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Comparative Analysis of Rover Systems for Operations on the Lunar Surface

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Un uomo che legge ne vale due
- Emilena Fabbretti

Abstract

The Space Economy has undergone a fundamental transition, shifting from a realm dominated by geopolitical considerations to a new paradigm characterised by economic and commercial drivers. Prior to the 21st century, the space market was predominantly led by government agencies; however, this evolution has culminated in the creation of a genuine space market, featuring a value chain composed of both public agencies and private companies. The upstream sector, in particular, is undergoing a significant transformation. This is marked by the entry of new launch and space manufacturing companies introducing novel business models, which are effecting a radical change in the market and establishing new trends.

This transformation is also impacting the Lunar Economy segment. In addition to scientific objectives, the new "Moon to Mars" ARTEMIS approach is generating new commercial demands and drivers. This shift is turning lunar exploration into a commercial endeavour and fostering the Lunar Economy paradigm. Despite its nascent state, this market demonstrates considerable potential, characterized by substantial projected growth rates and significant opportunities for the establishment and development of commercial enterprises. The development of key enabling technologies has largely been delegated to private entities, with space agencies increasingly aiming to function as regulators and market catalysts.

This thesis provides a comprehensive analysis of rover systems designed for operation on the lunar surface, offering a detailed overview of current and emerging technologies. This analysis distinguishes between systems developed by public agencies for scientific missions and those developed by private companies for commercial purposes. The public sector analysis examines state-sponsored missions and national flagship goals, focusing on their current development status. Conversely, the private sector analysis investigates commercial products, proprietary technologies, and the business models being adopted.

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Chapter 1

Introduction

The space economy is undergoing a period of change due to the changing role of agencies in the market. In fact, thanks to a more commercial model, companies are increasingly becoming market leaders, with agencies playing the role of regulators and market catalysts. The market is mainly dominated by the American segment, with Europe acting as a production satellite, hosting major companies involved in the manufacture of space products.

The space sector is divided into three main segments: upstream, midstream and downstream. These segments cover everything from the construction and launch of space infrastructure and products, to in-orbit management and services, to the sale of infrastructure-related services. Agencies cover all segments, while private companies specialise in a specific segment or application within a segment.

The market is growing, thanks to substantial government investment, especially in the defence segment. In fact, space technologies are mainly supported by military motives, although the commercial segment has been growing exponentially in recent years, with applications mainly downstream in agriculture, logistics, infrastructure and many other sectors.

Within the upstream sector, there is a rapidly expanding niche, namely the lunar market, which includes all activities carried out to reach lunar orbit and surface and related applications. This market, which has always been characterised by a very strong public matrix, is being privatised thanks to the arrival of new companies with innovative technologies and business models.

The reasons for going to the moon are mainly scientific. Another driver can be summed up by the motto of the ARTEMIS project, "Moon to Mars", as the lunar surface is a perfect environment for testing technologies for Mars. Behind this reason lies the commercial driver that is driving the lunar market, in addition to the fact that space exploration has always been the main driver of innovation on Earth.

The market is mainly divided into three segments: lunar transportation, data and resource utilisation. Market forecasts for these three sectors predict an increase in both the overall value of the market, thanks to the boost from ARTEMIS projects and the plans of large commercial companies, and the commercial segment, which is currently still small. This landscape therefore becomes fertile ground for the economic development of companies already present in the sector and new innovative businesses.

The technologies found in this market context can be grouped into several segments: launch, landing, surface mobility, payloads and lunar infrastructure. In particular, this paper focuses on the Lunar Rover segment, which falls within the Surface Mobility segment. A planetary rover is a surface exploration device engineered to move across the terrain of a planet or other celestial body and perform tasks.

The market is still very niche and underdeveloped, with few commercial players. The landscape of companies is divided into lander manufacturers that have also verticalised rover production and companies focused solely on rover production. These two companies compete in the same market with advantages and disadvantages linked to landing constraints and resource concentration.

The most innovative business model in the lunar sector, which is adopted by lander and rover manufacturers, is the “as a Service” model. This model involves the technology provider building the system and selling product-related services to customers. In this initial landscape, the main target customers are agencies, as they are the main entities interested in exploiting the Moon. Forecasts predict an opening up of the commercial sector over the next few years. In particular, Rover manufacturers use Logistic as a Service models, offering end-to-end missions, or Mobility as a Service (MaaS), offering only the transport of the customer’s payload, or Rover as a Service, offering task operation.

Chapter 2

Evolution of Space Economy

The Space Economy (SE) has fundamentally transitioned from a realm of geopolitical competition to a sophisticated global commercial ecosystem. For the purpose of managerial analysis, it is essential to establish a precise definition, trace the historical paradigms that shaped it, and understand its current operational segmentation.

2.1 Definition

The contemporary definition of the Space Economy extends far beyond the traditional budgets of governmental space agencies. The Space Economy is broadly defined as the full range of activities and the use of resources that create value and benefits to human beings in the course of exploring, researching, understanding, managing, and utilizing space. It is most accurately defined by the Organisation for Economic Co-operation and Development (OECD) as:

"The space economy is the full range of activities and the use of resources that create and provide value and benefits to human beings in the course of exploring, understanding, managing and utilising space. Hence, it includes all public and private actors involved in developing, providing and using space-related products and services, ranging from research and development, the manufacture and use of space infrastructure (ground stations, launch vehicles and satellites) to space-enabled applications (navigation equipment, satellite phones, meteorological services, etc.) and the scientific knowledge generated by such activities. It follows that the space economy goes well beyond the space sector itself, since it also comprises the increasingly pervasive and continually changing impacts (both quantitative and qualitative) of space-derived products, services and knowledge on economy and society." [1].

This definition, applied by the European Space Agency (ESA) and developed through the work of the OECD Space Forum, explicitly includes the value of the space sector itself (comprising upstream and downstream companies) and the value of impacts that space activities have on the broader economy, society, and sustainability [2].

2.1.1 Historical Evolution: Old Space vs. New Space

The history of the space industry can be characterised as a series of distinct 10–15 year development cycles that reflect the evolution of technology and its societal acceptance [1]. This progression began in the Pre-Space Age with foundational rocketry and the military development of ballistic missiles that culminated in Sputnik [1][3]. The subsequent cycles saw a clear evolution from the purely government-led Space Race, which established human spaceflight and early military satellites [4], to the introduction of space stations, reusable shuttles, and foundational applications like GPS, which marked the initial growth of commercial activities [1]. The modern era was ushered in by a fourth cycle (2003–2018) defined by digitalization and the rise of SmallSats, and has now entered a fifth cycle (2018–2033) representing an inflection point towards ubiquity, with the global space economy projected to reach $1.8 trillion by 2035 [1][5]. This current transformation is propelled by a synergy of key drivers [5]. Technologically, dramatically reduced launch costs and advanced miniaturization have democratized access, enabling new business models like mega-constellations [6][7], while a soaring demand for data processed by AI creates new service opportunities [7]. Financially, this growth is supported by a dual engine: a surge in private investment, which reached €7 billion globally in 2024, fostering innovation [7], and sustained, record-high public investment of €122 billion, which remains the cornerstone of space infrastructure and is increasingly catalyzed by defense spending [2][7].

2.2 Segmentation and Main Activities

The Space Economy encompasses the full range of activities and the use of resources that create and provide value and benefits to human beings in the course of exploring, understanding, managing, and utilizing space . This comprehensive concept extends beyond the space sector itself, comprising the pervasive impacts of space-derived products, services, and knowledge on the economy and society .

For measurement purposes, the space economy is broadly divided into three segments : upstream, downstream, and space-derived activities in other sectors [8].

The segmentation of space activities into upstream, downstream, and space-derived activities in other sectors provides the framework for analysts to pragmatically use concepts and definitions to measure the space economy. Despite the growth in the number of actors and the increasing importance of commercial space activities, the international comparability of space economy statistics remains limited [8].

2.2.1 Upstream

The upstream space sector represents the scientific and technological foundations of space programs, including the manufacturing and production of space infrastructure. These activities are conducted by the government sector, space business enterprises and the scientific community at large and they are essential enablers for downstream activities. Historically, upstream space activities have been the focus of space economy statistics put together by governments and industry associations. Recent and future space activities could also be included here, e.g. space tourism, on-orbit servicing, active debris removal, on-orbit manufacturing and resource extraction [8]. This segment is generally considered relatively easy to measure using both official and industry [8]. It represents the foundational layer of the value chain, highly capital-intensive and focused on hardware development [9].

Key activities within the upstream segment can be grouped into four main categories:

- **Research, engineering and other services:** The first category includes fundamental and applied research conducted by universities and public organizations to advance scientific knowledge. It also covers ancillary activities such as the legal, insurance, and financial consulting services that provide the economic and regulatory framework for the sector. Finally, it encompasses scientific and engineering support, which refers to the R&D, design, and testing services offered by engineering firms and research agencies to enhance technological readiness [8].
- **Space manufacturing:** This group concerns the design and production of all hardware and subsystems. This area is divided into two main activities. The first is the supply of materials and components, including both passive parts (cables, connectors) and active components (diodes, transistors) sourced from both general and specialized space-grade suppliers. The second is the design and manufacturing of complex equipment and subsystems for every part of a spacecraft, such as structures, on-board computers, guidance and navigation sensors, power and communication systems, and propulsion technologies. This field is populated by highly specialized manufacturers, many of whom also operate in the aeronautics and defence sectors, and has seen a notable growth in SMEs focusing on components for small satellites [8].
- **Integration and supply of full systems:** This stage involves the assembly and delivery of complete space systems, including satellites, orbital platforms,

launch vehicles, and the associated ground infrastructure like control centres and tracking stations. This part of the value chain is dominated by approximately twenty major global players, with governments remaining their key customers. However, a recent trend shows a growing number of integrators specializing in smaller, more agile systems [8].

- **Space launch and transportation:** This segment represents the critical interface between the ground-based manufacturing phase and in-orbit operations. It encompasses the governmental and commercial spaceports that provide the essential infrastructure and services required for launch campaigns. The United States currently has more than ten licensed spaceports, with several additional projects under development globally to meet growing demand [8].

Across this entire upstream value chain, investment is overwhelmingly characterized by significant government involvement. Governments acting as primary customers are particularly crucial for companies in space manufacturing and launch activities. To illustrate, in 2019, sales to the public sector accounted for 71% of the upstream segment's revenue in Europe and 76% in Korea, underscoring the sector's reliance on public contracts [8].

2.2.2 Midstream

The concept of a "midstream" segment is increasingly used to categorize space and ground system operations, thereby describing activities along the value chain. The OECD Space Economy Handbook 20222 recommends that these crucial activities, which constitute the link between satellites and terrestrial infrastructures, be conceptually classified as part of the downstream segment .

Activities traditionally categorized as "midstream" fall under Space and ground systems operations within the broader downstream definition [8]. This includes:

- Satellite operations, such as the lease or sale of satellite capacity for communications or Earth observation.
- Ground systems operations, which involve managing the networks of ground stations that link satellites and terrestrial infrastructures.
- As the complexity of managing an increasing number of orbiting assets escalates, new services such as on-orbit servicing and active debris removal are emerging, often being considered a component of the upstream segment.

2.2.3 Downstream

The downstream segment of the space economy refers to the ensemble of activities, products, and services that rely on data and signals originating from space-based infrastructure [1]. Unlike the upstream domain, which focuses on the design, manufacture, and deployment of space systems, the downstream segment is concerned with the exploitation and commercialisation of satellite outputs for societal and economic use. It represents the interface between space technologies and end-users, encompassing applications that generate direct value for both consumer and business markets.

It constitutes the most dynamic and rapidly expanding component of the global space value chain. The segment serves as the principal bridge between space infrastructure and terrestrial applications, transforming orbital assets into practical and commercial utilities. Through the integration of advanced digital technologies, data analytics, and cloud-based processing, downstream activities are driving the diffusion of space-derived benefits into nearly every sector of modern society, thus reinforcing the strategic and economic significance of the space domain in the 21st century [1].

Downstream activities can be broadly divided into several key domains:

- **Data distribution services:** These have grown substantially with the advent of cloud computing and artificial intelligence. Numerous companies now provide cloud-based platforms that facilitate access to, processing, and distribution of geospatial and satellite-derived information, making such data more usable and valuable to a wide array of sectors. These services underpin the rapid digital transformation of geospatial intelligence and are a cornerstone of the emerging data-driven space economy.

- **The supply of devices and equipment supporting consumer markets:** this includes the manufacturing of hardware such as chipsets, terminals, very small aperture terminals (VSATs), and global navigation satellite system (GNSS) receivers. It also covers the development of software solutions that enhance the functionality and accessibility of satellite-enabled applications. The organisations involved range from major telecommunications companies and electronic component manufacturers to specialised geospatial technology firms [8].

- **Provision of services for consumer and commercial markets:** it encompassing direct-to-home (DTH) television and radio broadcasting, broadband internet, and a wide range of positioning, navigation, and timing (PNT) services. Many of these services rely on the continuous transmission and reception of satellite signals to deliver high-precision and real-time data. Current applications include cartography and mapping, logistics and distribution, surveillance and security operations, meteorology, precision agriculture, and various industrial activities requiring synchronisation and timing accuracy.

Cloud-based services also play an increasing role in hosting, processing, and delivering geospatial data products tailored to user needs.

- **Data value-added services:** these involve the transformation of raw satellite data into actionable information through processing, integration, and analysis. These services combine satellite imagery and signals with other data sources, such as in-situ measurements and socio-economic datasets, to generate products that support decision-making across numerous domains, from environmental monitoring and disaster management to urban planning, transportation, and resource management. Many companies active in this segment do not consider themselves part of the space sector, despite their heavy reliance on satellite-derived inputs.

From an economic and analytical perspective, the downstream segment poses particular measurement challenges. The boundary between space-related and non-space-related activities can be difficult to delineate, as many industries incorporate satellite-enabled functionalities into broader technological ecosystems. As a result, the extent of space-specific value creation may be either underestimated or overstated in economic statistics [8].

2.2.4 Spin Off

Another rapidly developing segment that has been forming recently is the "spinoff" segment. A significant number of technologies originally conceived for the extreme challenges of space missions have been successfully adapted for terrestrial applications, where they operate independently of any space-based infrastructure. These technological "spinoffs" demonstrate how investment in space economy field yields a tangible return for society. A prominent example lies in the field of advanced materials. Shape-memory alloys, such as Nitinol, were developed to enable satellite antennas to autonomously deploy once in orbit. Today, this material is a critical component in the medical field for manufacturing cardiovascular stents and orthodontic devices, which leverage its ability to return to a predefined shape after deformation [10].

Another sector profoundly impacted is that of medical and consumer imaging. The imperative to create miniaturized, lightweight, and low-power scientific imaging systems for planetary probes drove the development of Complementary Metal-Oxide-Semiconductor (CMOS) sensor technology. This innovation, pioneered by NASA's Jet Propulsion Laboratory (JPL), now forms the basis for the vast majority of digital cameras, smartphones, and endoscopic cameras, thereby revolutionizing entire industries [11]. These cases highlight how the push for miniaturization and efficiency, mandated by the constraints of space missions, produces innovative solutions with a direct and pervasive impact on daily life.

2.3 Actors, Trends and Institutional Role

2.3.1 Public Actors

The global space economy reached a record valuation of $613 billion in 2024, a figure that underscores the sector's profound dynamism and integration into the broader global economic framework [12]. While the commercial sector's 78% share of this total often dominates contemporary discourse, the remaining 22%, representing a substantial $132 billion in annual government spending, is not merely a legacy component but the strategic core that underpins, directs, and shapes the entire ecosystem [12]. This report posits that in 2025 national and intergovernmental space agencies have decisively transitioned from being the primary implementers of space activities to serving as the principal architects of the space economy. The government sector plays a key role in the space economy as investor, developer, owner, operator, regulator and customer. National agencies, research centres and laboratories also perform space R&D and, in some cases, have a manufacturing role (e.g. India, Korea). The bulk of their funding tends to be public, but they may also receive private financing via contracts and licensing arrangements [8]. Their influence is wielded not through monolithic control, but through the strategic deployment of capital, the definition of ambitious, long-term missions, and the utilization of increasingly sophisticated industrial policy tools, including innovative procurement models and public-private partnerships (PPPs).

Public actors strategically employ their budgets and institutional mandates to catalyze private markets where they are nascent, secure critical national interests in an increasingly contested domain, and project geopolitical influence on Earth and beyond.

National Visions and Flagship Programs

An analysis of flagship space programs in 2025 reveals a domain defined not as a purely scientific endeavor, but as a complex arena for geopolitical, industrial, and diplomatic strategy. A clear bifurcation of strategic blocs is evident. The United States leads a broad international coalition centered on the Artemis program, designed to maintain its global leadership by extending human presence to deep space while concurrently transitioning Low-Earth Orbit (LEO) to a burgeoning commercial sector [13][14]. This bloc is supported by key partners like Japan, which pursues a dual strategy of integrating with Artemis while fostering its domestic space market [15][16], and emerging actors such as the UAE and South Korea who contribute to the alliance while building sovereign capabilities [17].

Conversely, China is executing a long-term strategy to become the preeminent space power, employing its Tiangong space station as a potent instrument of space diplomacy to build an alternative, non-Western alliance [18][19]. In partnership with

Russia, its International Lunar Research Station (ILRS) is a direct competitor to the U.S.-led framework [20]. Russia, facing isolation from the West, is attempting to preserve its status as a major space power through the sovereign Russian Orbital Service Station (ROSS) project, though it confronts significant financial and technical hurdles [21].

Between these blocs, other actors pursue distinct, intermediate strategies. Europe maintains a pragmatic focus on strategic autonomy and tangible societal returns through dual-use programs like the Copernicus Earth observation system and the Galileo navigation system [22][23]. India is positioning itself as a "bridge actor" and a leader for the Global South by balancing its participation in the Artemis Accords with the development of sovereign capabilities, including the Gaganyaan human spaceflight program and a national space station [24]. In sum, the 2025 space domain is a multipolar arena where leading and emerging powers utilize flagship programs to architect alliances, project influence, and pursue terrestrial strategic objectives.

Public Space Investment in 2025

Public investment remains the foundational bedrock of the space economy, setting strategic agendas and acting as the primary customer, even as the total global space economy reached $613 billion in 2024 [12]. However, the nature of this public funding is undergoing a fundamental, geopolitically charged realignment. A paradigmatic shift occurred in 2023 when global defense-related space expenditures ($59 billion) surpassed civil budgets ($58 billion) for the first time since the early 1990s, a trend driven by a starkly higher growth rate in defense (18%) compared to civil programs (7%) [25][26]. This pivot towards national security is accelerating globally, with the United States remaining the dominant public investor, accounting for approximately 58% of all government space spending [12]. The U.S. model uses public funds as a catalyst for its commercial sector, China and Russia prioritize state-led sovereign control and deep civil-military fusion, and the European model builds a distributed industrial base constrained by politically balanced return policies [27][28].

Market Catalysts and Global Regulators

Public agencies in the space sector wield a dual mandate as powerful market catalysts and indispensable global regulators, with their national strategic philosophies manifesting distinctly in both roles. As monopsony buyers, their procurement models function as potent instruments of industrial policy that shape their respective national industries [29]. A clear divergence in these models is evident: the United States employs a service-procurement and anchor tenancy model, transferring significant risk to the private sector to lower public cost and accelerate innovation, as exemplified by its Commercial Crew and CLPS programs [30, 31]. In contrast, Europe's industrial policy, constrained by the principle of juste retour, prioritizes the development of a geographically distributed industrial base, sometimes at the expense of pure market efficiency [25]. China, meanwhile, utilizes a top-down, state-directed model rooted in civil-military fusion to rapidly achieve sovereign capabilities and technological dominance [32]. This divergence in industrial strategy is mirrored in the increasingly fragmented approach to global space governance. As outer space becomes more congested and contested, creating a "tragedy of the commons" scenario [33], the need for a unified regulatory framework for Space Traffic Management (STM) and debris mitigation is paramount. However, while forums like UN COPUOS seek consensus [34], the inherently dual-use nature of key capabilities like Space Situational Awareness (SSA) is driving geopolitical competition. This has led to the emergence of competing normative blocs: a rules-based order promoted by the U.S. and its allies through frameworks like the Artemis Accords, and an alternative being developed by the China-Russia partnership on the International Lunar Research Station (ILRS), suggesting that the future "rules of the road" will be determined as much by a contest to establish facts in orbit as by multilateral agreement [35].

2.3.2 Upstream Private Actors

The transformation of the upstream space sector is propelled by a confluence of technological breakthroughs and innovative business strategies. These drivers are fundamentally altering the cost, accessibility, and scalability of space operations:

- **Launch Cost Reduction through Reusability:** The single most influential factor reshaping the upstream market is the dramatic reduction in the cost of launch. Over the past two decades, the cost to launch a kilogram of payload to orbit has fallen by an order of magnitude [5]. This revolution is almost single-handedly attributable to the development and operationalization of reusable rocket technology, a feat pioneered and dominated by SpaceX with its Falcon 9 rocket [36]. By recovering and reflying the most expensive component of the rocket—the first stage booster, SpaceX has been able to drastically lower its marginal launch costs and offer prices that legacy competitors with expendable rockets cannot match. This has not only captured a dominant share of the existing launch market but has also stimulated new demand by making previously uneconomical satellite business plans viable.

- **Vertical Integration:** A key business model innovation of the NewSpace era is a high degree of vertical integration. Companies like SpaceX have eschewed the traditional aerospace model of managing a vast, disaggregated network of subcontractors. Instead, they have brought the design and manufacturing of most critical components—including rocket engines, structures, and avionics—in-house. SpaceX is estimated to manufacture as much as 80% of its hardware internally. This strategy provides granular control over the entire production process, enabling rapid design iterations, reducing supply chain dependencies, and capturing more value [37]. It allows for optimization across the entire system, rather than at the component level, leading to significant cost savings and accelerated development timelines.

- **Advanced Manufacturing:** The adoption of advanced manufacturing techniques, particularly 3D printing (additive manufacturing), is revolutionizing the production of space hardware. This technology allows for the creation of highly complex and optimized parts, such as rocket engine injectors, as single components, drastically reducing part counts, weight, and assembly time. Companies are leveraging this to simplify their supply chains and accelerate innovation. Relativity Space represents the apex of this trend, with a long-term mission to manufacture nearly an entire rocket using its proprietary 3D printing platform [38]. The company's goal is to reduce the build time for a rocket from over a year to as little as 60 days, enabling a far more agile and responsive manufacturing system.

These drivers are interconnected. Vertical integration facilitates the adoption of advanced manufacturing, and both contribute to the primary goal of reducing costs and increasing production cadence, which is further amplified by the operational efficiencies of reusability. Together, they form the technical and economic foundation of the NewSpace paradigm. This paradigm has led to the growth of existing companies and the formation of numerous new ones. The following table lists the main companies.

2.3.3 Downstream Private Actors

The downstream segment of the space economy encompasses companies that transform satellite infrastructure and data into commercial and governmental services, operating across several interconnected layers of the value chain. These firms collectively drive the market's maturation through consolidation, vertical integration, and technological innovation [39, 40]. The principal categories of downstream companies include:

- **Operation of Space and Ground Systems:** Companies such as Northrop Grumman and L3Harris Technologies exemplify vertically integrated models for secure government missions, while European leaders like KSAT and SSC provide Ground-Station-as-a-Service (GSaaS) to commercial clients, reducing entry barriers for satellite operators [41, 42, 43].

- **Data Distribution Services:** Global operators including Viasat, SES, and Eutelsat are transitioning from GEO-only to multi-orbit constellations to enhance connectivity and resilience [44, 45, 46]. Sovereign commercial entities in China and India, such as China Satcom and NSIL, combine strategic state objectives with market-oriented frameworks.

- **Supply of Devices and Equipment:** Generating over $150 billion annually, this sector includes manufacturers like Hughes Network Systems, Viasat, and Thales, as well as GNSS leaders Trimble and Garmin, which are increasingly integrating software-based recurring revenues [47, 48]. National ecosystems are emerging around sovereign GNSS systems such as Beidou and NavIC.

- **Provision of Services for Consumer and Commercial Markets:** End-user services are led by SpaceX's Starlink, which has disrupted satellite internet through its LEO constellation, while incumbents like Viasat and HughesNet adapt through affordability and contractual flexibility [37]. MSS and satellite radio services, led by Iridium, Inmarsat, and SiriusXM, serve specialized and premium market niches.

- **Data Value-Added Services:** This rapidly growing segment converts raw satellite data into analytics-driven intelligence. Leaders such as Maxar, Planet, BlackSky, and Airbus offer diverse data products and digital platforms, while emerging players like ICEYE, Spire Global, and Pixxel pioneer SAR, RF, and hyperspectral data applications, marking a shift toward multi-sensor data fusion [49, 50].

2.4 Economic and Financial Issues

The Space Economy is undergoing a profound transformation, evolving from a domain historically dominated by government-led exploration and national prestige into a dynamic, commercially-driven ecosystem. This transition is reshaping capital markets, fostering innovative business models, and positioning space as an increasingly integral component of the global economic infrastructure. The following analysis examines the key financial and economic dynamics of this new era, focusing on the sector's macroeconomic scale, the evolving landscape of public and private investment, and the emergence of novel commercial strategies that are defining the future of space-based enterprise.

2.4.1 Value and Growth Projections

The economic trajectory of the Space Economy is widely recognized as exponential, with growth rates that significantly outpace the broader global economy. Current valuations place the global space economy at a record $613 billion in 2024, according to the Space Foundation, a figure largely consistent with joint analysis from the World Economic Forum (WEF) and McKinsey & Company, which estimated the market at $630 billion in 2023. These figures confirm that the sector has firmly surpassed the half-trillion-dollar threshold, establishing a robust baseline for future expansion [5].

Projections consistently forecast a period of sustained and rapid growth. The WEF and McKinsey project that the global space economy is poised to soar to $1.8 trillion by 2035 as shown in 2.1. This expansion is underpinned by an average annual growth rate of 9%, a velocity that substantially exceeds the projected growth of global Gross Domestic Product (GDP), signaling that the space sector is not merely growing but is becoming an increasingly influential component of the global economic architecture [5]. This immense potential for value creation is expected to be driven primarily by ongoing technological progress and the expanding activities of private companies.

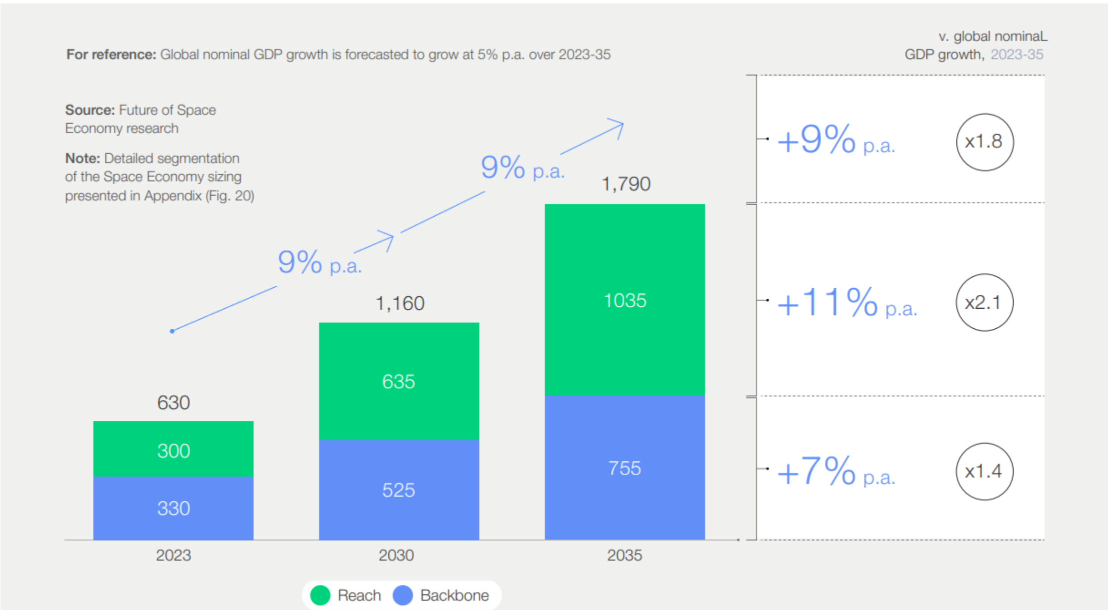

Figure 2.1: Gross Domestic Product of Space Economy

A critical analytical framework for understanding this growth is the distinction between the space "backbone" and its "reach". The "backbone" encompasses the core space industry, including the manufacturing of hardware and the provision of direct services like launch and satellite operations. The "reach," in contrast, comprises the vast array of terrestrial industries that are enabled by space-based technology, such as logistics, agriculture, and financial services that rely on satellite-derived data. While the backbone is forecast to grow at a healthy compound annual growth rate

(CAGR) of 7%, the reach is expanding at a much faster rate of 11% per annum. Consequently, the reach is expected to constitute nearly 60% of the total space economy by 2035, indicating a fundamental shift in where value is being created, as shown in 2.2.

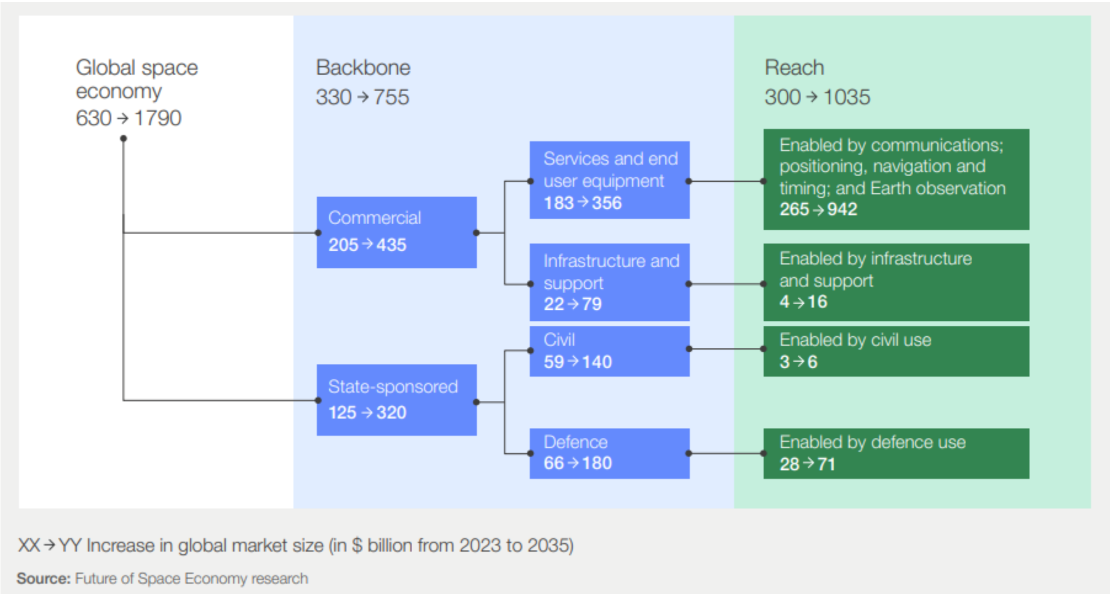

Figure 2.2: Components of Space Economy

This dynamic suggests an inversion of the traditional space value chain; whereas value was once concentrated in the high-cost, complex upstream segments of manufacturing and launch, the future of profitability is decisively shifting to the downstream monetization of data and services. The hardware is becoming a commoditized enabler, while the unique services it provides are becoming the primary source of commercial differentiation [5].

The WEF's analysis also includes a range of potential outcomes. An upside scenario projects a market valuation of $2.3 trillion by 2035, contingent on accelerated improvements in space data access and further reductions in launch costs. Conversely, a downside scenario caps the market at $1.4 trillion, a possibility should access to space stall or should terrestrial technological advancements provide viable alternatives to space-based solutions. This highlights that while the overall trend is one of robust expansion, the ultimate scale of the space economy remains sensitive to technological innovation and competitive market forces [5]. The sector's growth rate relative to global GDP signifies a structural evolution; it is transitioning from a discrete industry into a foundational infrastructure layer for the wider terrestrial economy, analogous to the role the internet has played over the past three decades 2.1.

2.4.2 Investments and Costs

The financial architecture supporting the Space Economy rests on two principal pillars: substantial government expenditure and an increasingly sophisticated private investment market. While government spending provides a stable foundation, the most dynamic segment of the market is driven by private capital, which has undergone a significant period of rationalization and strategic realignment.

Government spending remains a crucial driver, particularly in the United States, where it reached $77 billion in 2024 as part of a total global public space budget of €122 billion (approximately $132 billion). The primary engine of this growth of public expenditure growth is defence. In 2024, defence-related space spending increased by 12% and now constitutes approximately 54% of all global public space budgets, reflecting a heightened geopolitical focus on space as a strategic domain. This robust government demand creates a predictable revenue stream for established and emerging companies, playing a vital role in the sector's financial stability [2].

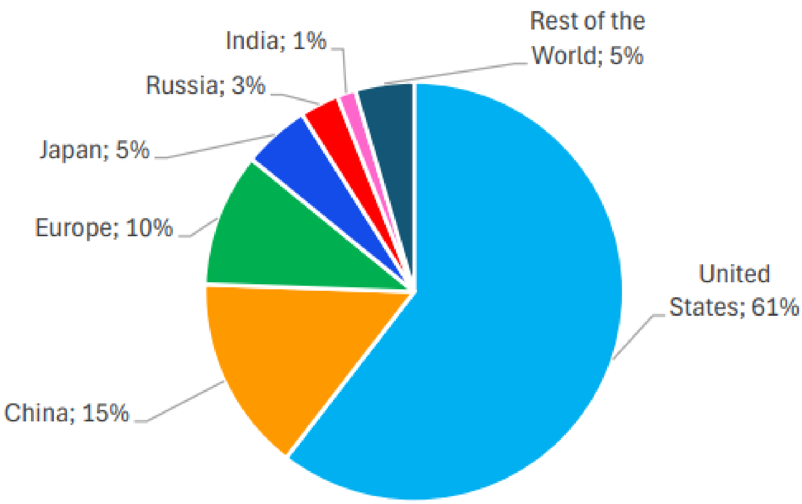

Figure 2.3: Distribution of institutional space budgets in 2024 (civil and defence)

The private investment landscape, meanwhile, tells a story of market maturation. Following a period of heightened activity partially driven by the Special Purpose Acquisition Company (SPAC) boom in 2021, the market underwent a significant correction. Global private investment contracted substantially, with venture capital funding decreasing from a peak of $18.0 billion in 2021 to $6.8 billion in 2023. This downturn was particularly pronounced in certain downstream applications, such as GPS-enabled services, which experienced steep declines. However, this contraction should be interpreted not as a market failure but as a rationalization, purging the speculative excess of the preceding years. The market has since stabilized at a substantial level, with analysis from BryceTech indicating that private investment into start-up space companies held steady at $7.8 billion globally in 2024.

This stabilization has been accompanied by a significant realignment of investment strategy. Recent trends, such as the $1.9 billion in global space investment recorded in the third quarter of 2024, are driven by a "growing alignment between space technologies and national defense agendas" and the increasing demand for dual-use technologies. This indicates a shift in investor preference toward companies with robust fundamentals and stable contracts. In the current risk-averse macroeconomic climate, investors are increasingly utilizing government spending as a mechanism for de-risking financial exposure. This has created a new, hybrid funding model where public expenditure acts as a powerful catalyst for private capital. Government contracts provide a revenue floor and a validation of technology, thereby lowering the cost of capital for strategically important companies and creating a symbiotic relationship where the public sector gains access to private-sector innovation and private investors gain the security of government backing.

This trend also suggests that the once-globalized ideal of "New Space" is beginning to fragment along geopolitical lines. Investment is increasingly flowing into companies that serve national, rather than purely international, commercial interests. The surge in European venture capital funding for Defence, Security, and Resilience (DSR) startups, driven by entities like the NATO Innovation Fund, alongside the dominance of U.S. and Chinese capital in their respective domestic markets, indicates that the flow of private investment is no longer a purely market-driven phenomenon. It is being heavily influenced by national strategic priorities, implying a more balkanized global space industry where a company's alignment with national security goals is becoming a key determinant of its ability to attract funding.

2.4.3 Business Models

The economic expansion of the Space Economy is being enabled by a paradigm shift in commercial strategy, moving away from traditional manufacturing-centric models toward more flexible, scalable, and service-oriented approaches. This evolution is critically dependent on the integration of advanced digital technologies, which are unlocking new efficiencies and creating novel value propositions.

The dominant emerging business model is Space-as-a-Service (SPaaS), a framework wherein profitability is shifted from the one-time sale of hardware, such as satellites and launch vehicles (upstream), to the recurring revenue generated by monetizing the data and services they deliver (downstream). This model mirrors the cloud computing revolution, allowing customers to rent access to space-based capabilities—such as Earth observation data, satellite communications bandwidth, or payload hosting—on a subscription or pay-as-you-go basis. By obviating the need for massive upfront capital expenditure on proprietary infrastructure, SPaaS effectively "democratizes" access to space, enabling a wider range of industries and smaller enterprises to leverage space-based assets that were previously beyond their financial reach. This "as-a-service" logic is proliferating across the entire value chain, creating a modular ecosystem of specialized providers offering everything from "Ground Station-as-a-Service" to "Payload-as-a-Service".

Crucial to achieving the efficiency and scalability required by the SPaaS model is the incorporation of advanced technologies, most notably Artificial Intelligence (AI). AI is bringing profound value and efficiency to the space industry in applications ranging from the initial processing of raw satellite data to running complex simulations on digital twins of in-orbit assets. The relationship between AI and SPaaS is not merely additive; AI functions as the essential scalability engine that makes the model economically viable, particularly for large satellite constellations. First, it enables the autonomy required to manage the operational complexity of constellations numbering in the hundreds or thousands of satellites, handling tasks like health monitoring, tasking, and collision avoidance that would be impossible to perform manually. Second, AI-powered edge computing on satellites allows for the on-orbit processing of vast data streams, ensuring that only valuable, actionable insights—rather than petabytes of raw data—are transmitted to the ground. This overcomes a critical data downlink bottleneck and dramatically improves operational efficiency.

However, this deep reliance on AI introduces new and significant managerial complexities and risks. As the industry integrates these systems more deeply, "questions remain around if and how to regulate AI systems to prevent ethical and cybersecurity risks". The full growth potential of AI-driven business models cannot be realized until a stable and predictable regulatory framework is established. Such a framework is not a hindrance to innovation but rather a necessary precondition for building long-term market confidence and attracting sustained investment. The successful development of clear governance for AI in space will therefore be a critical determinant of financial success and the ultimate trajectory of the service-based space economy.

Chapter 3

The Lunar Exploration

More than half a century after the last human footstep on its surface, the Moon has returned to the center of humanity's ambitions. However, today's context is radically different from that of the 20th-century Space Race. Programs like Artemis represent a fundamental paradigm shift: no longer a demonstration of geopolitical supremacy culminating in brief sorties, but the beginning of a strategic endeavor aimed at establishing a sustainable, long-term human presence [51]. The stated goal is not simply to return to the Moon, but to "go to stay." This new chapter of space exploration is underpinned by a powerful convergence of strategic, scientific, and, above all, commercial imperatives, which together outline a vision for humanity's future beyond Earth's orbit.

The central thesis of this analysis is that the return to the Moon is driven by a strategic synergy among three interdependent and mutually reinforcing pillars. First, the Moon serves as an indispensable testbed and logistical springboard for the next great leap in human exploration: a crewed mission to Mars. Second, our satellite offers an unprecedented scientific opportunity to decipher the secrets of the Solar System's formation and to open a new window into the primordial universe. Finally, and with increasing emphasis, the return to the Moon is propelled by the commercial imperative to catalyze and cultivate a new and robust cislunar economy, an ecosystem of industries and services extending from Earth to lunar orbit.

3.1 Moon To Mars

Humanity's return to the Moon is not an end in itself, but the first, crucial chapter of a long-term exploration strategy whose ultimate horizon is Mars [51]. The "Moon to Mars" approach adopted by NASA and its international partners is not a simple sequence of destinations, but a deliberate methodology to progressively mitigate the risks associated with a crewed interplanetary mission [52]. The Moon, just a three-day journey from Earth, offers a relatively accessible deep-space environment where the technologies, systems, and operational procedures necessary to survive and work for years millions of kilometers from home can be tested, validated, and perfected.

The challenge of a Mars mission is an order of magnitude greater than anything previously attempted. Systems will need to operate reliably for years, not days, with near-total autonomy due to significant communication delays.1 The Moon thus serves as a high-fidelity testbed, superior to any terrestrial or low-Earth orbit simulation, for so-called "Mars-forward capabilities" [53]. These capabilities include:

- **Long-Duration Systems:** The Artemis missions envision the construction of permanent infrastructure such as the Lunar Gateway in orbit and the Artemis Base Camp on the surface [51]. These platforms will allow for the testing of the long-term reliability of habitats, closed-loop life support systems, power generation and storage systems, and communication technologies in the harsh deep-space environment, characterized by radiation and extreme temperatures [51].

- **Surface Operations and Extravehicular Activities (EVAs):** EVAs on the lunar surface will allow astronauts to practice and optimize procedures that will be essential on Mars, such as collecting geological samples, maintaining equipment, and constructing infrastructure [53]. They will face similar environmental challenges, such as managing abrasive dust and operating in partial gravity, which, although different ($g_{Moon} \approx \frac{1}{6} g_{Earth}$ versus $g_{Mars} \approx \frac{1}{3} g_{Earth}$), will provide irreplaceable operational data to improve efficiency and safety [53].

- **Advanced Power Systems:** A Martian base will require a constant and powerful energy source, which will most likely be nuclear. The Moon is considered the ideal location to safely prototype and test a surface fission reactor, reducing the risks associated with implementation, cable deployment, long-term operation, and interaction with crew operations before committing such a critical technology to a Martian mission.

- **In-Situ Resource Utilization (ISRU):** The ability to "live off the land" is fundamental to the sustainability of a long-term presence on Mars. The Moon offers the opportunity to demonstrate the entire ISRU supply chain, from the extraction of water ice to the production of oxygen, water, and propellant. Mastering these technologies on the Moon is an essential step to validate models and reduce uncertainty before relying on them for survival on Mars [53].

Also, another important aspect about "Moon to Mars" strategy reveals that a more critical objective is the reduction of risk associated with the human factor [52]. A mission to Mars will expose crews to an unprecedented set of physiological and psychological stressors, including prolonged exposure to deep-space radiation, the combined effects of months of microgravity during transit and years in partial gravity on the surface, extreme isolation, and the impossibility of a rapid return to Earth [53, 52]. These long-duration missions on the Moon will serve as high-fidelity "analogs" to study human responses. They will allow for the collection of critical data on how the body adapts to prolonged periods in a deep-space environment and how the crew can maintain optimal performance under conditions of isolation and autonomy. NASA's strategic document "Mars-Forward Capabilities to be Tested at the Moon" explicitly mentions the need for "extended-duration analogs in the lunar vicinity" to study rapid acclimation to partial gravity excursions and the impact of long stays in microgravity aboard the Gateway, coupled with surface work [52]. The strategy shifts from simply "how do we build things" to the more complex "how do we keep humans alive, healthy, and productive for years far from Earth."

3.2 Scientific Motivations

Beyond its strategic role as a springboard to Mars, the Moon remains a scientific destination of primary importance [54]. Unlike Earth, a geologically dynamic planet whose primordial history has been largely erased by billions of years of tectonic activity, erosion, and volcanism, the Moon is a relatively inert planetary body. Its surface is an extraordinarily well-preserved archive, a time capsule that records 4.5 billion years of the inner Solar System's history. The Artemis missions, with their ability to access new regions and return samples more strategically than during the Apollo era, promise to revolutionize our understanding of planetary origins and our place in the cosmos.

3.2.1 Lunar Geology

Lunar geology offers a direct window into the fundamental processes that have shaped all rocky planets, including Earth. The analysis of new samples, particularly from unexplored regions like the South Pole-Aitken basin—the largest and oldest impact basin in the Solar System—can provide answers to fundamental questions that remain unresolved:

The leading theory suggests that the Moon formed from a cataclysmic impact between the proto-Earth and a Mars-sized body about 4.5 billion years ago. This event would have melted a large portion of both bodies, leading to the formation of a global “magma ocean” on the young Moon. The analysis of primordial rocks from the lunar mantle, potentially exposed by the South Pole-Aitken impact, could provide definitive evidence for this model and refine our understanding of this crucial event.

Analysis of Apollo samples suggests that the Moon (and, by extension, the entire inner Solar System) underwent a period of exceptionally intense meteorite bombardment between 4 and 3.85 billion years ago. This event would have had profound implications for the evolution of the early Earth and the origin of life. New samples from different impact basins can help confirm or refute this hypothesis, determining whether it was a sudden spike in impacts or the tail end of a more constant bombardment.

By studying the differentiation of the lunar crust and mantle and the history of its volcanism, geologists can better understand the basic processes of a rocky planet's evolution, a record that has been almost completely overwritten on Earth.

3.2.2 Lunar Radio Quiet Area

The far side of the Moon, the one that never faces Earth due to tidal locking, is a unique location in the Solar System. It is the only truly “radio-quiet” reachable environment, shielded by the Moon's rocky mass from all powerful radio-frequency interference (RFI) generated by Earth, both anthropogenic (telecommunications, radar) and natural. This cosmic radio silence opens the door to revolutionary astronomical observations, impossible to conduct from the Earth's surface or low orbit.

The installation of large low-frequency antenna arrays on the far side of the Moon, such as the proposed Lunar Crater Radio Telescope (LCRT), would open an unprecedented window into the universe, owing to its unique environment shielded from terrestrial radio interference [55]. Such an observatory would make it possible to probe the cosmic "Dark Ages" by studying the primordial hydrogen signal at ultra-low frequencies, allowing for observation of the universe before the formation of the first stars and galaxies and thus revolutionizing cosmology. Furthermore, it could discover and characterize exoplanets by detecting their radio emissions, offering a novel method for assessing their habitability [56]. The Moon would become an ideal site for low-frequency gravitational wave detectors, capable of sensing cosmic events like the mergers of supermassive black holes—phenomena beyond the reach of terrestrial observatories such as LIGO/Virgo [56].

3.2.3 The Science of In-Situ Resources

The discovery of significant quantities of water ice and other volatiles trapped in the Permanently Shadowed Regions (PSRs) at the lunar poles has transformed our view of the Moon, from an arid world to one with potentially accessible resources. While the commercial implication of this discovery is immense, its scientific importance is equally profound. The Artemis missions aim to conduct “ground truth”—the direct sampling and analysis of these deposits—to answer crucial scientific questions [54].

The scientific exploration of lunar volatiles is not an academic activity for its own sake; it is, for all intents and purposes, the geological prospecting phase that enables the entire business model of the cislunar economy. Science is, quite literally, creating the treasure map that commercial enterprises will follow. The entire concept of ISRU and a sustainable lunar economy is founded on the availability of local resources, primarily wate [54].

However, the existence, exact location, concentration, purity, and accessibility of this water are still unknowns that only scientific exploration can resolve. Orbital missions like the Lunar Reconnaissance Orbiter (LRO), with instruments such as the Lunar Exploration Neutron Detector (LEND), have provided the first maps indicating high concentrations of hydrogen (a proxy for water) in the cold traps of the PSRs. The Artemis III and subsequent surface missions will land in these regions precisely to perform in-situ verification [54]. The analysis of these ancient ices will allow us to determine:

- **Origin and Delivery of Water in the Solar System:** The isotopic composition of lunar ice can reveal whether its origin is linked to impacts from comets and asteroids, primordial volcanic outgassing, or the interaction of the solar wind with the regolith. This would provide fundamental clues about the history of the delivery of water and organic compounds to the inner planets, including Earth, with profound implications for understanding the origin of life.
- **Lunar Polar Processes:** Studying how volatiles migrate and are trapped in the PSRs will help us understand the dynamic processes operating on the lunar surface and on other airless bodies in the Solar System.

In this sense, the investment in scientific missions to characterize lunar resources is a direct investment in risk reduction for future commercial ventures. Without reliable scientific data on the availability and accessibility of resources, no private actor could justify the enormous capital required to develop extraction and processing infrastructure. Science, therefore, is not just a parallel motivation but a fundamental economic enabler for the commercial future of the Moon [54].

3.3 Commercial Motivation

If the “Moon to Mars” strategy provides the direction and science offers the knowledge, it is the commercial imperative that provides the economic engine for a sustainable human presence in space. Unlike the Apollo program, which was entirely funded by public money for geopolitical purposes, the Artemis era is defined by an intrinsic partnership between government agencies and the private sector.

NASA's strategy is no longer to be the sole actor, but to act as an "anchor customer" to stimulate demand, catalyze innovation, and foster the emergence of a self-sustaining cislunar economy [54]. This approach aims to reduce costs, accelerate technological development, and create a market where NASA becomes one of many customers, rather than the sole funder.

At the heart of this economic vision is the concept of In-Situ Resource Utilization (ISRU).

3.3.1 ISRU: The Cornerstone of the Cislunar Economy

ISRU is the process of collecting, processing, and utilizing materials found or manufactured on other celestial bodies to reduce dependence on supplies from Earth. The cost of launching mass from Earth is the primary limiting factor in space exploration. ISRU promises to break this "tyranny of the rocket equation" by transforming the Moon from a mere destination into a source of strategic resources.

The most critical and immediately accessible resource is the water ice found in the Permanently Shadowed Regions (PSRs) near the lunar poles. Once extracted, this ice can be purified and then split via electrolysis into its components, hydrogen and oxygen. These two elements are the basis for the two most important initial markets of the lunar economy [54]:

- **Life Support Consumables:** Oxygen for breathing and potable water are essential to sustain crews in surface habitats or orbital stations. Producing them on-site drastically reduces the mass that must be launched from Earth for long-duration missions.
- **Rocket Propellant:** Liquid oxygen (LOX) and liquid hydrogen (LH_2) are one of the most efficient chemical propellants known. Their production on the Moon is considered the true economic "game-changer." The vast majority of a spacecraft's mass destined for travel beyond Earth orbit is propellant. Producing it in space, where the gravity to be overcome for launch is only one-sixth of Earth's, offers an overwhelming economic and logistical advantage.

3.3.2 Space Propellant

The ability to produce propellant on the Moon has the potential to create an entirely new economic infrastructure, transforming deep-space logistics. A "propellant depot" or "gas station" in cislunar orbit, such as at the Gateway, supplied by reusable landers from the lunar surface, would radically change the architecture and economics of space missions.

This space propellant market would serve several segments:

- **Satellite Life Extension:** Many satellites in geostationary orbit are decommissioned not because their electronics fail, but because they run out of the propellant needed for station-keeping. In-orbit servicing vehicles, refueled with lunar propellant, could extend the operational life of these multi-billion-dollar assets.
- **Sustainable Cislunar Transportation:** Lunar landers, space tugs, and transfer vehicles between Earth and the Moon could be fully reusable, refueling in orbit instead of being single-use vehicles or having to carry all the propellant for the return journey from Earth.
- **Enabling Mars Missions:** A human mission to Mars requires an enormous amount of propellant for the trans-Mars injection phase (the push to leave the Earth-Moon system and head towards Mars). Assembling and refueling the Mars vehicle in cislunar orbit with propellant produced on the Moon would drastically reduce the mass that needs to be launched from Earth's deep gravity well, making the entire enterprise significantly more affordable and feasible.

This paradigm shift is at the core of the Artemis commercial strategy. Programs like the CLPS and the awarding of the *Human Landing System* (HLS) contract to commercial partners like SpaceX and Blue Origin are not simple procurement contracts. They are strategic investments aimed at creating independent industrial capabilities. The long-term goal is for these companies not only to serve NASA but to develop a diversified customer portfolio, creating a self-sufficient lunar economy in which NASA is just one of many players [54]. This represents a fundamental change in the role of government in space exploration: from the sole actor to a catalyst and facilitator of a commercial market. The strategic objective is not just to land on the Moon, but to make economic activity in cislunar space routine [54].

3.3.3 Helium-3 and Other Resources

In a longer-term perspective, the Moon hosts other resources of potential economic value. The most discussed is Helium-3 (^{3}He), a light isotope of helium that is extremely rare on Earth but abundant in the lunar regolith, where it has been implanted by the solar wind for billions of years, as the Moon is not protected by a magnetic field.

The interest in Helium-3 stems from its potential as a fuel for second-generation nuclear fusion reactors. The Deuterium–Helium-3 fusion reaction ($D+^3\text{He} \rightarrow$

$p+^4$He) produces energy by releasing primarily charged particles (protons) instead of high-energy neutrons, as in the Deuterium–Tritium (D–T) reaction. This would make it inherently safer, produce less radioactive waste, and allow for a more efficient conversion of energy into electricity.

It is estimated that about 25 tons of Helium-3 could meet the annual energy needs of the United States, with a potential value estimated at around $3 billion per ton. However, the extraction of Helium-3 presents immense challenges. The concentrations in the regolith are very low, requiring the mining and heating of enormous quantities of lunar soil. Furthermore, Helium-3 fusion reactor technology is still in the theoretical stage and has not been demonstrated on a commercial scale. Despite these difficulties, interest remains high, as evidenced by China's recent discovery of the mineral Changesite-(Y), which contains Helium-3 and has reinvigorated geopolitical interest in lunar resources.

Other potential resources include metals such as titanium (abundant in the mineral ilmenite), aluminum, and iron, which could be extracted from the regolith for the on-site production of components and structures, further reducing the need for materials from Earth.

3.4 Benefits for Earth

Space exploration has historically been one of the most powerful engines of technological innovation. The extreme challenges posed by operating in hostile environments like the Moon compel engineers and scientists to push the limits of existing technology, generating discoveries and capabilities that often find transformative applications on Earth. This phenomenon, known as technological "spinoff," represents an indirect but extremely significant return on investment (ROI).

While the direct cislunar economy, based on resource extraction, is a long-term goal, the most powerful and immediate economic driver of the return to the Moon is its ability to catalyze innovation in key sectors, generating tangible benefits and new markets on Earth.

The history of the Apollo program clearly demonstrates this. Although not conceived as an economic project, it generated an estimated ROI of between $7 and $8 for every dollar spent, primarily through technological spinoffs that fueled the digital revolution (e.g., microchips, structural analysis software) and improved countless aspects of daily life. Current estimates suggest the potential return is even greater today, with projections indicating that every dollar invested in basic space research could generate up to $40 in economic growth on Earth. The Artemis era is already following this pattern, pushing innovation in at least three crucial areas with direct terrestrial applications: advanced robotics, additive manufacturing, and closed-loop life support systems.

3.4.1 Advanced Robotics and Artificial Intelligence

The extreme and hazardous lunar environment—characterized by vacuum, severe temperature changes, abrasive dust, and communication delays—is a key driver for developing highly autonomous and intelligent robots. To succeed, these robots must be capable of navigating unknown terrain, manipulating objects, collaborating, and making decisions without direct human control.

Space agencies are actively developing these next-generation systems. Examples include NASA's CADRE, a team of cooperative mapping rovers; Canadarm3, an autonomous arm for the Gateway space station; and GLIMPSE, a four-legged rover for rugged polar terrain. These systems are powered by advanced AI, computer vision, and predictive control.

The technology developed for these space missions has high-value applications on Earth. In medicine, it has led to telerobotic microsurgery systems like neuroArm and minimally invasive robots like MIRA. In other industries, these robots can be adapted for disaster response, maintenance of critical infrastructure (like nuclear plants), and remote mining exploration in hazardous or inaccessible areas.

3.4.2 Additive Manufacturing and Sustainable Construction

3D printing (additive manufacturing) is considered fundamental for building infrastructure on the Moon (ISRU), as it allows local regolith to be used as a raw material, drastically reducing the need to transport heavy materials from Earth. This technological push is already generating commercial applications on Earth: companies like AI SpaceFactory, inspired by NASA challenges, are developing large-scale 3D printers for the construction industry. These machines use innovative "inks" that mix polymers, often derived from recycled plastic waste, with local fillers such as soil, sand, or debris. This approach promises to revolutionize construction on Earth, making it faster, cheaper, and more sustainable, with potential applications ranging from low-cost housing to the creation of environmentally friendly infrastructure, while simultaneously reducing the environmental impact associated with cement production.

3.4.3 Life Support Systems (LLS)

The development of bioregenerative closed-loop systems (BLSS) is critical for the viability of long-duration human space exploration, representing a paradigm shift from the partially regenerative life support systems currently reliant on terrestrial resupply. These advanced systems, exemplified by research programs such as ESA's MELiSSA and NASA's ACLS, are engineered as miniature artificial ecosystems.

They integrate physicochemical and biological processes—utilizing microbes, algae, and higher plants—to achieve near-total recycling of air, water, and waste, alongside in-situ food production. Concurrently, the intensive research required to "close the loop" is generating significant terrestrial spinoffs. These innovations span multiple sectors, including advanced water purification technologies applicable to arid or urban environments, novel discoveries in biomedicine (such as a cholesterol-reducing bacterium), advanced sensors for industrial fermentation, and the proliferation of controlled-environment agriculture techniques (e.g., hydroponics, aeroponics) now enhancing urban and vertical farming sustainability.

The most solid economic justification for public investment in the return to the Moon over the next decade lies not so much in the still uncertain and long-term value of lunar resources, but in the current and future value of technological spinoffs that solve urgent problems on Earth, create new industries, and increase global economic competitiveness. This indirect ROI is a strategic, quantifiable, and historically proven benefit of space exploration.

3.5 Governmental Programs & Missions

3.5.1 The United States (NASA)

At the forefront of the renewed global focus on lunar exploration is the United States' National Aeronautics and Space Administration (NASA), whose efforts are consolidated under the comprehensive Artemis program. The overarching goal of Artemis is to establish a sustainable, long-term human presence on the Moon, serving as a foundation for scientific discovery, economic development, and as a crucial proving ground for the technologies and operational strategies required for future crewed missions to Mars [51]. This represents a significant strategic evolution from the sortie-style missions of the Apollo era, which were focused on singular achievements, to a programmatic, multi-decade endeavor designed to build a permanent foothold in deep space. The program is structured as a series of missions with progressively increasing complexity, each building upon the capabilities of the last [51]. This incremental approach underpins a broader strategy where NASA acts not just as an explorer, but as the primary architect of a Western-led international and commercial deep-space consortium. By integrating partners into its core architecture, NASA is positioning its technological standards and policy frameworks, such as the Artemis Accords, to become the de facto norms for cislunar activities [57].

The architecture of the Artemis program is built upon several key technological pillars [51].

The mission roadmap is methodical: Artemis I, an uncrewed flight test of the integrated SLS and Orion system, was successfully launched on November 16, 2022, validating the spacecraft's performance and heat shield during a high-velocity reentry [51]. Artemis II will be the first crewed flight, sending four astronauts on a circumlunar trajectory to test Orion's life support systems with humans aboard [58].This will be followed by Artemis III, the mission slated to land the first woman and first person of color on the lunar surface [59], targeting the resource-rich south polar region. Subsequent missions, such as Artemis IV, will focus on the assembly of the lunar Gateway, an orbiting outpost that will serve as a staging point for surface missions [60].

A cornerstone of NASA's strategy to foster a lunar economy is the Commercial Lunar Payload Services (CLPS) initiative [31]. This innovative program shifts the procurement model from traditional government-owned hardware development to the purchase of end-to-end commercial delivery services from a pool of American companies [31]. By acting as an anchor tenant, NASA guarantees a market for these services, thereby de-risking private investment and stimulating a competitive industrial base capable of serving a broader customer base in the future [51] [31]. The initiative is designed to rapidly deploy scientific and technological payloads to the lunar surface, gathering vital data ahead of crewed landings [31]. Through CLPS, NASA is not just exploring the Moon; it is actively cultivating a self-sustaining commercial marketplace in cislunar space.

3.5.2 European Space Agency (ESA)

The European Space Agency (ESA) plays a pivotal role in the development of critical infrastructure for lunar exploration, positioning Europe as a key partner in the international return to the Moon. ESA's contributions encompass logistics, communications, navigation, and crewed mission support, under both collaborative and independent frameworks.

One of ESA's cornerstone projects is the Argonaut lander (formerly the European Large Logistics Lander, or EL3), a fully European autonomous cargo vehicle capable of delivering up to 1,500 kg of payload to the lunar surface [61]. Developed by an industrial consortium led by Thales Alenia Space, and launched aboard an Ariane 64 rocket, Argonaut is designed for versatility and longevity, with a surface lifetime of up to five years. It will be able to deploy scientific instruments, rovers, and infrastructure elements essential for the establishment of a sustainable lunar base [61]. The inaugural mission, ArgoNET, planned for 2031, will deliver key navigation, energy, and telecommunications components to the lunar surface [61]. This capability grants Europe the strategic autonomy to pursue scientific objectives—such as the proposed far-side Astrophysical Lunar Observatory—and to participate in international partnerships on its own terms.

In parallel, ESA is developing the Moonlight initiative, a constellation of communication and navigation satellites intended to provide continuous, high-bandwidth services to lunar missions [62]. Conceived as a commercial service led by a consortium including Telespazio, Moonlight will function as a lunar analogue to terrestrial GPS and telecommunications systems [62, 63]. This infrastructure aims to simplify future mission architectures by eliminating the need for each spacecraft to carry its own direct-to-Earth communication hardware, thereby reducing mass and cost while enabling continuous operations, even on the lunar far side [62, 63].

ESA's most significant contribution to the Artemis Program is the European Service Module (ESM) for NASA's Orion spacecraft, developed by a consortium led by Airbus [51, 63]. The ESM provides propulsion for lunar orbit insertion, electrical power through its 19-meter solar arrays, and critical life-support systems for astronauts. Contracts are in place for ESMs supporting missions up to Artemis VI, securing ESA's role as an indispensable partner in every crewed Artemis flight [63].

Beyond Orion, ESA contributes significantly to the development of the Lunar Gateway, building two primary modules: the Lunar I-Hab, a habitation module designed for crew operations, and Lunar View, which provides refueling, storage, and observation capabilities, including the station's main windows toward the Moon and deep space [63]. ESA is also developing the Lunar Link system, ensuring robust telecommunications support for the orbiting outpost.

Through this deep integration into the U.S., ESA is strategically reinforcing Europe's long-term position in lunar exploration. This combination of interdependence and independence ensures that Europe remains central to both collaborative and sovereign efforts in the emerging lunar economy.

3.5.3 China (CNSA & PLA)

The Chinese Lunar Exploration Program (CLEP), known as the Chang'e Project, is defined by its deliberate, methodical, and highly successful phased approach to exploration [64]. Each of its four phases has been designed to build technologically upon the last, creating a steady and impressive progression of capabilities. Phase I successfully placed two orbiters, Chang'e 1 and 2, around the Moon to create high-resolution surface maps [64]. Phase II achieved robotic surface operations with the Chang'e 3 lander and rover on the near side, followed by the historic Chang'e 4 mission, which performed the world's first-ever soft landing on the lunar far side [64]. Phase III mastered sample return with Chang'e 5 [65], which brought back 1,731 grams of the youngest lunar samples ever collected. China is now in Phase IV, its most ambitious yet, which focuses on establishing a robotic research station at the lunar south pole as a precursor to a permanent base [64].

The missions of Phase IV are designed to push the frontiers of science and technology. The Chang'e 6 mission, launched in May 2024, achieved another historic first by successfully collecting and returning samples from the Moon's far side, specifically from the vast and ancient South Pole-Aitken (SPA) basin.[20, 21, 23] Analysis of this material is expected to provide unprecedented insights into the early history of the Solar System and the geological dichotomy between the Moon's two hemispheres [66].The upcoming Chang'e 7 mission, planned for around 2026, will be a comprehensive exploration of the south pole, comprising an orbiter, lander, rover, and a novel mini-flying probe designed to enter and directly analyze the contents of permanently shadowed regions (PSRs) for water ice [64]. Following this, Chang'e 8, planned for around 2028, will be a critical technology demonstration mission focused on In-Situ Resource Utilization (ISRU). It will test key technologies for a future base, such as 3D printing structures using lunar regolith [64].

These missions are the building blocks for China's grandest lunar ambition: the International Lunar Research Station (ILRS) [67]. Co-led by the China National Space Administration (CNSA) and Russia's Roscosmos, the ILRS is a direct counterpart to the U.S.-led Artemis program [67]. In response to its effective exclusion from Western-led efforts by U.S. legislation, China has leveraged its demonstrated technological self-sufficiency to create a parallel cooperative framework. The ILRS is explicitly open to all international partners and has already attracted a number of countries, including Pakistan, South Africa, Egypt, and Thailand, among others [67]. With a clear roadmap for reconnaissance, construction, and utilization phases, and with plans for a crewed Chinese landing by 2030, the ILRS is being positioned as a viable and attractive alternative for nations not aligned with the Artemis program [67]. This development is actively shaping a bipolar geopolitical order for the future of lunar exploration and settlement.

3.5.4 Other Countries

Beyond the major established players, several other nations are making significant strides in lunar exploration, often through specialized capabilities and strategic partnerships. Japan's Aerospace Exploration Agency (JAXA) has established a leadership role in precision landing technology, successfully demonstrating a "pinpoint" landing with its Smart Lander for Investigating Moon (SLIM) mission in January 2024 [68, 69]. This capability makes JAXA a valuable contributor to the U.S.-led Artemis program, for which it is developing Gateway modules and a pressurized rover, and a crucial partner in other ventures [63, 61, 68].

The Indian Space Research Organisation (ISRO) achieved a landmark success with its Chandrayaan-3 mission in August 2023, becoming the fourth nation to soft-land on the Moon and the first to do so in the south polar region [70]. This achievement, following the instrumental water-discovery mission Chandrayaan-1 and the partially successful Chandrayaan-2, was accomplished on a remarkably modest budget, positioning India as a highly capable and cost-effective partner in deep-space exploration [70, 71]. The strategic partnership between Japan and India is exemplified by the joint Lunar Polar Exploration Mission (LUPEX), planned for no earlier than 2028, in which ISRO will develop the lander to deliver a JAXA-built rover to the lunar pole [72, 73].

Emerging space-faring nations are also marking their presence. The United Arab Emirates, through the Mohammed Bin Rashid Space Centre (MBRSC), is pursuing the Emirates Lunar Mission with its series of "Rashid" rovers. Despite the loss of the first rover on a failed private landing attempt in 2023, a successor mission is underway [74, 75]. The UAE has adopted a flexible, multi-aligned space policy as a signatory of the Artemis Accords while also expressing interest in the China-led ILRS [57, 76]. South Korea's Korea Aerospace Research Institute (KARI) successfully placed its first lunar spacecraft, the Danuri orbiter, into orbit in December 2022. The orbiter is currently conducting a comprehensive mapping campaign, utilizing instruments such as the NASA-provided ShadowCam to search for water ice in permanently shadowed craters, as a precursor to a planned robotic landing by 2033 [77, 78].

3.6 Lunar Technologies

The establishment of a permanent human presence on the Moon, serving as a planetary laboratory and a stepping stone to Mars, depends on an ecosystem of interconnected technologies. This section analyzes the critical technological areas required to create a sustained lunar architecture: launch systems, landing systems, surface mobility, mission payloads, and surface infrastructure.

3.6.1 Launch Systems

The lunar transportation market is characterized as a hybrid ecosystem, juxtaposing government-led programs, such as NASA's non-reusable Space Launch System (SLS), with commercial competitors. This sector is being revolutionized by entities like SpaceX, whose fully reusable Starship vehicle aims to fundamentally reduce launch costs. This market also includes Blue Origin's partially reusable New Glenn and sovereign capabilities developed by international programs in China and ESA, collectively creating a global market with divergent reusability strategies.

3.6.2 Landing Systems

Human Landing Systems (HLS)
For human-rated landers, NASA has adopted a competitive, service-based procurement model, funding parallel designs from partners including SpaceX and Blue Origin. This strategy is intended to stimulate a commercial market and mitigate

programmatic risk. Competing philosophies are evident: Blue Origin's strategy relies on industrial alliances and compatibility with future In-Situ Resource Utilization (ISRU) derived propellants, whereas SpaceX's vertically integrated approach represents a high-risk, high-reward dependency on in-orbit refueling capabilities.

Robotic and Commercial Cargo Landers
A commercial market for lunar logistics is being actively cultivated via NASA's Commercial Lunar Payload Services (CLPS) initiative. By serving as an anchor customer, NASA fosters innovation while accepting a higher mission risk tolerance for reduced costs, an approach validated by the success of entities such as Intuitive Machines, Astrobotic and iSpace [79, 80, 81]. Europe is concurrently developing its own sovereign capability, the Argonaut lander [61], to compete in this emergent global economy.

3.6.3 Surface Mobility Platforms (Rovers)

Crewed Mobility: The Lunar Terrain Vehicle (LTV)
For crewed surface transport, NASA has transitioned to a "Mobility-as-a-Service" model, acting as an anchor customer to catalyze a commercial market. The LTV is specified for dual-use (both crewed and remote-controlled cargo operations) to maximize asset utilization. To foster a competitive environment, NASA has awarded parallel development contracts to three distinct industry consortia.

Robotic Mobility
The robotic mobility sector provides essential support services. This includes versatile, standardized platforms designed to reduce mission costs, such as ESA's EMRS, as well as advanced, specialized robotics pursued by China. NASA's CLPS program leverages smaller, agile missions to validate next-generation technologies, including multi-robot autonomy. There are two main type of rover: crewed rovers and uncrewed rovers. The primary objective of the first group is to facilitate the transportation of astronauts around the lunar surface, with the option of either an open or pressurised cabin. The second group comprises autonomous or remotely operated robotic vehicles that are utilised for the investigation of extraterrestrial surfaces or the execution of tasks that are not feasible for astronauts.

3.6.4 Mission Payloads

In-Situ Resource Utilization (ISRU)
The transition to a sustainable, self-sufficient lunar presence is contingent on ISRU: the practice of using local materials to supplant terrestrial supplies. This involves a complex process chain. **Prospecting** utilizes a two-tiered approach, combining

broad orbital surveys (e.g., LRO) with surface missions that provide "ground truth" verification to establish a business case for extraction. **Water ice extraction**, a cornerstone for life support and propellant, is being de-risked via pilot projects (e.g., PRIME-1) to validate the economic viability of energy-intensive techniques like thermal mining. **Oxygen production** is focused on Molten Regolith Electrolysis (MRE), a technology favored for its dual output of propellant and valuable metallic byproducts, positioning it as a key element of a vertically integrated industrial model. The long-term strategy is an industrial ecosystem utilizing **in-situ manufacturing feedstock** for additive construction and 3D printing, transforming the Moon into a logistics hub.

Advanced Environmental Control and Life Support Systems (ECLSS)
For long-duration missions, regenerative systems are critical. **Portable Life Support Systems (PLSS)** for extravehicular activity are shifting from a disposable, consumables-based model to a reusable asset model employing regenerable technologies, such as Pressure Swing Adsorption (PSA) for CO2 removal. For habitats, the primary business driver is achieving the highest "degree of closure." The ultimate objective is a fully bioregenerative system, exemplified by ESA's MELiSSA project, which aims to create a closed-loop artificial ecosystem, or a true circular economy, by recycling all waste into oxygen, water, and food.

3.6.5 Surface Infrastructure

Surface Power Generation and Distribution
A reliable power supply is the most fundamental requirement for a lunar base, necessitating a hybrid architecture. **Solar power**, while mature, is challenged by abrasive dust and the 14-day lunar night. This is mitigated by selecting polar sites with near-permanent sunlight and employing Vertical Solar Array Technology (VSAT). For continuous, sun-independent power, **nuclear fission** is the key enabling technology. The NASA/DOE Fission Surface Power (FSP) project is de-risking a 40 kWe system as a foundational utility. **Energy storage** for solar systems is mass-prohibitive for Li-ion batteries; thus, more mass-efficient Regenerative Fuel Cell (RFC) systems are preferred. A sophisticated Power Management and Distribution (PMAD) grid is also required.

Habitation Systems and Surface Construction
Habitation strategy follows a phased evolution. It begins with low-risk, low-scalability **prefabricated modules** or mass-efficient **inflatable habitats**. The long-term solution lies in naturally shielded **subsurface structures** (e.g., lava tubes) or, more transformatively, **additive construction** using lunar regolith. This

on-site manufacturing is being pursued by public-private partnerships (NASA/I-CON) and state-led initiatives (China's Chang'e 8). The operational strategy will evolve from importing habitats, to using local regolith for shielding, to a final phase of full-scale construction where only high-value equipment is imported.

Lunar Communications and Navigation Infrastructure
Increased lunar activity necessitates a dedicated, interoperable network, as the Apollo-era direct-to-Earth model is an untenable bottleneck. NASA's **LunaNet** framework provides the "software" layer: a set of common standards and protocols for a "network of networks." The "hardware" layer is being developed by initiatives like ESA's **Moonlight**, a dedicated satellite constellation providing commercial-grade communication and navigation services interoperable with LunaNet. This orbital PNT (Position, Navigation, and Timing) architecture will be augmented by surface-based beacons for high-precision local positioning, creating a common utility that lowers the barrier to entry for commercial ventures.

Chapter 4

The Lunar Economy

The Lunar Economy refers to all economic activities on the Moon, in lunar orbit, and between Earth and the Moon. It is expected to involve several key markets, and its divided in three main segment:

- **Lunar transportation:** this first segment encompasses cislunar space and lunar orbits, including travel routes between Earth and the Moon. It is driven primarily by the need to ferry humans and resources to and from the Moon to develop our presence in its vicinity and on its surface [82].

- **Lunar data:** this second part involves utilizing data collected during lunar missions for applications on Earth. This primarily consists of technical data that supports the preparation of space missions and research on space resources. To a lesser extent, it also includes entertainment data for various leisure applications [82].

- **In-situ resource utilization (ISRU):** This includes activities such as mining, manufacturing, infrastructure development, and the export of goods and materials. These efforts can serve scientific purposes, support a sustained human presence, or develop into commercial activities in the medium and long term. Such activities, closely mirroring their terrestrial counterparts, are the foundational building blocks for establishing a self-sufficient lunar economy [82].

4.1 Lunar transportation market

The principal challenge common to all lunar-bound actors is access, whether to lunar orbit or its surface. Stakeholders adopt one of two primary logistical strategies: some develop proprietary transportation systems in a vertically integrated approach, while others focus on their core payload development and outsource their transportation needs to third-party providers.

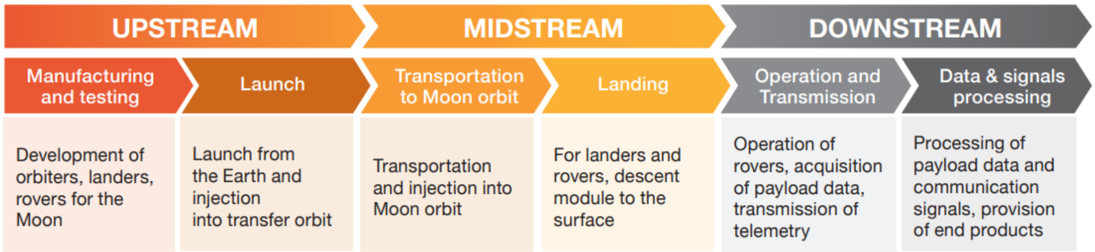

Figure 4.1: Transportation Market - Value Chain

The figure 4.1 illustrates the value chain for the lunar transportation market, segmenting the process into three distinct phases: upstream, midstream, and downstream.

- Upstream segment encompasses the foundational stages of mission preparation, including the design, manufacturing, and testing of lunar assets such as orbiters, landers, and rovers. This phase culminates with the launch from Earth and the vehicle's injection into a transfer orbit.
- The midstream phase then covers the critical transportation and arrival components, which involve the transit to and injection into lunar orbit, as well as the complex landing sequence for surface missions.
- The downstream segment focuses on value realization once the asset is in its operational environment. It includes the in-situ operation of the payload, data acquisition, telemetry transmission, and the subsequent processing of raw data into finished intelligence or end products for customers on Earth. This model effectively delineates the entire mission lifecycle from hardware development to the ultimate delivery of services.

4.1.1 Market Drivers & Challenges

The growth of the lunar market is propelled by three principal drivers. Firstly, a renewed geopolitical interest in exploration among international space agencies is leading to the dedication of substantial institutional budgets for ambitious, collaborative programs. This is complemented by a clear technological progression in mission architecture; as nations master orbital missions, they are increasingly shifting focus to more complex and massive surface operations involving landers and rovers, driving demand for heavier transport capabilities. Furthermore, government bodies are actively fostering the involvement of the private sector, utilizing commercial procurement models and other initiatives to encourage participation from both established space companies and non-space industries in emerging business opportunities. An analysis of the transportation of lunar market reveals three principal challenges that could influence its development trajectory: budgetary instability, technological immaturity, and the economic profile of orbital payloads [82].

Despite these positive drivers, the market is constrained by several significant challenges. A primary concern is the instability of institutional budgets, as the market's heavy reliance on public funding makes it vulnerable to fiscal volatility and programmatic revisions, particularly for long-term projects. This is compounded by the technological immaturity of critical systems, notably for In-Situ Resource Utilization (ISRU), which limits the large-scale engagement of terrestrial industries pending successful in-situ technology demonstrations. Finally, the market exhibits a structural paradox where orbital payloads, despite a consistent demand, will have a negligible impact on total market value due to their cost-per-kilogram being an order of magnitude lower than that for high-value surface assets [82].

4.1.2 Market Forecast

The global lunar transportation market is forecast to expand significantly in the future. In 2021 PWC estimated a Compound Annual Growth Rate (CAGR) of 10% and an evaluation of the market of $9 billion. Projections indicate a cumulative payload mass of 187 tons and a total market size of $79 billion under a nominal scenario [82]. Alternative scenarios provide a range for these estimates:

- Conservative Scenario: 128 tons, corresponding to a $55 billion market.
- Optimistic Scenario: 230 tons, corresponding to a $102 billion market.

The market's growth is anticipated to occur at a consistent pace. The optimistic scenario, for instance, illustrates this incremental expansion, with the market value segmented into $19 billion (2026-2030), $32 billion (2031-2035), and $42 billion (2036-2040) 4.2.

Last analysis shows that the current market reached $2.1 billion in 2024 with an annual growth rate of 19.8%. This rapid expansion is primarily fueled by increased investments in lunar exploration, growing public-private partnerships, and technological advancements in spacecraft and payload delivery systems. As per our latest research, the lunar transportation market is poised to become a cornerstone in the next era of space exploration and commercialization [83].

The exhibits a key disparity: while orbital payloads will comprise a higher cumulative mass, rover payloads, will generate significantly higher revenue per

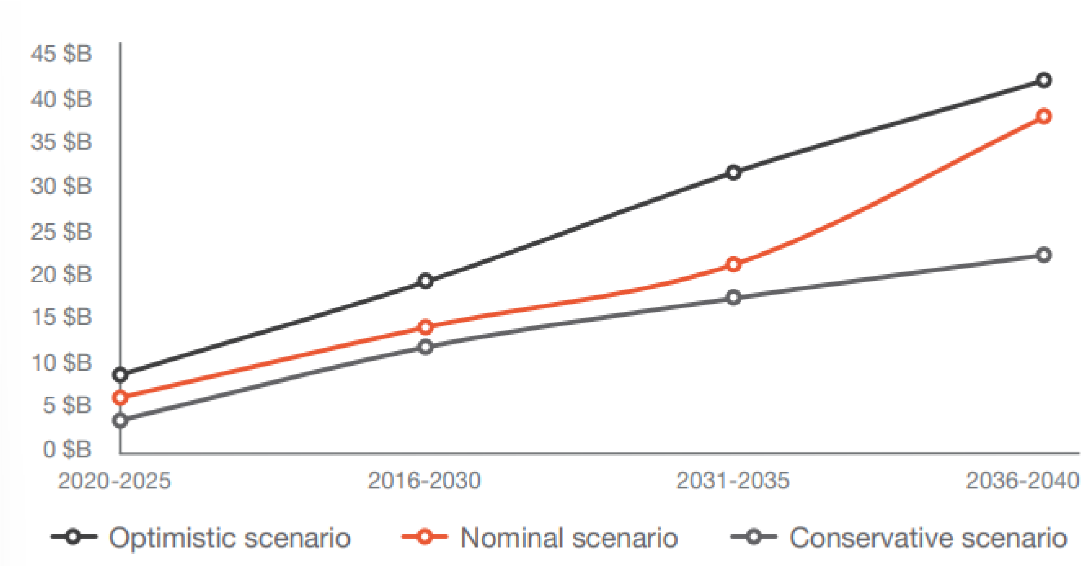

Figure 4.2: Scenarios of market size for the global lunar transportation market

mission due to their high costs. As is visible in the figure 4.3, in the short term national lunar exploration programs are expected to assign a central role to orbital payloads, prioritizing them as the most affordable and technically accessible mission profile. Concurrently, space agencies and commercial entities are anticipated to pursue increasingly complex missions incorporating landers and rovers. These missions will serve to demonstrate critical technologies and enable more extensive operations on the lunar surface.

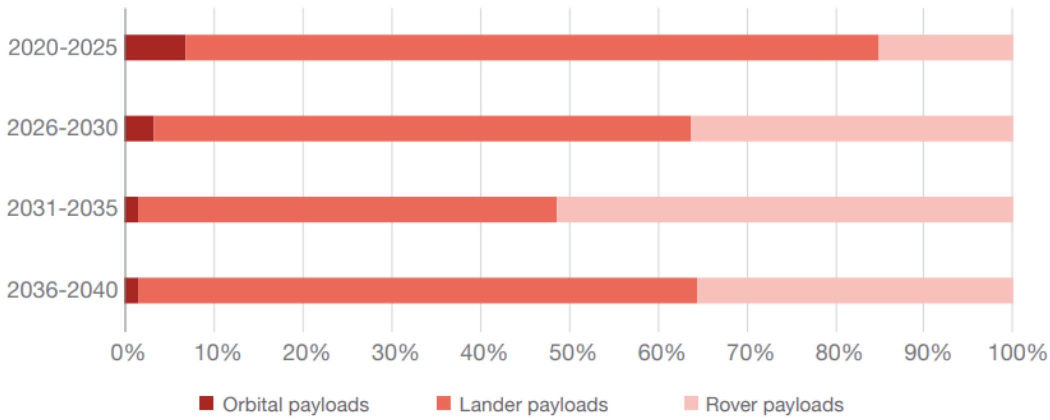

Figure 4.3: Distribution of the transportation market value ($) between the types of payloads - PWC 2021

The market is expected to remain institution-driven (science-focused) for the next decade, but the commercial sector's market share will steadily increase. This growth will initially come from space companies supporting sustainable lunar activities (e.g., ISRU, support for crewed missions). A larger commercial expansion is expected to be stimulated by non-space actors, who will be incentivizes to invest in lunar missions as they identify opportunities for technology spin-offs and spin-ins. [82].

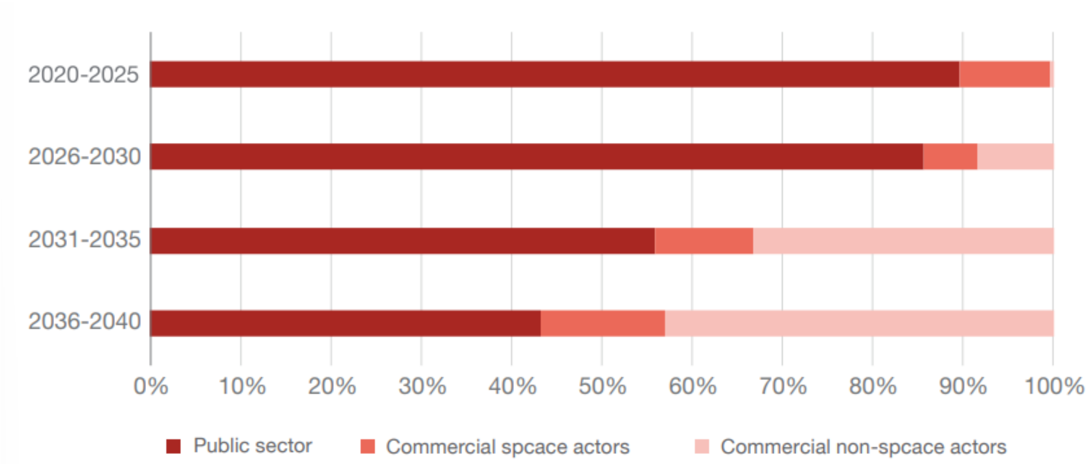

Figure 4.4: Distribution of the transportation market value ($) between the profile of customers - PWC 2021

As shown on Figure 4.4, in 2021 private sector's share of the lunar transportation market has been projected to expand dramatically, rising from just over 10% (2020-2030) to over 50% (2031-2040). This shift has been postponed caused the delay of space exploration mission. So, the market will be dominated by non-space industries after 2030/2035, which are expected to constitute 75% of all commercial demand, overtaking traditional space companies. This new demand will be driven by the mining, automotive, energy, and construction sectors applying their terrestrial expertise to lunar operations.

4.2 Lunar Data

Access to the lunar environment is fundamental for acquiring critical data on its physical and geological characteristics. Such data encompasses a wide spectrum of parameters, including surface temperature, radiation levels, terrain topography, dust concentrations, the presence of water ice, the abundance of volatiles, and the composition of the regolith.

Although a foundational body of knowledge has been established by previous missions, there is persistent scientific value in augmenting this dataset. Further data acquisition is crucial for extending survey coverage to new regions, refining spatial resolution, increasing the depth of analysis, and improving the temporal frequency of measurements.

The figure 4.5 outlines the value chain for the lunar data market, illustrating the process from initial hardware development to the final delivery of processed information:

- The upstream segment encompasses the foundational stages, beginning with the manufacturing of scientific payloads and their supporting platforms. This phase concludes with the launch and transportation of these assets from Earth to their operational deployment in lunar orbit or on the Moon's surface.
- The midstream phase focuses on the core data acquisition activities. This includes the remote or in-situ collection of scientific data and physical samples, which is immediately followed by the on-board pre-processing and storage of the raw data on the lunar vehicle.
- Finally, the downstream segment is dedicated to creating value from the collected information. It begins with the transmission of payload data back to Earth and culminates in the sophisticated processing and analysis required to transform raw data into valuable, refined services and products for end-users.

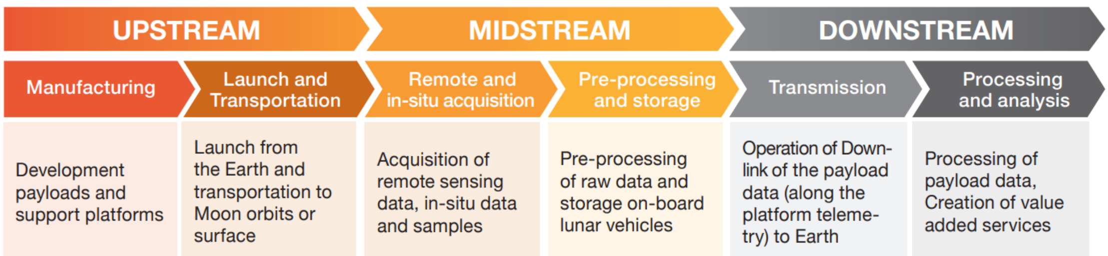

Figure 4.5: Lunar Data - Value Chain

PNT (Positioning, Navigation, Timing) e Comunicazioni: Modelli di vendita di servizi di rete (LunarComms) a rover, lander e habitat. Dati Scientifici e Osservazione: Vendita di dati lunari, geologici e astronomici a istituzioni e clienti commerciali.

4.2.1 Lunar Data Characterization

The lunar data market can be classified into three distinct categories, including environment data, telemetry data and entertainment data. Each lunar data category has different applications and a varied customer base [82].

Telemetry data is derived from lunar instrumentation and vehicles, providing critical information on system performance and health. This data is segmented into two categories: exploratory data, which is used for technology development within the lunar context, and terrestrial spin-off data, where insights from lunar systems (e.g., automated drilling) are applied to enhance terrestrial technologies. Key use cases for this data include technology development for lunar exploration by both public and private entities, as well as the application of spin-off data to improve systems in non-space commercial industries.

This data category consists of multimedia content, including video, imagery, and audio recordings of lunar activities, equipment, and landscapes. Historically generated by public sector missions, it is anticipated that future private missions will also become significant sources. The primary use case for this data is in the commercial sector, where the entertainment industry utilizes it for the production of films, documentaries, television programs, and video games.

Lunar environment data, collected from scientific payloads, provides information on the Moon's surface and orbital characteristics. As the market commercializes, this data will be segmented into non-SRU (Space Resource Utilization) specific data (e.g., topography, radiation, geology) and SRU-specific data focused on resource identification and characterization (e.g., water ice, volatiles, regolith). The demand is driven by the need for higher-resolution remote sensing and ground truth validation. Public and private entities utilize this data for mission planning and to validate scientific and operational models.

4.2.2 Market Drivers & Challenges

The expansion of the lunar data market is propelled by distinct drivers across its three main segments. Demand for telemetry data is primarily driven by the development of a sustainable lunar presence, which requires a new generation of rovers and utility equipment, with secondary interest from the terrestrial automotive sector for rover technology enhancement. In the entertainment sector, growth is fueled by the booming gaming industry's need for realistic content for virtual reality applications and by the increasing content expenditure of Over-The-Top (OTT) streaming services seeking high-fidelity footage for original productions. The environment data market is driven by a clear willingness among public and private entities to pay for information that addresses critical knowledge gaps, supports Space Resource Utilization (SRU) activities, and provides high-resolution "ground truth" data to validate and improve upon existing low-resolution remote sensing surveys.

Conversely, each data market faces significant developmental challenges. The telemetry market is constrained by issues of intellectual property and data sovereignty, as companies are reluctant to share proprietary subsystem data that could be reverse-engineered or data from third-party component suppliers. The entertainment market struggles with an underdeveloped and inconsistent monetization model, characterized by variable pricing and a tradition of providing footage to documentaries free of charge. The environment data market faces a fundamental conflict between commercialization and the scientific community's expectation of free, open-access data. Furthermore, its value is hindered by data fragmentation, where incomplete datasets for a specific region reduce the actionability of the information, especially for complex applications like SRU.

4.2.3 Market Forecast

While the lunar data market is an order of magnitude smaller than the transportation market, it is perceived to hold significant potential for generating valuable business spin-offs and additional revenue streams for organizations establishing a sustainable lunar economy. Based on an analysis of market drivers and constraints, cumulative revenues for the 2020-2040 period are forecasted at approximately \$8.5 billion under a nominal scenario and \$11.9 billion under an optimistic scenario [82].

Figure 4.6: Cumulative data market forecast on 2021-2040 (nominal scenario)

The lunar data market is anticipated to be dominated by sales related to space mission planning and execution, as well as by data for industries, both space and non-space. The environmental market segment is projected to account for \$8.3 billion between 2020 and 2040. This is further segmented into Space Resource Utilization (SRU) data (forecasted at 59% of the total) and non-SRU data (41%). Under the nominal scenario, **the environmental data market** is expected to grow approximately 3.7 times, increasing from \$1.8 billion in the 2021-2030 timeframe to \$6.5 billion in the 2031-2040 timeframe. This forecast also indicates a significant shift toward SRU data, which is projected to grow from 45% to 63% of the market share. The optimistic scenario forecasts a cumulative market value of up to $12 billion over the 2020-2040 period. This higher projection is stimulated by slightly increased demand from the space segment and, to a greater extent, by increased demand from non-space sectors, such as the mining industry, for ground truth validation.

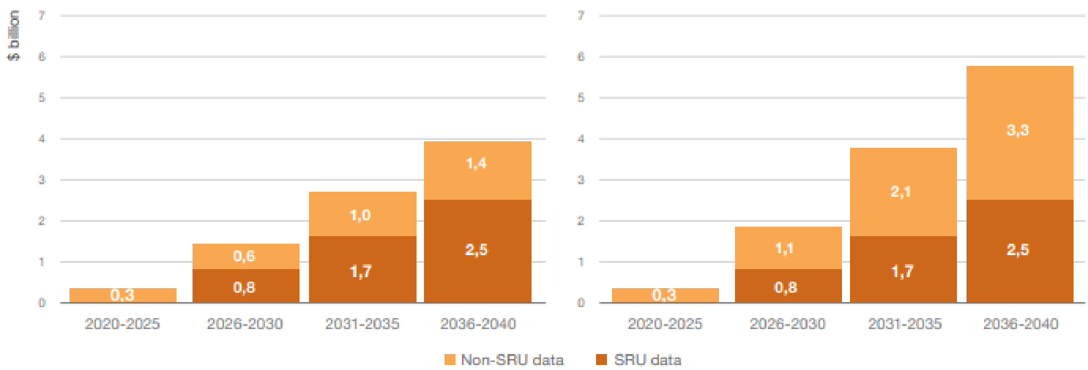

Figure 4.7: Cumulated revenues for the lunar environmental data market on 2020-2040 (nominal scenario on left, optimistic scenario on right)

The lunar telemetry data market is projected to be an order of magnitude smaller than the lunar environment data market, primarily due to significant supply-side constraints. Manufacturers of lunar assets (e.g., orbiters, landers) are expected to be reluctant to sell telemetry data, largely driven by concerns over intellectual property and the potential for replication by competitors. Despite these barriers, demand is anticipated to grow. The market may evolve through inter-organizational agreements to facilitate data sales. Cumulatively, the telemetry data market is forecasted to generate $115 million in revenues between 2020 and 2040. The following graph resume a decadal forecast reveals a significant structural shift: first period dominated by the public sector and second phase projected to witness a major shift toward private sector capitalization. **The lunar entertainment data** market is projected to constitute a negligible segment, accounting for only 0.2% of the total cumulative data market. This low penetration is primarily attributed to the high cost of original lunar imagery and a corresponding lack of willingness to pay, particularly when viable, cost-effective alternatives such as green screens and software-based video/image augmentation platforms (e.g., Adobe After Effects, Autodesk Maya) are available. However, a future increase in the quantity and quality of available data, resulting from an anticipated rise in lunar missions, is expected to stimulate demand. This would enable production companies to integrate more realistic video footage, audio recordings, and images into movies,

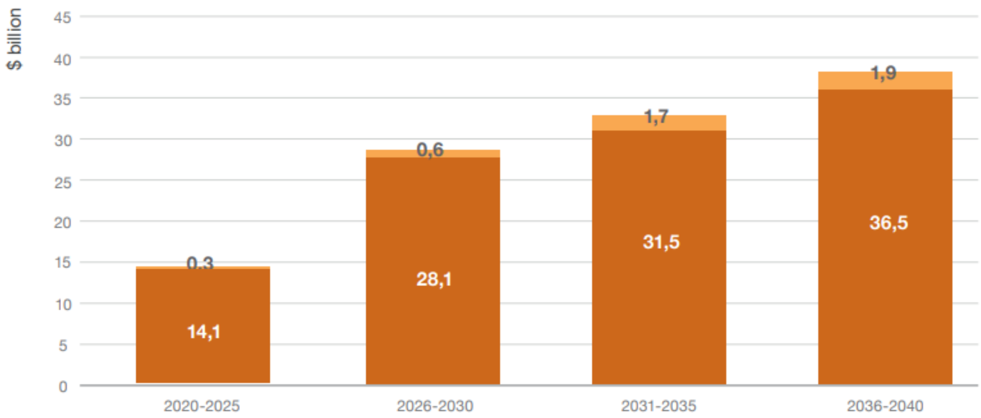

Figure 4.8: Cumulated revenues for the lunar telemetry data market on 2020-2040 (nominal scenario)

documentaries, television programs, and video games. The market is expected to be dominated by two primary verticals: documentary production, followed by movie production. These segments are collectively forecast to grow four-fold, from \$3.5 million in cumulative revenues during the 2020-2030 timeframe to \$14 million in the 2031-2040 timeframe. The video gaming industry is projected to be the smallest vertical, representing a cumulative \$0.6 million market between 2020 and 2040. Notably, this sub-segment is heavily back-loaded, with more than three-quarters of its total revenues expected to be generated in the 2031-2040 decade [82].

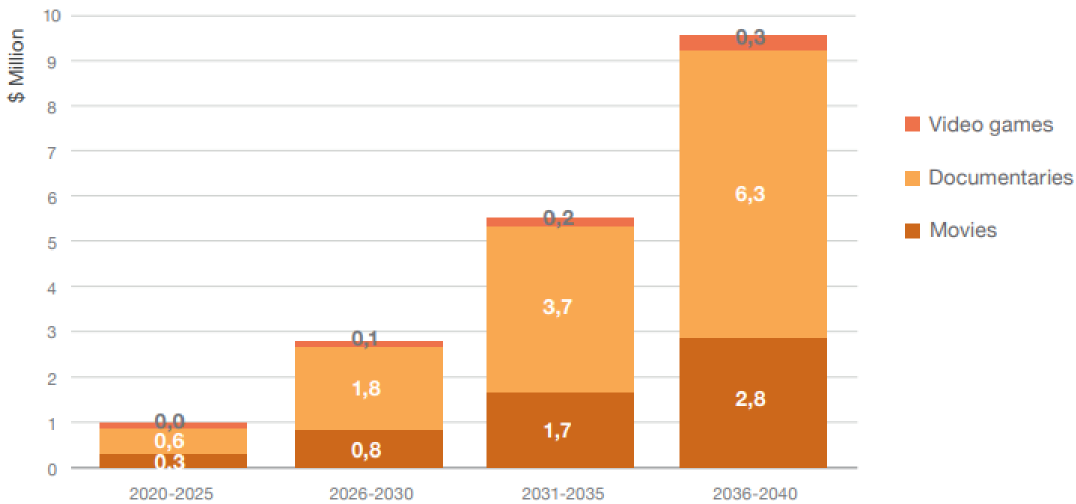

Figure 4.9: Cumulated revenues for the lunar telemetry data market on 2020-2040 (nominal scenario)

4.3 Space Resource Utilisation

Beyond lunar transportation and lunar data collection activities, sustained human and robotic presence on the Moon opens the path for local resources extraction and utilisation which will unlock the potential of future space missions. Many actors have started to develop technologies and concepts to work with and utilise the volatiles, minerals, and energy resources on the Moon particularly as In-Situ Resources Utilisation (ISRU) is foreseen as a vital and integral enabler of future space missions.

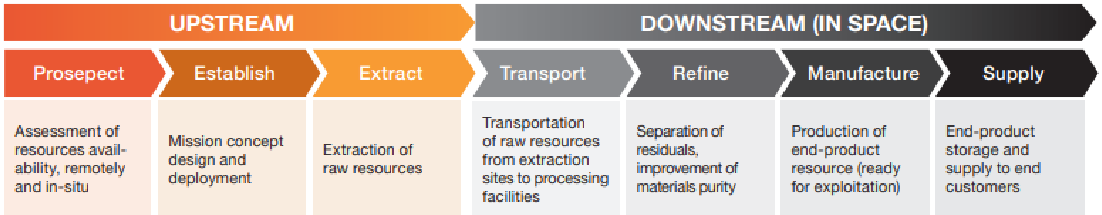

Figure 4.10: Space Resource Utilisation - Value Chain

The figure 4.10 illustrates the value chain for Space Resource Utilisation (SRU), outlining a complete, in-situ process from initial resource identification to final product delivery within an off-world environment. The process begins with the upstream segment, which encompasses the foundational activities. This sequence starts with prospecting—the remote and in-situ assessment of resource availability—followed by the establishment of the mission architecture, including concept design and infrastructure deployment. This preparatory phase culminates in the physical extraction of raw, unprocessed resources from the celestial body. The subsequent downstream (in space) segment details the conversion of these raw materials into valuable end-products entirely off-Earth. This begins with the transport of extracted materials to processing facilities. There, they undergo refinement to separate waste and improve purity before being used in manufacturing to create finished goods (e.g., propellant, construction materials). The value chain concludes with the supply phase, which involves the storage and delivery of these end-products to in-space customers, thereby creating a self-sufficient industrial ecosystem.

4.3.1 SRU demand and supply

The demand for Space Resource Utilisation is driven by a diverse set of applications, both in-space and potentially on Earth, predicated on the exploitation of local volatiles (such as oxygen, hydrogen, and water) and minerals found in lunar or asteroid regolith. Once extracted and processed, these resources are envisioned to serve three primary functions: the production of life support consumables for crewed missions, the generation of propellant for in-space transportation, and the manufacturing of infrastructure, equipment, and facilities to support a sustained human and robotic presence off-Earth 4.11.

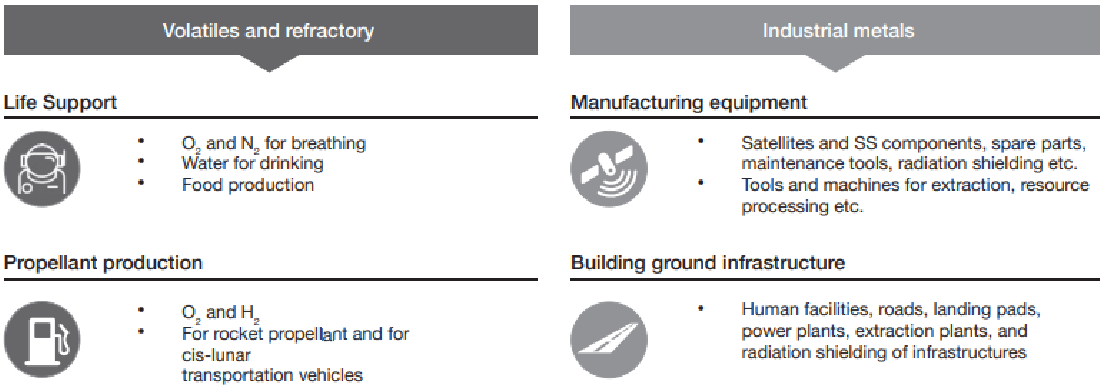

Figure 4.11: Space Resource Utilisation - Demand

The demand landscape is composed of a mix of public and private sector interests. The most immediate and well-defined demand originates from institutional space agencies, whose crewed exploration programs are the primary drivers for life support and propellant needs. Concurrently, an emerging and ambitious demand is being shaped by private actors. Visionary endeavors, such as the development of commercial space stations with private astronauts (e.g., Axiom Space) and high-cadence interplanetary transportation systems (e.g., SpaceX), create a significant future market. Furthermore, the development of in-space manufacturing capabilities would serve both institutional exploration activities and the broader ecosystem of private companies operating alongside government programs.

The supply side of the SRU market is currently in a nascent stage, with industry efforts concentrated on technology maturation and demonstration missions. The primary focus of the SRU community is on the initial prospecting stage of the value chain, which is essential for establishing the location, composition, and abundance of viable space resources. The progression of these activities is highly dependent on future technological advancements and the establishment of viable business cases. A critical step in this process is the transition from decades-old remote sensing data to indispensable in-situ measurements, which are required to achieve the necessary analytical accuracy and characterize sub-surface deposits.

Despite its early stage, the sector is characterized by dynamic activity across multiple stages of the value chain, evidenced by a growing number of public and private missions. Notable examples include ESA's PROSPECT demonstrator, commercial landers from companies like Astrobotic, Blue Origin, and Lockheed Martin, and rovers from a diverse group of international actors including ispace, NASA (VIPER), and the national agencies of China and India.

The development of this SRU ecosystem reflects a synergistic and complementary relationship between the public and private sectors 4.12.

Figure 4.12: Space Resource Utilisation - Supply

In a dynamic common to other space domains, public programs are acting as a market catalyst. They not only advance foundational technology but also serve as primary, or anchor, customers, which de-risks the market and enables private companies to emerge, mature their technologies, and develop sustainable commercial models.

4.3.2 Market Drivers and Challenges

The evolution of the Space Resource Utilization market is fundamentally driven by future missions to the Moon and Mars, which stimulate demand for rocket propellant and infrastructure for a sustainable human presence. The materialization of this market, however, remains contingent upon several critical drivers and the resolution of significant challenges.

Space agencies worldwide have repositioned the Moon as a key strategic element for crewed exploration beyond Low Earth Orbit. Institutional mission programmes are essential for maturing SRU technology, conducting resource prospecting, and increasing the support of the commercial sector. These programmes create direct opportunities for private actors as contractors. Future Mars missions are a significant long-term driver for lunar SRU, could benefit substantially from in-orbit refuelling in cis-lunar space maximizing Mars payload capacity.

Despite these drivers, the market faces barriers. A primary obstacle is the remaining gap in resource characterisation, advancing from the simple identification of surface molecules to a comprehensive geological analysis of the regolith and subsurface. Also, market demand is contingent upon the maturation of critica, unproven technologies. The feasibility of many core concepts has yet to be demonstrated. Last significant barrier is the lack of an internationally recognized regulatory framework for the commercial exploitation of space resources, mainly in Europe.

4.3.3 Market Forecast

The total projected cumulative value of the aggregate SRU market is estimated at just over $63 billion by 2040, dominated by a single element: Propellant Market (99%). A defining characteristic of the forecast is a period of negligible growth from 2020-2030, followed by a drastic and exponential increase in growth post-2030, as shown in 4.13.

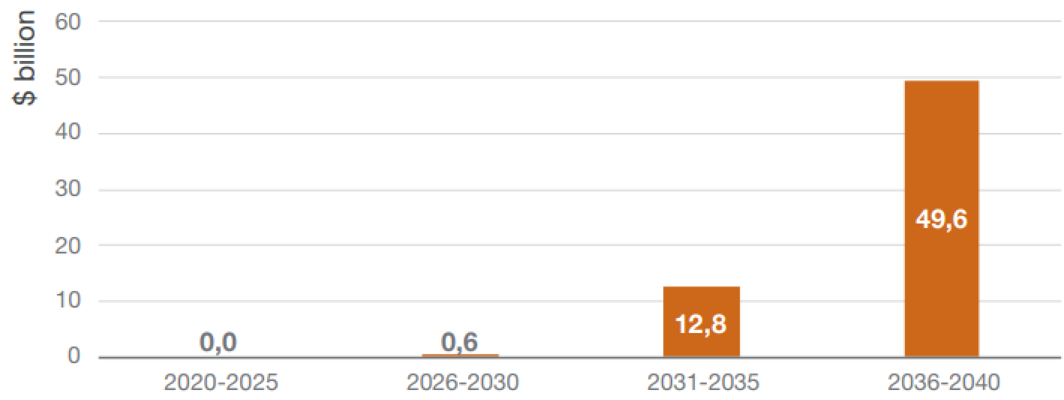

Figure 4.13: SRU projections for launcher propellant marke

This inflection is attributed primarily to a projected surge in demand for propellant, which is driven by two factors: increased mission frequency and payload mass. An exponential rise in missions to both the Moon and Mars is anticipated, stimulated by a shift from purely institutional programs to a mixed economy involving private, commercial ventures. Furthermore, future missions are expected to involve larger payloads, necessitating greater propellant volumes. Inter-planetary missions to Mars are identified as the predominant driver for the entire SRU market, given the substantial propellant needs for such missions.

4.4 Assessment of Public Private Partnership Trends

Public-private partnerships (PPPs) are crucial for developing a lunar economy, as they combine government expertise and funding with private sector innovation and capital for high-cost, high-risk ventures like resource utilization and infrastructure development. Main examples is the NASA's Commercial Lunar Payload Services (CLPS) program and collaborative efforts for technologies like lunar landers and rover tires. These models are seen as essential for aligning diverse public and private interests and for creating frameworks that facilitate investment and manage the complexities of space resource utilization [82, 84, 31].

4.4.1 NASA's Commercial Lunar Payload Services (CLPS) Program

At the forefront of the American robotic strategy is a paradigm shift in procurement and mission architecture: the Commercial Lunar Payload Services (CLPS) program.

Established in 2018, the CLPS initiative represents a strategic pivot by NASA away from monolithic, government-owned missions towards a model of public-private partnership . The program's primary objective is to contract with a diverse portfolio of commercial vendors for the end-to-end delivery of science and technology payloads to the lunar surface. This approach is designed to foster a competitive commercial lunar economy, drive innovation, and accelerate the cadence of NASA's own exploration goals at a lower cost .

This programmatic approach signifies a fundamental shift in NASA's risk tolerance. The initial CLPS missions have experienced technical anomalies, including the propellant leak that prevented Astrobotic's Peregrine lander from attempting a landing and the tipping of Intuitive Machines' IM-1 lander, which limited its operational lifetime . However, NASA has not curtailed the program in response to these setbacks, instead continuing to award new task orders to its commercial partners . This pattern of accepting a higher probability of individual mission failure in exchange for programmatic speed and market stimulation is a calculated strategy. The underlying logic is that the aggregate success and rapid iteration of multiple, lower-cost missions will yield greater long-term benefits than a single, slow, and prohibitively expensive flagship mission. This creates a resilient lunar access ecosystem where the failure of one company does not cripple the nation's ability to reach the Moon, a stark contrast to the single-point-failure risks of past programs.

Key missions contracted under the CLPS program include:

- **Intuitive Machines (IM):** Following the partial success of IM-1, which achieved the first-ever commercial soft landing on the Moon, the company has several follow-on missions planned . IM-2 and IM-4 will deliver payloads to the lunar south pole, including the PRIME-1 ice-drilling experiment, while IM-3, targeting a 2026 launch to the Reiner Gamma magnetic anomaly, will carry a diverse suite of international payloads from partners including NASA and the European Space Agency (ESA) [31] .
- **Astrobotic Technology:** Despite the loss of its Peregrine Mission One, Astrobotic remains a key CLPS provider. Its upcoming Griffin Mission One, a medium-class lander scheduled for launch on a SpaceX Falcon Heavy in

late 2025, will target the Nobile Crater region near the south pole . Its primary payload will be the FLIP (FLEX Lunar Innovation Platform) rover from Astrolab, a significant demonstration of surface mobility . A future Astrobotic mission is also slated to deploy the LunaGrid-Lite experiment, a critical technology demonstration for transmitting 1 kW of power over a 500-meter cable on the lunar surface—a foundational step toward a permanent power grid [31] .

- **Firefly Aerospace:** Firefly's Blue Ghost lander series has been contracted for multiple missions. The first mission will target Mare Crisium . The second, Blue Ghost Mission 2, scheduled for mid-2026, is a particularly complex two-stage mission. It will first deliver ESA's Lunar Pathfinder communications satellite to lunar orbit before the lander descends to the far side of the Moon with the LuSEE-Night (Lunar Surface Electromagnetics Experiment-Night) payload, showcasing advanced multi-objective mission capabilities [31].

- **Draper/ispace:** This partnership will utilize the APEX 1.0 lander to deliver the LuSEE-Lite (Lunar Surface Electromagnetics Experiment-Lite) payload to the Schrödinger Basin on the lunar far side, further expanding the scientific reach of the program into unique geological and radio-quiet environments [31].

- **Blue Origin:**Blue Origin's Blue Moon Mark 1 lander is scheduled to conduct its inaugural Pathfinder Mission no earlier than the first quarter of 2026, launching aboard the company's new heavy-lift New Glenn rocket . This mission is a critical flight test for key technologies that are essential for the company's larger Human Landing System (HLS), including the high-performance BE-7 engine, cryogenic fluid management systems, and precision landing algorithms . Under a CLPS contract, the lander will carry NASA's SCALPSS (Stereo Cameras for Lunar Plume-Surface Studies) payload to analyze the interaction between the engine's exhaust plume and the lunar regolith [85, 31].

Chapter 5

Lunar Rover

The lunar rover, once a bespoke symbol of superpower ambition, is undergoing a fundamental redefinition. It is transforming from a state-funded scientific instrument, designed for singular missions of exploration, into a commercially scalable asset class that is foundational to the emerging cislunar economy. This chapter posits that the convergence of new public procurement strategies and innovative commercial business models is repositioning lunar rovers as the primary enablers of surface exploration, in-situ resource utilization (ISRU), and the development of permanent infrastructure on the Moon.

The historical precedents set by the Soviet Union's robotic Lunokhod program and the United States' crew-centric Apollo Lunar Roving Vehicle (LRV) serve as critical points of departure. These early missions established the foundational principles of lunar mobility but were products of a bipolar world driven by geopolitical competition [86].

Today, the landscape is defined by a new era of public-private partnership and economic ambition [86]. National space agencies, led by NASA, are transitioning from the role of sole developer and operator to that of an anchor customer, intentionally stimulating a commercial market to drive down costs and accelerate progress [86].

This strategic shift is most clearly embodied in programs like NASA's CLPS [31], which procures end-to-end delivery services from private companies. This has, in turn, catalyzed the development of new business models, chief among them being MaaS, where surface mobility is sold as a utility rather than a product [84, 87].

5.1 Technology Definition

A planetary rover is a surface exploration device engineered to move across the terrain of a planet or other celestial body. While the concept is straightforward, the execution is extraordinarily complex, dictated by the need to operate reliably in one of the most hostile environments imaginable. The design of any lunar rover is a direct response to a set of severe environmental and operational constraints, which in turn gives rise to a classification system based on mass, scale, and mission application.

Lunar rovers must be designed to withstand a series of extreme environmental challenges that have no parallel on Earth. These constraints are the primary drivers of their engineering and design principles:

- **Thermal Extremes:** The lunar surface experiences dramatic temperature swings, from approximately 127°C in direct sunlight to -173°C during the 14-day lunar night. Rovers must incorporate robust thermal management systems to protect sensitive electronics and mechanical components from these cycles.
- **Vacuum:** The near-perfect vacuum of space requires materials and lubricants that do not outgas, and it presents unique challenges for heat dissipation, which must be managed through radiation rather than convection.
- **Cosmic Radiation:** With no protective atmosphere or magnetic field, rovers are constantly bombarded with high-energy cosmic rays and solar particles. This necessitates the use of radiation-hardened electronics to prevent system failures.
- **Lunar Regolith:** The fine, abrasive, and electrostatically charged lunar dust is a pervasive hazard. It can infiltrate mechanical joints, obscure optical sensors, and abrade surfaces. Dust mitigation is a critical design consideration for any long-duration mission.
- **Autonomy and Reliability:** For robotic rovers, the communication delay between Earth and the Moon makes real-time control impractical. Therefore, a high degree of autonomy is required for navigation and hazard avoidance. Given the impossibility of repair, all systems must be designed for extreme reliability and often incorporate redundancy to withstand component failures.

5.2 Rover Classification

There are two main type of rover: crewed rovers and uncrewed rovers.

Crewed rovers are designed to transport astronauts across the lunar or planetary surface, enabling the exploration of wider areas than would be possible on foot. These systems typically include either an open or pressurized cabin, life-support equipment, manual control interfaces, and direct communication links with a lander or base. Notable examples include the Lunar Roving Vehicle (LRV) used during NASA's Apollo 15, 16, and 17 missions (1971–1972) [4], the Lunar Terrain Vehicle (LTV) currently being developed by NASA for the Artemis program in collaboration with Lockheed Martin and General Motors, and the JAXA–Toyota Lunar Cruiser, a pressurized rover designed for future human exploration of the Moon.

In contrast, **uncrewed rovers** are autonomous or remotely operated robotic vehicles used to investigate extraterrestrial surfaces without human presence. They are equipped with sensors, cameras, scientific instruments, and autonomous navigation systems. A lunar example is the NASA's upcoming VIPER rover [88].

The technical solutions to these challenges manifest in rovers of vastly different scales, with each class corresponding to specific mission architectures and, crucially, the funding mechanisms that enable them.

- **Micro Rovers (<10 kg):** This class prioritizes low cost and accessibility, opening the door to new mission concepts. Characterized by a mass of less than 10 kg, micro rovers are designed to carry small, single-instrument payloads. The guiding philosophy is that a fleet of several low-cost micro rovers, deployed from a single lander, can achieve greater spatial coverage for prospecting or mapping than a single, expensive, large-scale rover. This approach reduces mission costs and allows for greater mission redundancy. A prime commercial example is Astrobotic's CubeRover, which leverages the standardized CubeSat form factor (where a 1U payload is a 10 cm cube weighing 1 kg) to provide a modular, scalable, and affordable mobility platform. This class of rover exists because business models like "mobility-by-the-kilogram" and programs supporting small payload delivery have become viable.
- **Medium-Class Rovers (10-500 kg):** This category represents a proven balance between scientific capability, mobility, and mission cost. The archetypes for this class are NASA's highly successful Mars Exploration Rovers (MER), Spirit and Opportunity. In the lunar context, this class is being driven by the capabilities of the commercial landers developed under NASA's CLPS program, many of which are designed to deliver payloads in the 100 kg range. At the upper end of this class is NASA's Volatiles Investigating Polar Exploration Rover (VIPER). With a mass of approximately 400 kg, VIPER is a specialized scientific rover designed for a targeted mission: to prospect for water ice in the permanently shadowed regions of the lunar south pole. Its size and complexity are directly tied to its specific, high-priority scientific objectives.

- **Heavy-Lift / Crew-Support Rovers (>500 kg):** This class is defined by its large payload capacity and its function in supporting human operations and building surface infrastructure. The primary examples are the next-generation LTVs being developed under NASA's Artemis program. These rovers are designed to transport two astronauts, handle significant cargo loads (with payload capacities exceeding 1,500 kg), and operate autonomously for robotic missions when crews are not present. Companies like Lunar Outpost (with its Eagle rover) [89] and Venturi Astrolab are developing these large-scale platforms in response to NASA's multi-billion-dollar LTVs contract, which procures mobility as a long-term service rather than a one-time hardware purchase. The existence of this rover class is a direct result of the architectural needs of a sustained human presence and the service-based procurement model created to fulfill them.

5.3 Market Analysis

The European Lunar Rover Market includes all European activities and stakeholders involved in designing, building, and deploying robotic rovers for lunar missions. The following PESTLE analysis will show the market in detail.

Political Landscape
The market is fundamentally shaped and driven by institutional actors, primarily the European Space Agency (ESA) and various national space agencies. These governmental bodies provide the strategic direction for the sector and are the principal source of funding for major programs. This strong institutional backing reflects a clear political ambition for Europe to establish strategic autonomy and leadership in lunar logistics and exploration. However, this heavy reliance on public institutions also exposes the market to risks associated with shifting political priorities and government budgetary cycles, which can directly impact project timelines and the overall pace of development.

Economic Environment
From an economic perspective, Europe holds a significant position in the global lunar sector, accounting for nearly a quarter of worldwide revenues. The market is characterized by high financial and technical barriers to entry, which results in limited competition but creates substantial opportunities for established players and highly specialized new entrants. The viability and growth of the market are demonstrated by the awarding of major contracts, such as the €862 million Argonaut lander, which signals a robust pipeline of future opportunities. Nevertheless, the sector's dependence on public funding streams, combined with regulatory

fragmentation, can create uncertainty for private investors, potentially slowing the infusion of commercial capital.

Technological Framework

Europe is actively strengthening its technological capabilities in space robotics and autonomous systems. Development is focused on advanced, modular rover platforms designed for a range of applications, including scientific exploration, prospecting, and In-Situ Resource Utilization (ISRU). The technological readiness of these systems is being significantly enhanced by sophisticated testing infrastructure, such as the LUNA analogue facility in Germany, which allows for high-fidelity simulations of lunar conditions. Furthermore, strategic initiatives like Moonlight, MAGPIE, and ESA's Moon Village aim to develop critical lunar infrastructure, which will reduce the complexity and cost of future robotic missions and enhance the needs to perform robotic operations.

Legal & Regulatory Environment

The legal landscape for commercial lunar activities in Europe remains highly fragmented. There is currently no single, harmonized regulatory framework that governs all member states, which can create complexity and uncertainty for commercial operators. While nations like Luxembourg have pioneered a favorable legal environment with their Space Resources Law, setting a precedent for commercial authorization, this remains an exception. This lack of uniformity is a key challenge that needs to be addressed to foster greater private investment and streamline cross-border commercial ventures.

Environmental Considerations

Environmental and sustainability principles are becoming increasingly influential in the planning of lunar missions. In line with the social view of the Moon as a common heritage, there is a growing expectation that all activities will be conducted responsibly to protect the pristine lunar environment. This is likely to lead to the development of specific sustainability requirements and environmental regulations, especially for activities involving In-Situ Resource Utilization (ISRU). Future rover operations will need to integrate these principles of responsible stewardship into their mission architecture and operational protocols.

The ecosystem for developing and operating lunar rovers has transformed from the state-led duopoly of the Cold War into a complex, multi-layered network of public agencies, established aerospace corporations, and agile NewSpace startups. This modern industrial landscape is characterized by a symbiotic relationship between government and private enterprise, with value being created and captured at multiple stages, from upstream research and development to downstream mission operations and data services.

5.4 Main actors

The contemporary lunar rover ecosystem is comprised of several key categories of actors, each playing a distinct but interdependent role:

- **Public Agencies (The Anchor Tenants):** Government bodies like NASA, ESA, and JAXA are the primary architects and anchor customers of the new lunar economy. Through large-scale programs such as Artemis, they establish the overarching strategic goals for lunar exploration and settlement. Critically, through procurement mechanisms like NASA's CLPS initiative, they provide the foundational demand and contract funding that enables the commercial market to exist.
- **Prime Commercial Contractors (The System Integrators):** A new class of companies has emerged to serve as prime contractors for end-to-end lunar services. Firms such as Astrobotic, Intuitive Machines, and Firefly Aerospace have won major CLPS contracts to deliver NASA and commercial payloads to the Moon. They act as system integrators, managing the entire mission from payload integration and launch procurement to landing and surface operations.
- **Specialized Rover Developers:** Alongside the integrators, there are companies focusing specifically on the mobility segment. Lunar Outpost and Venturi Astrolab, for instance, are competing to develop the next-generation LTV for NASA, often forming strategic alliances to bolster their bids.
- **Legacy Aerospace & Automotive Giants (The Industrial Backbone):** The complexity and capital intensity of space missions mean that traditional industrial powerhouses remain critical players. Companies such as Lockheed Martin and General Motors are partnering with newer firms, bringing decades of experience in systems engineering, manufacturing reliability, and vehicle dynamics to rover development projects. This fusion of NewSpace agility with legacy industrial scale is a defining feature of the current ecosystem.

5.5 The Value Chain

The process of creating and utilizing a lunar rover can be modeled as a value chain with several distinct stages:

- **Upstream (Enabling Technologies):** This stage includes the fundamental research, development, and manufacturing of the components and software that make a rover possible. This encompasses everything from specialized sensors, actuators, and power systems (batteries, solar arrays) to advanced materials and, critically, the software for autonomous navigation and robotic control.

- **Midstream (Integration and Delivery):** This is the domain of the prime contractors. It involves the assembly of the rover, its integration with a lunar lander, and the procurement of a launch vehicle to transport the entire system from Earth to the lunar surface. This stage is focused on the complex logistics of space transportation.

- **Downstream (Surface Operations):** Once on the Moon, this stage involves the execution of the mission. This includes tele-robotics, surface mobility, data acquisition and transmission back to Earth, and the performance of specific tasks like sample collection, instrument deployment, or construction activities. This is the stage where "as-a-service" business models are realized.

- **Value-Added Services (Data and Applications):** This emerging final stage involves the analysis and monetization of the data collected by the rover. This could include selling scientific data to research institutions, providing resource maps to prospective mining companies, or even licensing imagery and video for media and entertainment purposes.

This value chain is not purely linear. The relationships between players are often complex and characterized by "coopetition." For instance, a rover developer like Lunar Outpost might compete against Intuitive Machines for an LTV contract while simultaneously being a potential customer for Intuitive Machines' lunar data relay services. Strategic alliances are essential for success; Lunar Outpost's LTV team includes industrial giants Lockheed Martin and General Motors, demonstrating how companies bundle their complementary expertise to compete for large contracts. This dynamic network of partnerships, acquisitions, and collaborations is a hallmark of a maturing and sophisticated industrial sector.

5.6 Agencies Project

A new phase in lunar surface exploration has commenced, driven by the convergence of national space agency initiatives and the rapid emergence of commercial enterprise. In the past, lunar rovers were conceived as unique, mission-specific systems, such as the Soviet Union's Lunokhod series and NASA's Apollo Lunar Roving Vehicle [88]. These foundational missions successfully demonstrated the fundamental principles of navigation, power management, and mobility in the harsh lunar environment.

At present, the development of lunar rovers is at a stage of maturity analogous to that of CubeSats in the early 2000s. The CubeSat model transformed the space industry by democratizing access, lowering development costs, and enabling iterative design. An equivalent transformation is now underway for lunar rovers, which are transitioning from bespoke, agency-centric platforms toward reconfigurable, scalable, and commercially viable systems. Although the engineering hurdles are formidable, the industrial dynamics mirror this earlier shift, with standardization, modular design, and economies of scale beginning to redefine the paradigm for developing planetary surface mobility.

CNSA

China's lunar strategy demonstrates methodical progression and a constant operational presence. The Yutu-2 rover has been launched on 7 December 2018 and operating on the far side of the Moon since January 2019, representing the only rover currently active on the lunar surface. The mission was planned to be 3 months but the rover on November 2025 is still working, holding the record for the longest working time on the moon 5.1. A day after landing, Yutu-2 went into hibernation for its first lunar night and it resumed activities on 10 January 2019, with all instruments operating nominally. During its first full lunar day, the rover travelled 120 m (390 ft), and on 11 February 2019 it powered down for its second lunar night. In September 2019, the Yutu-2 rover found a mysterious, unusual "gel-like" substance on the lunar surface inside a small crater in the central region of the Von Kármán crater on the south pole of the far side of the Moon. Further analysis found that the substance resembled rock melted by a lunar impact, and the research indicates that the bright, green material is a rock that was melted by the heat generated by a meteorite impact [90].

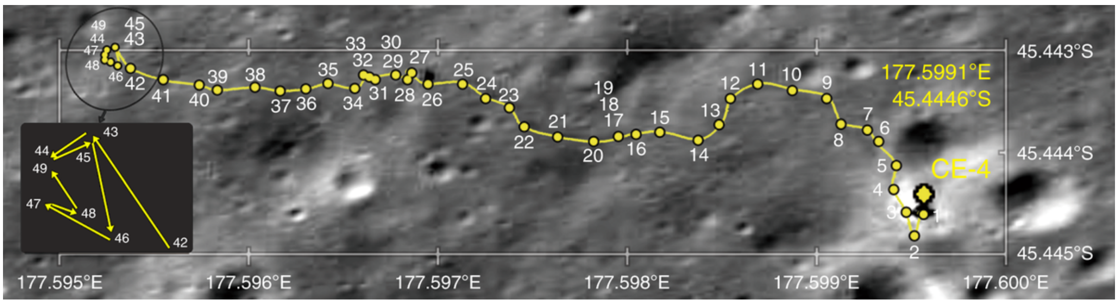

Figure 5.1: The routing path of the Yutu-2 rover

Yutu-2 is a 140 kg, six-wheeled lunar rover that operates as part of the Chang'e-4 mission on the far side of the moon. Its key technical features include solar panels for power, radioisotope heater units for warmth during lunar nights, and a suite of scientific instruments for remote sensing and in-situ analysis. Its primary instruments are a panoramic camera, a visible and near-infrared imaging spectrometer (VNIS), the Lunar Penetrating Radar (LPR) for subsurface imaging, and the

Advanced Small Analyzer for Neutrals (ASAN) [90]. Its mission is dedicated to in situ geological analysis of the South Pole-Aitken basin, using ground-penetrating radar to map the subsurface and a spectrometer to identify the composition of the regolith.

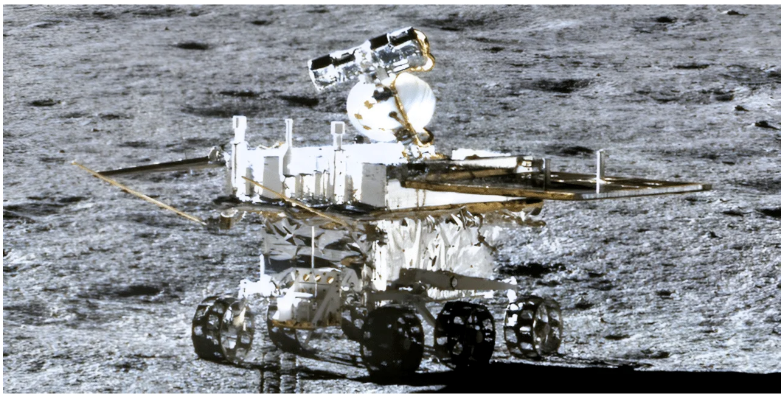

Figure 5.2: Yutu 2 Rover CNSA

Looking ahead, the CNSA is developing complex missions such as Chang'e 7 (scheduled for 2026), which will include a rover designed specifically to explore the permanently shadowed craters at the South Pole, with the primary objective of searching for and analysing water ice [91].

NASA

The US space agency is pursuing a diversified robotic lunar exploration strategy, integrating scientific missions with infrastructure development for the Artemis programme.

- **CADRE (Cooperative Autonomous Distributed Robotic Exploration).** NASA's Jet Propulsion Laboratory (JPL) is currently developing the CADRE project, a multi-agent system of compact, mobile robots. The primary objective of this project is to enable autonomous robotic exploration of the Moon, Mars, and other celestial bodies, specifically targeting high-risk or difficult-to-access locations such as craters, caves, and lava tubes [92].

  This autonomous architecture is designed to mitigate the operational inefficiencies of communication latency. While real-time control is feasible for lunar missions, the processing delays associated with ground control review consume valuable mission time. For more distant targets, such as Mars or Europa, significant time lags render direct remote operation impractical. The CADRE system, designed to explore independently after deployment from a lander, significantly increases potential science return by minimizing the necessity for robots to "phone home" for instructions [92].

The system's operational methodology relies on inter-robot communication (potentially WiFi-based) linked to a base station on the lander. This base station functions as a "high brain," aggregating the collective data—such as maps and sensor readings—from all units. It then processes this synthesized information and redistributes the compiled data back to the rovers, enhancing their situational awareness and path planning [92].

The multi-agent nature of CADRE enables novel scientific applications. By sharing sensor data, the network can perform functions beyond the capability of a single rover. Examples include utilizing ground-penetrating radar from multiple units to create subterranean maps at variable depths, arranging rovers equipped with telescopes to function as a synthetic aperture, or dispersing sensors to conduct comprehensive seismic surveys. This cooperative model also permits high-risk exploration, where one agent can enter an area (e.g., a lava tube) and transmit data back through the network, even if retrieval is uncertain [92].

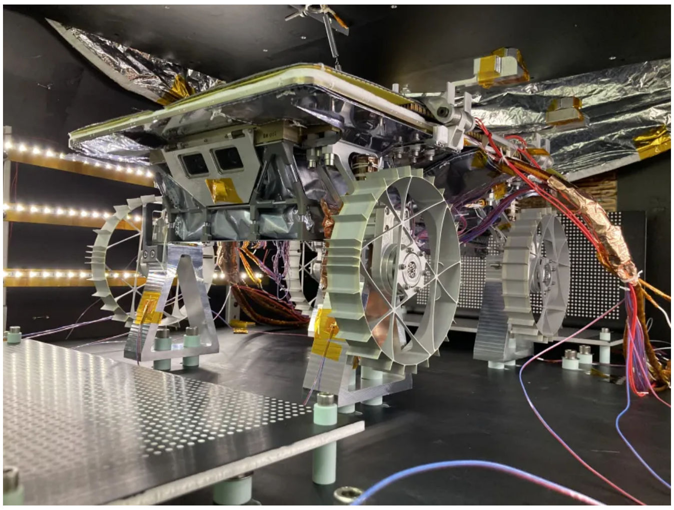

Figure 5.3: CADRE Rover on integration phase

The CADRE technology is currently undergoing ground testing using lunar terrain simulants to validate cooperative tasks such as mapping and subsurface imaging. The project is being considered for a technology demonstration mission via a commercial lunar lander. The ultimate objective, as stated by the project management, is for the CADRE software to evolve into a versatile, commercial off-the-shelf (COTS) standard. This standard would be designed to host diverse (including non-NASA) science instruments and to ensure interoperability with other commercial robotic systems, thereby establishing a new paradigm for autonomous space exploration [92].

- **VIPER (Volatiles Investigating Polar Exploration Rover)** NASA's VIPER was conceived as a 100-day mobile robotic mission specifically designed to conduct in-situ analysis of the Moon's South Pole 5.4. The primary objective of the mission was resource prospecting, specifically the search for water ice and other volatiles.

  VIPER was intended to be the first mission to conduct resource mapping on another celestial body. The data acquired was deemed critical for identifying the location, distribution, and accessibility of lunar ice deposits. These resource maps were intended to directly support the strategic goals of NASA's Artemis program, which aims to establish a sustainable, long-term human presence on the lunar surface by enabling ISRU [93].

  The rover's instrumentation includes three scientific instruments and a 1 meter drill, enabling it to detect the composition and physical state of lunar soil environments at various depths and temperatures. A key design capability was the rover's ability to traverse and operate within Permanently Shadowed Craters (PSRs), which are hypothesized to contain ancient ice reserves preserved in some of the coldest regions of the solar system [93].

  Beyond its resource-mapping function, the mission possessed significant scientific objectives. By analyzing the composition and distribution of these ice deposits, VIPER aimed to provide empirical data regarding the origin of lunar polar water, offering broader insights into the distribution and migratory history of water and other volatiles within the inner solar system [93].

  

  Figure 5.4: VIPER - NASA

  On July 2024, NASA announced its intention to discontinue the VIPER mission, citing constraints within the Science Mission Directorate budget, future financial risks, and delays in the commercial lander's development. The agency has since been exploring alternative partnership options to facilitate the rover's delivery to the lunar surface and the accomplishment of its scientific goals [93].

- **LTV (Lunar Terrain Veichle)**
  The resultant LTV is specified to be a highly advanced surface platform. It must integrate sophisticated systems for power management, autonomous driving, and state-of-the-art communications and navigation. These features, along with other technologies engineered to withstand the extreme lunar environment, are required to provide robust capabilities for scientific collection and analysis, while simultaneously ensuring astronaut safety and maintaining vehicle integrity for subsequent missions. NASA selected three companies to develop this technology: Intuitive Machines, Lunar Outpost, and Venturi Astrolab **??**.

JAXA
Japanese space agency conducts the The Smart Lander for Investigating the Moon (SLIM) mission. The 200 kg (dry mass) class spacecraft, was launched on September 7, 2023, and performed a precision lunar landing on January 19, 2024. The mission successfully achieved the world's first "pinpoint landing," demonstrating an accuracy of approximately 10 meters (evaluated at 50m altitude), which significantly exceeded the 100-meter target. This precision was attained despite a critical anomaly involving the loss of thrust in one main engine just prior to touchdown.Before landing, SLIM successfully deployed two autonomous micro/nano rovers, which subsequently captured imagery of the lander [94]. LEV-1 and LEV-2 (SORA-Q) operated autonomously on the lunar surface. The 2.1 kg LEV-1 micro rover, designed to demonstrate leapfrog mobility, was equipped with direct-to-Earth communication. Conversely, the 228 g LEV-2 nano rover, developed with commercial partners, featured a metamorphic design, transforming from a spherical stowage configuration into a mobile platform. LEV-2's primary mission was to image the SLIM lander; however, it lacked direct-to-Earth communication and instead relayed data to LEV-1 via Bluetooth. This cooperative system functioned with full autonomy, as no ground commands were issued. Notably, LEV-2 utilized an onboard algorithm to autonomously select and prioritize the "best shots" of the lander for transmission, thereby overcoming severe communication bandwidth limitations and successfully returning key imagery [94].

ISRO
The Indian space agency achieved historic success in 2023 with the Chandrayaan-3 mission, which positioned India as the first nation to perform a soft landing

and operate a rover in the lunar South Pole region. The Pragyan rover, although small in size and with an operational life limited to a single lunar day (approximately 14 Earth days), successfully completed its primary scientific objectives. The system is a six-wheeled lunar rover. It is solar-powered, weighs about 27 kg, and moves at a speed of 1 centimeter per second. Its primary purpose is to explore the lunar surface, analyze the elemental and mineral composition of rocks and soil, and study seismic activity. It conducted spectroscopic analyses (LIBS and APXS) that confirmed the elemental composition of the soil, identifying the presence of sulphur and other elements. The rover's subsystems are described in the figure 5.5.

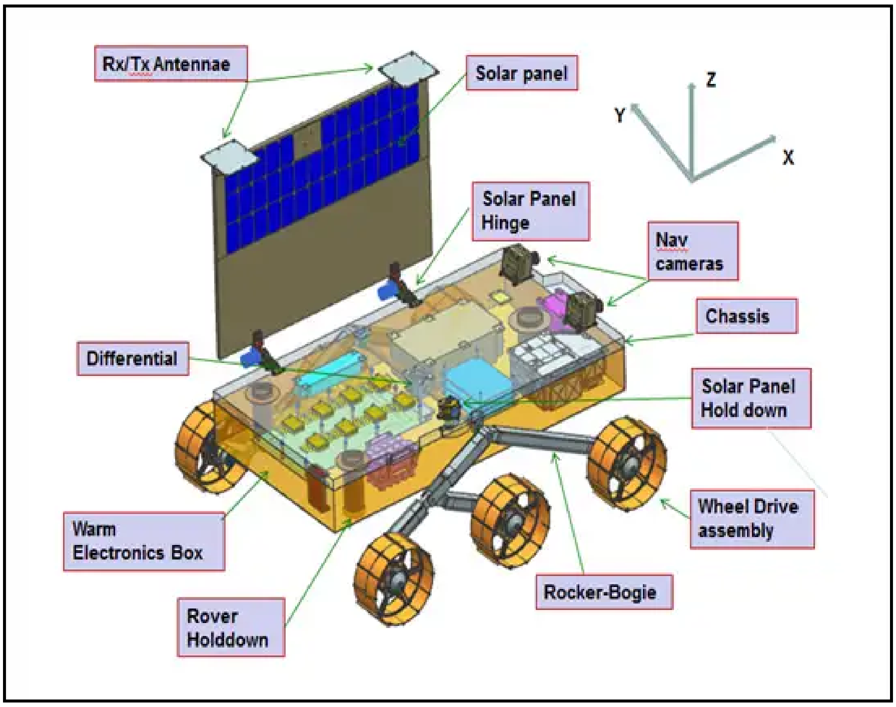

Figure 5.5: Pragyan rover subsystems

India's next strategic step is the LUPEX (Lunar Polar Exploration Mission), an ambitious collaboration with the Japanese agency JAXA **??**. The LUPEX project is an initiative aimed at exploring the Moon for water and other resources and gaining expertise in exploring the surface of the Moon. Observation instruments from NASA and the European Space Agency (ESA) will also be mounted on the rover.

UAE Space Agency

The Rashid 2 rover signifies a substantial advancement in the United Arab

Emirates' space exploration program, building upon the preceding Rashid 1 mission. This upgraded platform is dedicated to high-resolution lunar exploration, with primary scientific objective of conducting detailed studies of the lunar regolith, which is considered a fundamental step for planning future research bases and potential human settlements.

Figure 5.6: Rashid 2 rover from UADE

The rover is equipped with a sophisticated, latest-generation instrument suite, including XRF and Raman spectrometers for detailed mineralogical analysis, automatic regolith samplers, portable microscopes, local magnetic field sensors, and imaging systems capable of operating in extreme lighting conditions. This mission highlights the UAE's strategic transition from a technology consumer to an active developmental partner in aerospace.

5.7 Private Companies

The commercial lunar economy is transitioning from theoretical concept to operational reality, catalyzed by sustained government investment and the emergence of a new generation of private enterprises. Driven by innovations in reusable launch technology that are drastically reducing the cost of access to orbit and beyond, a new generation of private companies is emerging to build the foundational infrastructure for a sustainable off-world economy. These entities are no longer just suppliers to government agencies; they are developing and owning critical assets, offering end-to-end services, and creating new markets for in-space transportation, logistics, and labor. The private landscape can be summarized in two main segment:

- Lander & Rover Providers: Companies that verticalise the business developing both Landers and Rovers, providing end to end mission. This segment consists of vertically integrated companies that offer a complete, turnkey lunar transportation service. They do not just build a rover or lander, but manage the entire mission supply chain.
- Niche Rover Providers: Companies that focus the business on producing and commercializing the rover technology. This segment consists of highly specialised companies that focus all of their resources on the design, development and commercialisation of lunar mobility technology. They do not build landers or manage transport missions.

The two segments compete in the same market, with the advantage of lander and rover providers having access to landing services. On the other hand, the segment that focuses solely on rovers has a greater focus on individual technology. In the following subsections has been illustrate the main private developers of lunar rovers and its business models.

5.7.1 Lander & Rover Providers

Their main product is not the vehicle itself, but the payload delivery service to the lunar surface. Their business model is the Logistic as a Service, based on obtaining contracts from government space agencies (such as NASA or ESA) and private customers (research institutes, universities or other companies) that need to send scientific instruments, technological experiments or other rovers to the Moon. They internally develop (or manage as the prime contractor) the lander's design, its construction, the integration of the customer's payload, procuring the launch from a provider like SpaceX, and mission operations (including the Earth-to-Moon journey and the lunar landing). The business is based on the "High Risk, High Reward" model, because building and successfully landing a lander is one of the most complex and costly engineering challenges. The failure rate is historically high, but success opens the door to multi-million dollar contracts. These companies also develop their own rovers, which can be offered as part of the mission package or used for their own technology demonstrations. The following companies are included in this segment:

Astrobotic Technology (USA)
Astrobotic has positioned itself as a comprehensive "lunar logistics" company.

Its strategy involves a high degree of vertical integration and a diversified product portfolio. It develops its own landers (Peregrine and Griffin), its own lines of rovers and enabling technologies like power infrastructure (LunaGrid) and autonomous navigation software (HazNet). By offering a full suite of services, from payload delivery to surface mobility, Astrobotic aims to be a one-stop-shop for customers seeking access to the Moon. The acquisition of Masten Space Systems to bring propulsion technology in-house further underscores this strategy of controlling key elements of the value chain [79]. It develops its own lines of rovers: CubeRover and Polaris. CubeRover is a modular vehicle designed to provide affordable mobility for scientific instruments and other payloads to operate on the surface of the Moon. Polaris was designed to accommodate diverse lunar payloads with distinct mission profiles, like lunar regolith digging or water ice harvesting. Polaris can support up to 90 kg of payload mass, traverse long distances, and provide direct-to-Earth (DTE) communication. For its CubeRover platform, it offers an end-to-end mobility service at a price of $4.5M per kilogram of mobile payload, a price that includes integration, launch, landing, and surface operations [79].

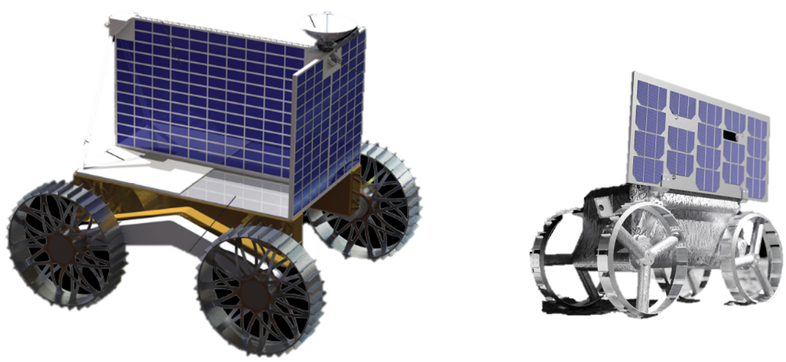

Figure 5.7: Polaris and CubeRover - Astrobotic

Astrobotic's strategy is to offer a broad spectrum of lunar logistics services. Its primary revenue stream is payload delivery, with its Peregrine lander offering capacity at an industry-defining initial price of $1.2 million per kilogram [95]. For its CubeRover platform, it offers an end-to-end mobility service at a price of $4.5 million per kilogram of mobile payload, a price that includes integration, launch, landing, and surface operations [95]. Beyond payload services, Astrobotic actively pursues government R&D contracts through programs like the Small Business Innovation Research (SBIR) program to mature enabling technologies like its HazNet hazard detection software, creating additional revenue and building a valuable intellectual property portfolio [79].

Intuitive Machines (USA)
As the first private company to successfully land a spacecraft on the Moon under the CLPS program, Intuitive Machines has established significant credibility [31]. Its corporate strategy is explicitly built on three pillars: Delivery Services, Data Transmission Services, and Infrastructure as a Service. This framework reveals a clear strategic intent to move beyond being a simple transportation provider [81]. By investing in a lunar data network and other surface infrastructure, the company aims to capture higher-margin, recurring revenue from data and operational services [81]. This focus on the downstream and value-added segments of the value chain positions them as a long-term service and infrastructure provider, not just a hardware manufacturer.

It launched two lunar landers (Nova-C class) and developing Nova-D, a scaled heavy-cargo lander built for larger payloads and advanced lunar infrastructure. Intuitive Machines is developing the infrastructure services to support lunar prospecting, focusing on autonomous surface mobility, lunar data relay enhanced observation, and is currently responsible for the operations and data analysis for NASA's Lunar Reconnaissance Orbiter and ShadowCam cameras. NASA selected Intuitive Machines for the agency's Lunar Terrain Vehicle Services Feasibility.

Intuitive Machines' revenue is primarily driven by large, milestone-based government contracts that align with its three strategic pillars: Delivery Services (CLPS missions), Data Transmission Services (Near Space Network Services contract), and Infrastructure as a Service (LTVS contract). For the full fiscal year 2024, the company reported revenue of $228.0 million, a nearly threefold increase over the previous year, demonstrating rapid growth fueled by these contracts. The company's strategy involves significant vertical integration, such as bringing satellite manufacturing in-house and acquiring key technology providers like the space navigation firm KinetX, to control its supply chain and capture more value from its service offerings [81].

iSpace (Japan/USA)
iSpace is a global lunar exploration company with headquarters in Japan and major subsidiaries in the United States and Europe. Founded in 2010, the company is pursuing an ambitious, long-term vision to create a fully integrated Earth-Moon ecosystem, supported by a high-frequency, low-cost cislunar transportation network [80]. The overarching mission of iSpace is to *"Expand our planet. Expand our future."* by establishing a world where *"the Earth and Moon are one ecosystem".* The company's foundational premise is

that the utilization of lunar resources, particularly water ice, is critical for developing the space-based infrastructure necessary for humanity's future. The strategic exploitation of lunar water for life support and as a source for rocket propellant is positioned as a transformative step that could fundamentally alter the economics of deep-space exploration.

The main program is HAKUTO-R commercial lunar exploration program 5.8, that begins with technology demonstration missions and is designed to evolve into a high-frequency, cost-effective cislunar transportation service. To facilitate this, iSpace is developing a scalable portfolio of spacecraft, including the "RESILIENCE" Series 1 lander for initial low-cost missions, the larger APEX 1.0 lander to serve clients such as NASA, and a future Series 3 lander with significantly increased payload capacity. This program has encountered significant technical setbacks, with both Mission 1 (2023) and Mission 2 (2025) failing to achieve a soft landing due to software and hardware anomalies to the altimeter subsystem.

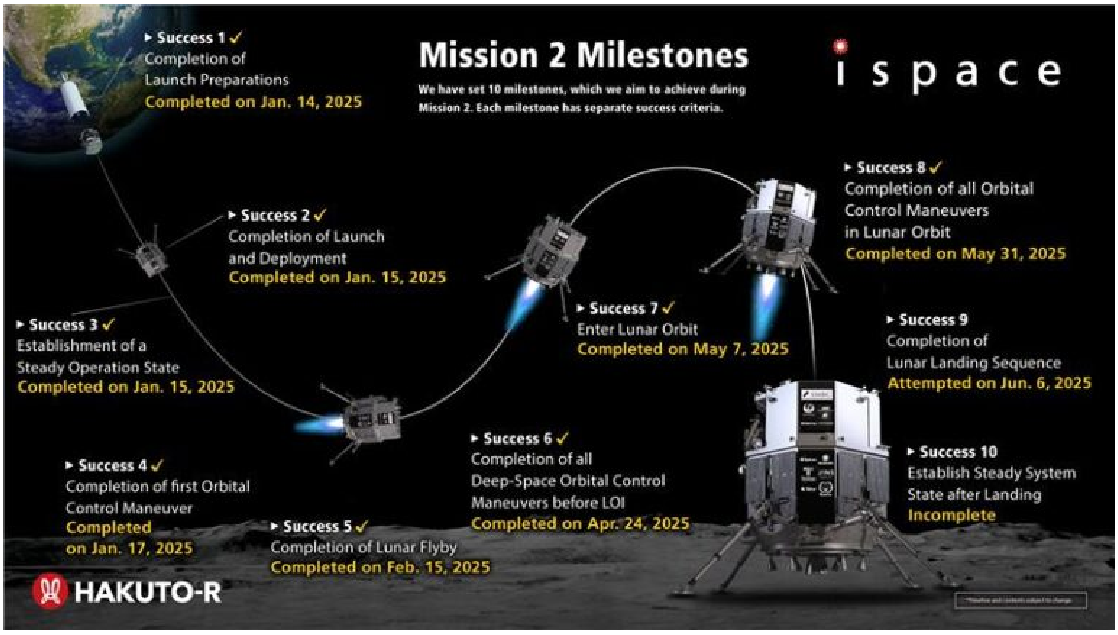

Figure 5.8: HAKUTO-R Mission 2 Milestones

For surface mobility and resource prospecting, the company has developed the "TENACIOUS" micro rover 5.9, with the long-term goal of deploying collaborative rover swarms for in-situ resource utilization (ISRU) operations.

The iSpace business model is structured in three distinct phases:

– Technology Demonstration: Proving core landing and surface exploration

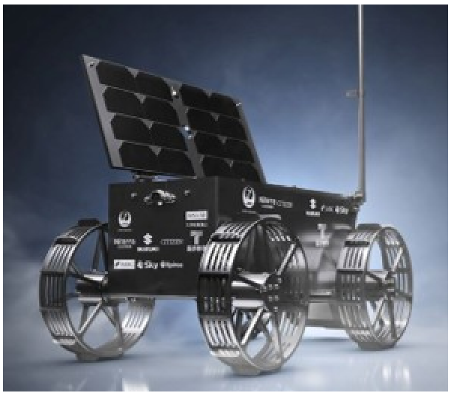

Figure 5.9: TENACIOUS Micro Rover - iSpace

capabilities.

- Transportation Service: Establishing a reliable, high-cadence logistics business.
- Resource Provision: Transitioning to an industrial platform for the large-scale development of lunar water resources.

Primary revenue streams are derived from Payload Services, which involves transporting customer equipment to the Moon, and Data Services, which entails the collection and sale of proprietary lunar data to support mission planning and development activities. Despite a clear strategic framework, While the company's engineering ethos embraces an iterative "fail fast, learn faster" methodology, leveraging data from unsuccessful missions for future improvements, this approach is in tension with the expectations of public financial markets. Financial reports indicate significant revenue growth from payload contracts, but these are offset by substantial and widening net losses driven by high operational and development expenditures. Consequently, the company has had to secure new rounds of capital to fund subsequent missions, creating a high-stakes environment where the success of its next launch is not merely a technical objective but a critical test of market confidence and the viability of its entire business model.

5.7.2 Niche Rover Providers

This group comprises companies that specialise in the development and marketing of rovers. The company's commercial activities are centred on the establishment of contractual agreements with both agencies and private individuals, with the objective of transporting payloads to the Moon's surface and subsequently managing their operations there. The following companies are included in this segment:

Venturi Astrolab (USA)
The commercial space company singularly focused on developing the mobility and logistics infrastructure required for a sustained human and robotic presence on the Moon and Mars [96]. The company's strategy is centered on addressing the critical "last mile" of planetary surface transportation, and aims to become the premier provider of surface logistics, effectively serving as the foundational utility for the burgeoning lunar economy. The business model is centered on providing logistics-as-a-service for the lunar surface. The primary revenue stream will be generated by performing tasks such as unloading payloads from landers, transporting them to their final destinations, and providing essential services to these payloads, including regulated electrical power, data connections, and thermal management through the rover's standardized interface.

Astrolab's core mission is to "design, build, and operate a fleet of multi-purpose commercial planetary rovers to extend and enhance humanity's presence in the solar system" [96]. This vision is underpinned by a development philosophy encapsulated by the mantra "Build. Break. Repeat.". This agile methodology emphasizes rapid experimentation, iterative hardware design, and extensive terrestrial field testing to produce robust systems capable of withstanding the harsh environment of space.

Flexible Logistics & Exploration (FLEX) rover 5.10 is the cornerstone of the company's strategy. It is designed as a multi-functional and adaptable commercial platform for a wide range of activities on the lunar surface, including crewed and uncrewed transportation, scientific exploration, and construction support. To advance the FLEX rover's technology, Astrolab is also developing the FLIP rover 5.10, a smaller demonstration platform. Its landing at the Lunar South Pole is scheduled for 2026 and will serve to test and validate critical subsystems in the lunar environment, providing essential data for the final design of the FLEX vehicle.

Astrolab's strategic positioning is to function as the essential link between large lunar lander and the final destinations of their payloads. The approach is not to build a single-use scientific instrument, but rather a reusable, multi-purpose logistics platform analogous to a terrestrial forklift or flatbed truck. By designing its primary rover platform around a standardized, modular payload interface, the company intends to lower the barrier to entry for a wide range of commercial, scientific, and government payload developers [97], thereby helping to "spur the development of a vibrant off-Earth economy". This

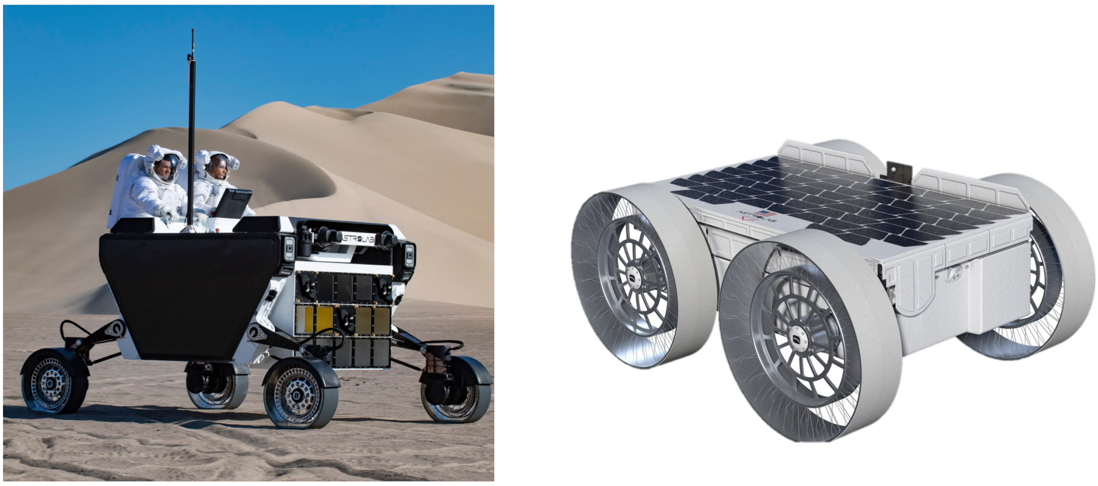

Figure 5.10: FLEX & Flip Rover - Astrolab

standardization shifts the focus from one-off flagship missions to a business model based on the volume and frequency of logistics operations.

The company is targeting three distinct customer segments. The first and most developed segment is commercial payloads. Astrolab has already signed multiple contracts for its inaugural commercial mission, designated "Mission 1," which is scheduled to launch as early as mid-2026 aboard a SpaceX Starship. Initial customers include Argo Space Corporation for a water-harvesting technology demonstration, Astroport Space Technologies for an experiment in manufacturing lunar bricks from regolith, Interstellar Lab for the deployment of small plant pods on the lunar surface and LifeShip, that want to send on the Moon a DNA seed bank archive [98]. The second key segment is government agencies, with NASA serving as a cornerstone customer through the Lunar Terrain Vehicle Services contract [96]. The third, more novel segment is "brand payloads," where Astrolab is marketing opportunities for non-space companies to place their brands on the Moon, opening a potential new revenue stream based on marketing and public relations value.

Lunar Outpost (USA)
This company exemplifies a more specialized strategy, focusing on becoming a market leader in surface mobility. Rather than developing its own landers, Lunar Outpost concentrates on its portfolio of rovers, including the MAPP (Mobile Autonomous Prospecting Platform) for robotic missions and the Eagle 5.11 concept for crewed LTV operations [89]. The MAPP is the most advanced

Figure 5.11: MAPP Rover & Eagle - Lunar Outpost

lunar roving platform ever built. Fully customizable, it allows commercial and scientific customers unlimited access to the lunar surface. The rover is a versatile and cost-efficient platform designed to support a wide range of scientific and commercial missions on the Moon. Its lightweight design allows for high payload capacity, while its architecture supports multiple partners on a single mission, enabling broader access to the cislunar economy. Real-time sensor data further enhances mission efficiency and performance [89]. Eagle concept aims to develop the most capable crewed and cargo transport ever built for the Moon, Mars, and beyond. The rover builds the infrastructure critical to human permanence on other planets, operating continuously in extreme environments with minimal maintenance. Designed with astronaut safety in mind, it supports Artemis missions and the development of a sustainable Moon base, while enabling new mission profiles for infrastructure, resource extraction, and long-range exploration [89]. The company business model relies on partnering with lander providers for delivery and with larger corporations for systems integration and manufacturing scale, as seen in their LTV collaboration [99]. This approach allows them to focus their R&D and capital on their core competency: designing and operating robust and capable rovers.

Canadensys (Canada)
Canadensys Aerospace Corporation is a Canadian space systems and advanced vehicle development company that strategically leverages its nation's esteemed heritage in space robotics to serve a global clientele [100]. Headquartered in Bolton, Ontario, the company has carved out a distinct niche by blending Canada's historical expertise, epitomized by the Canadarm, with an agile and modern commercial business model. The company maintains a highly

diversified portfolio and the corporate strategy fuses the national expertise with modern micro/nano space technologies and commercial business practices to create cost-effective, ruggedized solutions for planetary, orbital, and terrestrial applications. A key focus is developing affordable and robust systems for long-duration operations on the lunar surface. About Lunar Systems, Canadensys is a central player in Canada's national space ambitions, selected by the Canadian Space Agency (CSA) to build the nation's first lunar science rover. The rover will have the ability to drive into and operate inside of permanently shadowed regions for up to one hour survive lunar nights, which can last up to 14 Earth days at less than 200 °C use multiple modes of communication maximize lunar surface operations and scientific data return provide panoramic imagery and video of the lunar surface [101]. It is also conducting

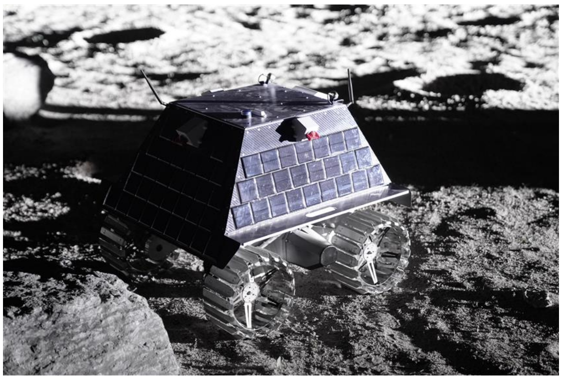

Figure 5.12: Canadian Space Agency - Lunar Rover

studies for a larger Canadian Lunar Utility Rover as part of the Artemis program. Commercially, it pursues a MaaS model, supplying rover platforms for NASA's CLPS missions in partnership with U.S. firms. Canadensys also actively transfers its space technology to industrial and defense markets, developing advanced off-road vehicles like the Hybrid Amphibious Wheeled Carrier (HAWC) and the unmanned Raptor for mining, forestry, and defense sectors. The company exemplifies a successful public-private partnership, leveraging government R&D funding, such as the CSA's Lunar Exploration Accelerator Program (LEAP), to mature and flight-qualify its technologies. This government support, while a small part of its overall business, is a critical enabler that allows Canadensys to prove its hardware in space and subsequently win lucrative commercial contracts on the international market [102].

Deeply integrated into national and international initiatives, Canadensys serves as a prime contractor for the CSA and is a key partner in international missions, supplying subsystems to companies like iSpace and instruments for the International Lunar Observatory Association (ILOA). This strategy has successfully position Canadensys as an indispensable part of the global commercial space supply chain, using its national heritage as a springboard for international commercial success [100].

GITAI (Japan/USA)
GITAI is a space robotics company, originally founded in Japan and now headquartered in the United States, with the mission to automate labour in space and reduce associated costs by a factor of 100 [103]. The company positions itself as the provider of "work" in the space ecosystem, complementing launch companies that provide "transportation". GITAI employs an Agile development methodology and a high degree of vertical integration, producing all core technologies in-house. Its business model is centered on offering for on-orbit services (satellite maintenance, refueling, debris removal) and lunar infrastructure construction, supplemented by the direct sale of satellite components [103]. The company's main products are advanced robotic arms,

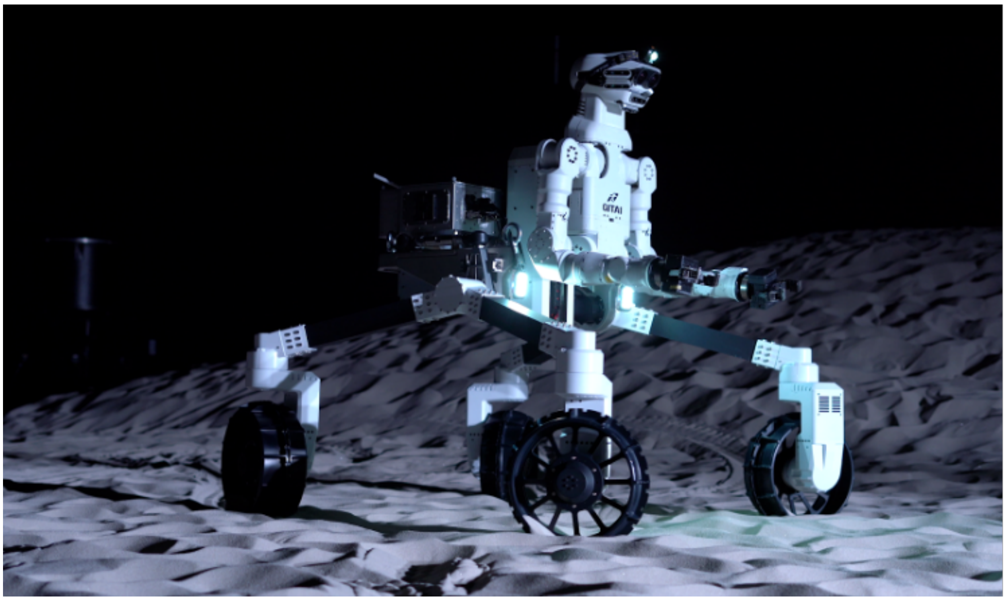

Figure 5.13: Lunar Rover (R1) - GITAI

including the versatile "Inchworm Robot" (achieved TRL-6 for lunar use). It is developing the Lunar Rover (R1), a mobile robotic platform designed specifically for infrastructure construction tasks, such as building communication towers and assembling solar panels. GITAI's business model is structured around Robotics-as-a-Service. The Lunar business is about lunar infrastructure construction, which will see the company deploy its rovers and robotic arms to build essential infrastructure on the Moon [103].

A pivotal and defining element of GITAI's corporate strategy was its decision in 2023 to execute a corporate inversion, shifting its headquarters and parent company from Japan to Torrance, California. By becoming a U.S. company, GITAI gained the ability to hire U.S. persons without export control complications and to compete directly for sensitive U.S. government and defense contracts.

GITAI has secured several key government contracts that validate its market access strategy. It was awarded a contract by the Defense Advanced Research Projects Agency (DARPA) for the 10-Year Lunar Architecture (LunA-10) study, focused on developing concepts for lunar infrastructure. It was also selected for NASA's Small Business Innovation Research (SBIR) program to develop robotic construction techniques for building tall power and communication towers on the Moon. While now a U.S. company, GITAI maintains strong ties to its country of origin, having been awarded a contract by the JAXA to conduct a concept study for a robotic arm for Japan's planned crewed pressurized lunar rover. On the commercial front, the company has a joint research and development agreement with Toyota Motor Corporation for a robotic arm intended for the "LUNAR CRUISER" pressurized rover project [104].

Space Application Services (Belgium)
Space Application Services NV/SA is an independent Belgian company that stands as a veteran and foundational pillar of the European space industry. The core mission of Space Application Services is to "research and develop innovative systems, solutions, and products and provide services to the aerospace and security markets and related industries" [105].

A key element of the company's long-term strategy is diversification. Space Application Services operates across multiple markets, including Space, Health, Security, and Environment, and has a proven ability to transfer knowledge and technologies developed for the demanding space domain to terrestrial applications.

In the domain of robotics and planetary exploration, the company is developing the LUVMI-X. The LUMVI-X team is made up of scientists and engineers from a consortium of public and private-sector organisations, like Open University (UK), Technical University of Munich (GER), OHB, Dynamic Imaging Analytics, The German Aerospace Center (DLR) and Laser Zentrum Hannover e.V. (LZH) [106]. LUVMI-X (5.14) is a lightweight lunar rover bound for the polar regions of the Moon. The goal of the rover is to search for water and other volatiles, scoping out the lunar environment in support of the establishment of a lunar economy and of future human missions to the Moon

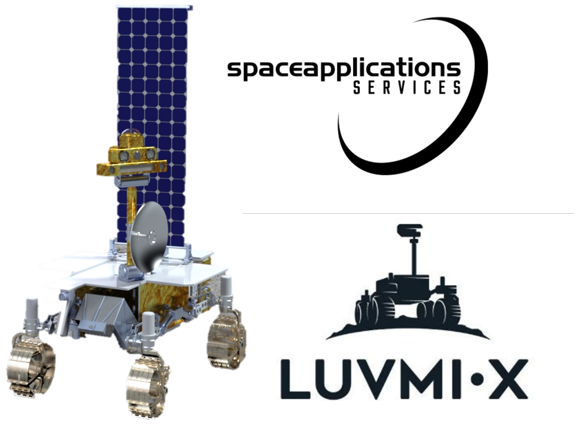

Figure 5.14: LUMVI-X - Space Application Services

and beyond. The project focuses on the design of a mobile platform with standardised instrument interfaces, featuring cutting-edge payloads able to feature cutting-edge instruments able to analyse volatiles remotely, and others that measure radiation. The rover will have room for custom instruments that other scientists may wish to send to the Moon in the near future [106]. They are also working on the HOTDOCK [107], a standardized docking interface. It allows assembly and reconfiguration of spacecraft and payloads on-orbit and on planetary surfaces. It is designed to support launch loads and makes it straightforward to replace failed modules, or to swap payloads and provides chainable data interfaces for multiple module configurations. Mounted on the tip of robotic manipulators, HOTDOCK performs as a quick connect /disconnect interface for end-effectors and tools [107].

The strategic positioning of these companies illustrates a crucial trend: the most forward-looking firms are not defining themselves by the hardware they build, but by the services they provide. The rover is the means, not the end. The long-term economic potential lies in operating these assets on the lunar surface to generate continuous streams of data, services, and resources.

5.7.3 Analysis of the Panorama

A key trend across the sector is the shift from selling hardware to offering "as-a-service" business models. Companies are positioning themselves as long-term utility providers rather than just manufacturers, aiming for recurring revenue streams. Two dominant strategic archetypes are emerging, and each of them has strengths and weaknesses.

Companies adopting an "end-to-end" model, developing both lunar landers and rovers, pursue a highly integrated but complex business strategy. The primary advantage of this approach is the ability to offer a comprehensive, "one-stop shop" service, managing all mission phases from launch procurement to surface operations. This turnkey solution is highly attractive to clients, such as space agencies, seeking to avoid payload integration complexities. Furthermore, this model allows for optimized technical integration between the lander and rover—enhancing systems like deployment, power-sharing, and communications—while granting the company full mission control and enabling greater value capture. However, this strategy carries substantial drawbacks, chiefly the extreme technical complexity and high-risk nature of lunar landing, which demands immense capital investment. This creates an "all-or-nothing" risk profile, where a single landing failure results in the catastrophic loss of the entire mission, including the rover.

On the other hand, the specialized business model, in which companies exclusively focus on rover development, prioritizes technical excellence in surface mobility. By focusing resources on solving challenges such as regolith, thermal extremes, and autonomy, these companies aim to produce more reliable and innovative vehicles. This specialization requires significantly lower development capital and affords greater market flexibility; a "lander-agnostic" rover can be sold to any entity with transport capabilities, diversifying business risk away from the success of a single lander partner. However, the critical disadvantages are the total dependency on third-party lander providers for lunar access and the inherent design complexity of ensuring that the rover is compatible with multiple, varied lander interfaces. This specialization also means that the company captures a smaller portion of the total mission revenue, since it provides a product rather than a complete end-to-end service.

Geostrategic factors are critical. A U.S. domicile provides a significant advantage in securing lucrative government and defense contracts, a fact highlighted by the Japanese company GITAI moving its headquarters to the U.S. Meanwhile, international players like Canadensys (Canada) and iSpace (Japan) leverage strong national government support to build their capabilities and compete globally.

Finally, the market is characterized by high risk. The case of iSpace, which has faced landing failures, illustrates the tension between the engineering need to "fail fast and learn" and the unforgiving expectations of public financial markets, making capital resilience a key factor for survival.

5.8 "Moon as a Service" Business Models

The renewed global focus on lunar exploration is accompanied by a significant evolution in operational and business strategies. A pivotal development in this landscape is the emergence and adoption of the MaaS business model. This approach represents a strategic departure from traditional, government-led space missions towards a more collaborative and economically sustainable framework for establishing a long-term human presence on the Moon [87].

5.8.1 Conceptual Framework and Key drivers

The MaaS model entails government agencies, primarily NASA, procuring lunar services from commercial entities rather than owning and operating all the requisite hardware and infrastructure. This is encapsulated in NASA's selection of companies like Intuitive Machines, Lunar Outpost, and Venturi Astrolab for the development of lunar terrain vehicles under an "as-a-service" acquisition model. This arrangement utilizes an indefinite-delivery/indefinite-quantity, milestone-based contract framework, which in the case of the LTVs holds a potential value of USD 4.6 billion [87].

This strategic shift is largely driven by a commitment to mitigate the fiscal uncertainties and historical budget overruns associated with large-scale space programs like Artemis. By outsourcing specialized services through firm-fixed-price task orders, space agencies can leverage the expertise of the private sector, access cutting-edge technology with minimal upfront investment, and share developmental risks. The core tenets of the MaaS model—cost (effectiveness, resilience, and sustainabilit) are expected to increase reliance on commercial vendors for a range of activities, from payload integration to complex mission management [87].

5.8.2 Market Dynamics and Economic Outlook

The lunar market is poised for significant growth, with forecasts predicting over 450 missions between 2023 and 2033, generating a cumulative revenue of USD 151 billion. While commercial players are expected to lead approximately 50% of these missions, government and military organizations will remain the primary drivers of demand and will dominate the economic activity, accounting for an estimated 75% of the total revenue. Public-private partnerships are instrumental in this economic structure [82, 87].

The market is anticipated to undergo a significant transition post-2029, following the projected success of crewed Artemis missions. The focus is expected to shift towards infrastructure development and in-situ resource utilization (ISRU), creating new opportunities for commercial entities in resource extraction and the establishment of a self-sustaining lunar economy [87].

A key examples of "as-a-service" models pivotal for lunar development is the European Space Agency's Moonlight. This initiative is a prime example of a governmental push to foster such commercial services, aiming to create a shared network available to any future lunar mission on a subscription basis [62, 63].

5.8.3 Future Prospects and Strategic Imperatives

The MaaS model is projected to become the standard procurement method for capital-intensive and long-term lunar development projects. This will enable commercial players to secure stable, recurring revenue streams through multi-year contracts and scale their capabilities according to customer needs. As foundational infrastructure for transportation, communication, and navigation services becomes more reliable, the prevalence and impact of MaaS models are expected to grow significantly [87].

For commercial entities, a dual-focus strategy is imperative. They must continue to secure governmental and military contracts, which form the cornerstone of market opportunities in the near term, while simultaneously incorporating commercial ventures into their strategic roadmap. By capitalizing on the infrastructure built for government missions, these companies can position themselves at the forefront of the evolving lunar landscape, ready to service a burgeoning commercial demand for resource extraction and infrastructure building. This strategic alignment will be crucial for the development of a robust and sustainable off-world industry [87].

5.9 Logistic as a Service

Logistics as a Service (LaaS) is a business model based on outsourcing logistics processes to a specialised provider, which delivers these services through a technological platform, often cloud-based. Instead of building and managing its own logistics infrastructure (warehouses, transport fleets, software), a customer can purchase only the services it needs, when it needs them, paying flexibly.

This business model is based on a number of key features that differentiate it from traditional logistics or classic outsourcing (such as 3PL - Third Party Logistics):

- **Flexibility and scalability:** This is the main advantage. Companies can quickly increase or decrease their logistics capacity without having to incur fixed costs for unused resources.
- **Pay-Per-Use Model:** Costs are variable and linked to actual use of services. This transforms fixed costs (CAPEX) into variable operating costs (OPEX), freeing up capital.
- **Access to Networks and Expertise:** The LaaS provider makes available knowledge and assets that would be too expensive for a single company, especially a small or medium-sized one, to develop internally.
- **Focus on Core Business:** By delegating the complexity of logistics, the client can focus its resources and management on its core activities.

Logistics as a Service transforms logistics from a fixed and complex cost centre into a flexible, technological and on-demand service, enabling companies to be more agile and competitive in the market. In a highly technological and expensive market such as space exploration, this business model shows all its advantages and has been adopted by Launchers and Landers producer companies.

Company such as Intuitive Machines, iSpace and Astrobotic adopts this business model.

5.10 Mobility as a Service

The quintessential example of the new commercial paradigm is the MaaS model, which is being applied to the procurement of the next-generation LTV for the Artemis program [87].

In this model, NASA does not purchase and own the rovers. Instead, it buys mobility services from a commercial provider who is responsible for the entire life cycle of the vehicle: design, development, launch, landing, and long-term operations on the lunar surface [99].

In April 2024, NASA awarded contracts for feasibility studies to three industry teams led by Intuitive Machines, Lunar Outpost, and Venturi Astrolab. Following this phase, the agency intends to select a single provider for a demonstration mission and subsequent long-term service provision [99]. LTV contract is structured as a milestone-based IDIQ with a potential total value of $4.6 billion over a service period extending to 2039 [87].

The value proposition of MaaS is compelling for all stakeholders:

- **For the Customer:** The model minimizes large upfront capital expenditures and shifts development and operational risk to the commercial partner. NASA gains access to cutting-edge technology and innovation from the private sector while paying only for the services it consumes, leading to significant potential for cost optimization and budget stability [87].
- **For the Provider:** The long-term nature of the service contract provides a stable, predictable revenue stream. Crucially, the provider retains ownership of the asset and has the right to use the LTV for other commercial purposes when it is not being used for NASA missions. This allows the company to serve multiple customers, such as other space agencies, private research institutions, or resource extraction companies. It allows to diversify its revenue base and maximize the return on its investment [99].

This business model is the true innovation. It aligns the incentives of the government and the private sector. The provider is motivated to build a highly reliable, durable, and capable rover because its revenue is tied to the vehicle's successful operation over a decade or more, not just its initial delivery. This focus on long-term performance and sustainability is a powerful driver for creating robust and cost-effective lunar infrastructure.

5.11 Rover as a Service

Rover as a Service (RaaS) is a business model in which the customer does not buy or develop a robotic rover (the hardware), but purchases the service that the rover performs, paying a pay-as-you-go fee or a subscription. The supplier takes care of everything, design and construction of the rover, navigation, data and operational management, maintenance, recharging and updates.

The customer only pays for the result: the data collected, the kilometers travelled, the deliveries made or the payload transported.

This model has become a disruptive business model, particularly in the space sector: NASA is not purchasing the rover; it is purchasing a lunar transport and mobility service. This reduces costs and greatly accelerates the pace of exploration [31].

In this business model the customer does not have to spend to purchase or develop the robot. It transforms a capital cost into an operating cost (OPEX), reducing CAPEX (Initial Cost). Also, the scalability become easier, because if the demand for the rover increase the customer doesn't have to produce more hardware but just increase the hours of service needed.

In space exploration field, the necessity of prioritizing the core business is paramount. Agencies needs to focus on scientific research, with robotics engineering being the domain of the rover service provider.

Commercializing a Lunar Rover with RaaS includes the provision of different services that can be provided to the customer:

- **Payload Hosting:** This service targeted customers that developed their own payload and want to operate it on the Moon surface.
- **Data Service:** Sensors needed for rover system to survive and operate on the Moon surface collects data. These data can be sold to customers for their own business or scientific studies.
- **Task Service:** This service consists of performing tasks with the robotic lunar infrastructure. In a future in which there will be a permanent human base on the moon surface, a robotic system capable to operating in the lunar harsh environment will be fundamental. Customer are space agencies and space industries, that need to operate, build or maintain their infrastructure on the Moon surface.

This business maximizes infrastructure profitability, differentiating risks. A Rover system on the moon is comparable to an infrastructure difficult to maintain, and having multiple revenue streams is an effective strategy for optimizing the economic efficiency. It enables the depreciation of launch costs and facilitates risk distribution, thus reducing the likelihood of economical mission failure. The services provided are few and have high added value and there are no observable past cases. So prices has been negotiated per mission and forecasted magnitude is in the order of millions of dollars.

Chapter 6

Conclusions

This study concludes that the Space Economy is experiencing a period of significant growth. The Upstream Space Segment, in particular, is witnessing an influx of new companies and novel business models, which are stimulating increased investment in the sector. Notably, defense applications account for a significant percentage of this financial growth.

Although still in its nascent stages, the lunar domain is expanding and presents considerable opportunities for commercialization. While the political and strategic interests driving lunar exploration are evident, the primary commercial driver currently remains the development of terrestrial technology spin-offs. The market landscape is witnessing the increasing prominence of private entities as key actors. The ARTEMIS program, guided by its 'Moon to Mars' philosophy, is acting as a key catalyst for the sector, fostering the emergence of new corporate ventures characterized by the introduction of innovative technologies and business models.

The Moon-as-a-Service model has been identified as a viable business framework and represents a primary trend for commercializing technologies on and for the Moon. This model enables public agencies to offload significant development costs and timelines, thereby fostering a genuine market economy that, in turn, can propel further technological innovation. It is anticipated that this framework will accelerate the establishment of lunar infrastructure, supporting long-term human habitability and the creation of a permanent lunar base within the next two decades.

The analysis of the current global landscape for lunar rover development highlights that while public agencies remain focused on technology development and scientific projects, private companies are steadily increasing their market share. The private segment will become dominant in the future.

Furthermore, it reveals a specific competitive gap within the private sector: a notable absence of native European companies dedicated to developing lunar rovers is evident.

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