration architectures and reduce launch mass, making them strategically aligned with current space-agency objectives. In contrast, platinum-group metal return missions face long time horizons, high operational costs and potential market impacts, including price depression if large volumes reach terrestrial markets [13], [22].

Risk–benefit evaluations therefore depend not only on geological abundance but also on accessibility, mission duration, technological maturity and operational costs. Water-rich near-Earth asteroids and lunar polar regions combine relatively high resource potential with strategic value for life-support and propulsion systems, whereas more speculative concepts such as helium-3 extraction remain contingent on major advances in energy technologies and large-scale surface processing [12], [13].

This distribution of risks and benefits explains why most current initiatives emphasize ISRU, in-space material use, and incremental mission demonstrations, with terrestrial commodity supply generally viewed as a long-term possibility rather than an immediate economic objective [12], [22].

### G. Challenges in Extra-terrestrial Mining

While the potential benefits of space-based mineral exploration are immense, the challenges are equally significant. Developing the technology, infrastructure, and legal frameworks necessary for sustainable mining beyond Earth requires overcoming multiple barriers.

1) **Technological Barriers:** Extraterrestrial mining faces unique technical difficulties due to the extreme and unpredictable conditions of space.

**Energy supply:** Mining operations require continuous, reliable energy sources, yet the lack of atmosphere and fluctuating solar radiation on celestial bodies make energy generation and storage complex. Solar panels may be insufficient in shadowed lunar craters or deep space, necessitating nuclear-powered solutions.

**Transportation:** The cost and complexity of transporting mining equipment, raw materials, and processed

resources between Earth and celestial bodies remain a major hurdle. Developing reusable launch vehicles and efficient propulsion systems is essential to reduce costs.

**Processing in microgravity:** Traditional mineral processing methods depend on gravity-based separation techniques, which do not function in microgravity environments. New approaches, such as magnetic or electrostatic separation, must be designed to operate in space conditions.

2) **Economic Feasibility and Cost-Benefit Analysis:** The economics of space mining remain uncertain. Initial capital investment for developing spacecraft, mining robots, processing plants, and transportation infrastructure is enormous. Even if valuable resources are discovered, bringing them back to Earth could be cost-prohibitive compared to terrestrial mining. Companies must balance the potential long-term profitability of space mining against these upfront costs, leading to hesitation among investors [24]. Additionally, the fluctuating market value of minerals, especially those abundant on Earth, may undermine the economic rationale for extraterrestrial mining. For instance, an oversupply of precious metals from asteroids could depress global prices, eroding profitability.

3) **Legal and Ethical Issues:** The legal framework governing space mining is complex and still evolving.

**Outer Space Treaty (OST):** Ratified in 1967, the OST prohibits any nation from claiming sovereignty over celestial bodies. This raises questions about who has the right to extract and own space-based resources [25].

**Ownership rights:** Although countries like the United States and Luxembourg have passed national laws allowing private entities to own resources they extract, these laws remain contested under international space law.

**Ethical concerns:** There are unresolved debates about equitable access to space resources. Should wealthy nations and corporations dominate space mining, or should benefits be shared globally? These questions could intensify geopolitical tensions.

4) **Environmental Concerns in Space and Planetary Protection:** Mining in space introduces unique environmental risks. Disruption of celestial bodies could generate hazardous debris, alter orbital trajectories, or contaminate potentially habitable worlds. Planetary protection guidelines require that missions avoid biological contamination that could compromise scientific research or harm alien ecosystems. On a broader scale, large-scale space mining could change the dynamics of the solar system, such as destabilizing asteroid belts or removing resources critical to future missions. Developing strict environmental protocols is therefore essential for responsible resource extraction.

## CONCLUSIONS

Although space missions and laboratory studies increasingly demonstrate the technical feasibility of extracting metals, volatiles and oxygen from extraterrestrial materials, commercial viability remains considerably more uncertain. Robotic sample-return missions, ISRU demonstrations, and remote-sensing surveys confirm that resources exist and can be accessed, yet the operational scale, energy requirements, launch costs and market demand continue to limit near-term profitability. As a result, the principal economic argument currently favours in-space utilisation of water and oxygen to support propulsion, life support and infrastructure, while bulk return of metals to Earth remains a longer-term possibility contingent on technological maturity, infrastructure availability and viable business models [12],[13],[22].

The pursuit of mineral exploration beyond Earth represents a transformative step in addressing the dual challenges of resource scarcity and environmental degradation on our planet. As terrestrial reserves face increasing pressure from growing global demand, particularly for critical minerals used in clean energy and advanced technologies, space offers a frontier of untapped wealth that could complement Earth's resources and fuel both industrial and exploratory ambitions. Celestial bodies such as the Moon, asteroids (16 Psyche), and Mars hold substantial quantities of valuable materials, including rare earth elements, water ice, and metals like nickel, cobalt, and platinum-group elements, often at concentrations far exceeding those found on Earth. Technological advancements in Launch Vehicles and autonomous spacecraft driven by multi-stage system,

electric propulsion, reusability, deployment techniques, engine reliability as well as robotics, AI and remote sensing have brought the once-speculative field of space mining within reach, with early successes from missions such as NASA's OSIRIS-REx and JAXA's Hayabusa2 showcasing the feasibility of in-situ exploration and resource retrieval. Despite these opportunities, space mining faces formidable obstacles. Technological limitations, high initial investment costs, legal ambiguities surrounding ownership and access rights, and concerns about planetary protection pose significant barriers to large-scale extraterrestrial resource exploitation. Moreover, the economic viability of returning materials to Earth remains uncertain, emphasizing the need for detailed cost-benefit analyses and long-term planning. Nonetheless, the strategic importance of diversifying resource supplies, securing critical materials, and enabling sustainable human presence in space is driving both public and private sectors to invest in this frontier. International collaborations, evolving legal frameworks and the integration of space mining into broader planetary exploration goals suggest that, with responsible governance and continued innovation, extraterrestrial mineral exploration could become a key pillar of humanity's future, one that ensures prosperity on Earth while opening new chapters in space exploration.

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