2.1 Economic Rationale

In the last decades, the increasing use of Low Earth Orbit (LEO) has brought huge benefits to the whole space economy. Indeed, as of 2018, the combined size of the global space economy was estimated to be $345 billion USD (US Federal Aviation Administration, 2018). The Moon and cislunar space offer great potential to further boost the space economy beyond LEO in the future. The lunar surface offers valuable resources such as trapped water ice, and other valuable elements. Moreover, cost and performance efficiency gains can be realized through the formation of a new lunar services economy (Hall and Miller, 2016).

> ***"We need to expand the human 'economic sphere' beyond geostationary orbit to the Moon. The Moon represents a critical platform for humanity, [a] foothold into the solar system for the acquisition of water, resources and energy"***
> \- Peter Diamandis, chairman and executive chairman of the X Prize Foundation.
> (Moskowitz, 2011)

Table 2.1 summarizes potential cislunar (the space between Earth and the Moon) market verticals based on current activities and proposed business cases, from a study performed by Entrena Utrilla (2017). However, this section will focus only on potential market verticals that depend on the extraction and utilization of lunar resources and services provided on, from, and to the Moon.

Table 2.1. Prospective cislunar market verticals (Entrena Utrilla, 2017)

Vertical	Description	Activities	Potential companies
1. Water mining	Extraction of water from asteroids or the Moon	Propellant production, consumables, radiation shielding	ispace, DSI, Planetary Resources, Moon Express, TransAstra
2. Metal mining	Extraction of structural metals and semiconductors from asteroids or the Moon	Manufacturing of structures, components, solar panels	DSI, Planetary Resources, TransAstra
3. On-orbit manufacturing	Manufacturing of structures, components, and solar panels; on-orbit assembly	Satellite manufacturing, spare parts, retrofit and repair services	Made in Space, DSI
4. In-space transportation	Tug services, propellant depots	Spacecraft delivery to operational orbit, refueling station	ULA, Altius Space Machines, Shackleton Energy
5. Cislunar stations	Stations in key orbits in cislunar space (LEO, EML1/2, HEO)	Way station, orbital tourism, repair station	Bigelow Aerospace, Axiom Space

6. Lunar landers	Crewed and cargo Lunar landers	Surface payload delivery, crew sorties, lunar base support, lunar exports	ispace, Moon Express, Astrobotic, ULA
7. Lunar base	Central hub in Lunar surface.	Infrastructure deployment and construction, surface activities support, lunar tourism	Bigelow Aerospace
8. Advanced orbital services	Services to satellites, stations, and other spacecraft.	On-orbit refueling, repair, and retrofit, station-keeping, debris management	Skycorp, Vivisat, Effective Space Solutions, Space Logistics
9. Satellite services	Data-based satellite services.	Data relays, navigation and positioning, space internet	Kepler Communications
10. Off-Earth science	Off-Earth research activities and instrumentation.	Planetary science probes, prospecting instruments, astronomy, biology research	DSI, Planetary Resources
11. Beamed power	Beamed power from an orbiting platform.	Beamed power to lunar surface, to spacecraft	Solaren

2.1.1 Economic Rationale for Going

2.1.1.1 Lunar Resources Extraction and Utilization

According to a study performed by PricewaterhouseCoopers (PwC) and the Luxembourg Space Agency (PwC, 2018), SRU (Space Resources Utilization) has the potential to bring humankind many socio-economic benefits.

> The space resources utilization industry is: ***"[...] expected to generate a market revenue of 73 to 170 B€ (Present Value 2018) over the 2018-2045 period, supporting a total of 845,000 to 1.8 million full time employees-years. Efficiency gains in the form of cost savings for the end-users (i.e., customers of space resources) are estimated at 54 to 135 B€ (present value 2018)"*** (PwC, 2018).

Lunar resource utilization is important for sustainable and affordable robotic and human lunar missions because it has the potential to reduce mass, cost, and risk for missions. Indeed, different raw resources, such as water ice, rare Earth elements, and structural metals are available on the Moon and could be utilized for energy production and transportation (Kutter and Sowers, 2016).

The lunar resources extraction and utilization could actually foster the growth of new space-related market, drastically increasing the value of the space economy, and thereby furthering the economic growth of space faring nations. This Earth-centric economic benefit is one of the reasons why humankind should return to the Moon, and is elaborated upon in Section 2.1.1.3.

Water and Metal Resources

Although liquid and vapor water cannot be sustained on the lunar surface, recent scientific studies confirm the presence of a significant amount of water ice on the Moon (6.6 billion tons of water estimated according to Williams (2012)). The extraction of water from the lunar poles could be used for producing propellant and for supplying the water needed by a human settlement on the Moon. Spacefaring nations and private companies involved in lunar missions would also be able to purchase water directly on the Moon, overcoming the expensive transportation of this essential resource from Earth, and making lunar missions more routine and crucially more profitable (Kornuta, 2018; Spudis, 2016). Therefore, a space-based market for water could emerge, given the high economic value of this resource in space, in which water becomes the lunar gold standard and the main medium of exchange (Allison, 2017).

Besides water, the lunar soil is rich in metals in the form of oxides. The majority of the oxides in the lunar regolith are silicon, aluminum, calcium, iron, magnesium, and titanium. Metal production from the lunar soil is interconnected to oxygen production, which is necessary to sustain human life on the Moon, since the latter must be extracted from minerals separating the oxide molecules. The in situ metals production could be one of the sources of raw material to build spacecraft and launcher structures, along with other facilities and tools (Larson, 2012). These resources serve as an enabler for the potential market verticals described in the introduction to this section, and the lunar-based services market described below in Section 2.1.1.2.

Electrical and Nuclear Power

Generating electrical power in space for transmission back to Earth is a potentially rewarding space economic activity (Asgardia.space, 2018). A concrete example of this idea is lunar-based Solar Power (LSP), a concept developed by Dr. David Criswell in the early 1970s and is currently still favorable, involving solar array bases that could be installed on the lunar surface to power not only a small lunar settlement but to support the entire Earth.

The idea consists of 10 initial collecting bases at the edges of the lunar nearside, equipped with microwave reflectors that from Earth would appear to overlap. Therefore, the power transfer from the Moon and the Earth would be based on small and cheap satellites in Earth orbits receiving the microwave beams and redirecting them to the Earth-based receiving antennas, which would convert the microwave radiation into electrical power.

The market for electrical power could create a new economic market on the Moon,, which could turn out economically favorable over Earth-based solar power, if supported by a large-scale power production on the Moon. Besides the economic benefits, a power generation/transfer system would alleviate the scarcity of resources and the environmental damages due to fossil fuels production and consumption, which translates into direct benefits for Earth in terms of establishing clean power and sustainable cities.

LSP has been contentious in the past. As reported by John Mankins, President of Mankins Space Technology Inc., “A power station on the Moon would deliver roughly 200 gigawatts to a single location on Earth. There are no markets that need that amount of power in a single large chunk” (Dorminey, 2017).

Power generators on the Moon and Moon-Earth power transfer systems could be based also on a different source: nuclear energy. Indeed, many studies have assessed the feasibility of mining the rare isotope ^{3}He to power fusion reactors on the Moon and at the same time high quantities of the radioactive element thorium have been identified in different region of the lunar surface (Redd, 2011). Although it is a potentially lucrative source of energy on the Moon, it has always been contested for different reasons, namely because nuclear fusion has not been technologically developed sufficiently to be used as a power source. Additionally, the amount of mining required to extract enough radioactive material for the nuclear fusion could potentially destroy the Moon surface (Spudis, 2016).

2.1.1.2 Lunar Services

Private companies are striving to access space to be the pioneers of innovative space services, such as space tourism and in-orbit manufacturing. This has been defined by many as "New Space", where the space market is open to private actors (Hay, et al., 2009).

New Space, along with the commercialization of space resources, enhanced by Public-Private Partnerships (PPPs), capital investments, and new business models, represents the future of the space economy. This section describes the major new space services that could be created on the Moon and the economic rationale behind them.

Lunar Propellant Production and Refueling Service

As already mentioned in Section 2.1.1.1, the water extracted on the Moon could be used as drinkable water, but also for rocket propellant production and oxygen for life support systems through the separation of the water molecule into hydrogen and oxygen molecules.

It can create a new fuel production and transportation service, which seems to be the best near-term opportunity for the new space entrepreneurs interested in investing in lunar services. This is due to expectations about demand and availability of water on the Moon. For instance, United Launch Alliance (ULA) has already offered to pay $3,500 USD/kg for liquid hydrogen/liquid oxygen fuel in LEO and $500 USD/kg on the Moon's surface.

Table 2.2. Cost of LO2/LH2 propellant transported from Earth or the Moon in different locations (Kornuta, 2018)

	From Earth (USD/kg)	From Moon (USD/kg)
Earth Surface	1	--
LEO	4,000	3,000
GTO	8,000	1,500
GEO	16,000	1,500
EML1	12,000	1,000
Lunar Surface	36,000	500

As shown in Table 2.2, the cost of propellant (in this case liquid hydrogen/liquid oxygen fuel) is primarily driven by the cost of transportation of that propellant to a given location. According to Kornuta (2018), the current cost of propellant on Earth is only $1 USD/kg, while the transportation from Earth to space would dramatically increase the cost up to $36,000 USD/kg. On the other hand, propellant produced directly on the lunar surface will be cheaper on the Moon ($500 USD/kg), while transporting it to Earth would increase the cost again (Kornuta, 2018).

Fuel production on the lunar surface would also foster the growth of a service economy on the Moon for refueling spacecraft.

"If we are serious about living and working in space for the long haul, we are not going to discard our hardware every time it breaks down or runs out of propellant"

- Dr. James Vedda, senior policy analyst in the Center for Space Policy and Strategy at the Aerospace Corporation

Indeed, a lunar refueling service would help to overcome the mission limitations related to the amount of fuel that can be currently carried, and that is necessary for orbit and attitude control maneuvers. For instance, crewed lunar missions would benefit from lunar surface refueling for lander reuse, instead of transporting new systems from Earth for every landing.

Lunar Transportation

Today, lunar transportation services already exist. For instance, XEUS is able to deliver 70 metric tons of liquid hydrogen/liquid oxygen propellant produced on the Moon for future transportation between the lunar surface and Earth-Moon Lagrangian point 1 (EML-1). The estimated cost is only one thousandth of the cost of delivery from Earth (Asgardia.space, 2018; United Launch Alliance, 2017).

Currently nine American companies are eligible to bid to deliver science and technology payloads for NASA through Commercial Lunar Payload Services (CLPS) contracts, which involves providing launch from Earth and landing on the lunar surface, besides payload integration and operations.

"The Commercial Lunar Payload Services contracts are indefinite delivery, indefinite quantity contracts with a combined maximum contract value of $2.6 billion [USD] during the next 10 years […] Lunar payloads could fly on these contracted missions as early as 2019"

(Warner and Knotts, 2018).

This is just a first step towards the growth of a much more complex lunar transportation service where both private and public agents will be involved.

Furthermore, achieving robust and sustained rocket reusability is a major imperative for the future of the lunar transportation economy. Following the breakthroughs achieved recently by SpaceX in this area, which significantly reduced the cost of spaceflight, a reusable vehicle with the ability to provide frequent transportation of resources and people to and from the lunar surface would open access to the Moon for new space actors.

Lunar Tourism

According to LP Information (LPI), by 2023 the Space Tourism sector will register a 17.3% Compound Annual Growth Rate (CAGR) in terms of revenues, reaching the peak of $1.27 billion USD (LPI, 2018).

The lunar touristic missions will likely bring part of those revenues to the space tourism market. A 1-2 week round trip could be practically and operationally convenient for travel companies, without exposing lunar tourists to the long-term risks of the lunar environment. Lunar tourism may also bring economic benefit to Earth, through an emerging lunar travel service industry (Collins, 2003; Van Pelt, 2005).

In the past, more than one company have proposed lunar touristic mission concepts. Over a decade ago, Space Adventures announced plans to send people to the Moon, using a Soyuz to reach the International Space Station (ISS) and dock with a habitation module, before being launched again towards the Moon and completing a trip around it. The almost two week mission originally costed $100 million USD a ticket, later the price raised to $150 million USD, but demand did not match the expectations. S.P. Korolev Rocket and Space Corporation (RSC) Energia and Constellation Services International (CSI) are two other companies that have expressed the intentions of developing their own lunar tourism plans (Foust, 2017).

Nevertheless, today, SpaceX is in a better position than others to provide such a service. On March 8th 2019, the SpaceX's Crew Dragon ended its first mission to the ISS, with a splashdown in the Atlantic ocean after a 6-day flight. This will give USA the possibility to bring astronauts to the ISS again after the Space Shuttle's last mission in 2011 (Wall, 2019). Furthermore, in September 2018, Elon Musk announced plans that the first private lunar passenger flight mission of the BFR (Big Falcon Rocket), scheduled for 2023, which could represent the first lunar tourist in space: the Japanese art curator and fashion innovator Yusaku Maezawa. The mission, consisting of a flyby of the Moon and the completion of a lunar transit before going back to Earth, will last one week (Williams, 2018a).

In order to increase the demand for the space tourism market (in particular lunar tourism), cost and safety are fundamental drivers to achieve a more economically viable service. Spaceflight is still expensive, but the New Space private agents are contributing to reduce the costs, by developing new reusable, low cost vehicle prototypes (e.g. Virgin Galactic, Blue Origin, SpaceX). At the same time, the risks of spaceflight are still relatively high and the number of people who have been to space is relatively low. It could take time for spacecraft to become suitable for tourism, in the same way that it took time for airplanes to evolve for tourism (Van Pelt, 2005; Toivonen, 2017).

2.1.1.3 Other Socio-Economic Benefits

Economic Growth and Employment Multiplier

The space industry has an economic impact on both economic growth and creation of employment. Space activities are very profitable investments: "every €1 [EUR] invested in space returns an average €6 [EUR] to the wider economy" (ESA, 2012). Furthermore, space activities can foster the creation of high-qualified jobs in the space sector itself, but also in other related industries. An example is given by Sadlier (2015), which analyzes the UK space industry, which was characterized by a Gross Value Added ratio of 2.2 and an employment multiplier ratio of 3.1 in 2014, meaning that for every job in the UK space industry, more than three new jobs are created.

Spin-Offs

Several terrestrial application spin-offs will transfer knowledge and technology from space to many different technical domains, such as material science, manufacturing, additive manufacturing, robotics, and data analytics. PwC states that: "It is forecasted that these spillover benefits will be in the order of 2.5 B€ over 50 years (present value 2018)" (PwC, 2018).

Network and knowledge spillovers will also have a very strong impact on the growth of new industrial partnerships, facilitating the exchange of personnel between different public and private agents, as well as between developed space nations and developing space nations through employee training (PwC, 2018).

Spin-Ins

The space sector is also a client for existing products and services. The money that would be spent in order to accomplish human settlement on the Moon is still spent within the markets here on Earth. Therefore, the products and services that would contribute to this effort would stimulate economic activity. As the number of humans in space or on the Moon increases, the amount of Earth products and services that will apply to the space sector will increase.

The global market size for digital transformation has a growth rate of over 18.5% CAGR and is expected to surpass $462 billion USD by 2024 (Bay, 2018). The size of the entire space industry is expected to value $558 billion USD by 2026, at a CAGR of 5.6%: this means that the vast amount of innovation in cyber-physical systems will come from Earth-based applications, due to the much higher investment in the development of this technology (Smith, 2018). Section 3 (Roadmap) outlines the various applications of robotic systems in space throughout the five phases of lunar settlement. Therefore, the spin-ins of robotic systems from Earth-based contexts will enable the future phases of the Roadmap as well as stimulate the economy on Earth.

2.1.2 Economic Arguments Against Going and Responses

2.1.2.1 Cost Efficiency

Returning to the Moon is not the most cost efficient investment that governments or private agents could make in space. Nevertheless, the payoff is sufficient to justify this endeavor.

The costs of establishing a lunar base are much higher than any other future Lunar exploration missions. This is highlighted by (Sadlier, 2015), which performs a cost estimation of a future international lunar exploration endeavors, as shown in Table 2.3, with an estimation error of ±30%.

Table 2.3. Cost estimates of an international lunar exploration endeavor (2015 prices) (Sadlier, 2015)

Activity	Cost Estimation (USD)
First footsteps back on the Moon (single provider)	$4.6 B
Lunar base producing 200 MT/yr propellant	$38 B
Private passenger trip to the Moon	$0.8 B

However, the potential cultural, social, and scientific benefits of establishing a lunar base as opposed to just walking on the Moon again or sending a private passenger are incomparable. While the aforementioned missions are little more than political or touristic stunts, a lunar base would stimulate the economy, promote scientific endeavors, and lead to the benefits mentioned in the sections above and below within this section.

2.1.2.2 Opportunity Cost

When investing in a new project, it is critical to consider the best option foregone, also known as the opportunity cost.

The more recent opportunity cost of the Lunar Orbital Platform Gateway (LOPG) could be equivalent to up to twenty different interplanetary missions, according to Wang (2018). Therefore, if forced to decide between building a platform in lunar orbit, or an outpost on the lunar surface, the latter option is the one to choose due to the large amount of natural resources offered by the Moon, and the new markets and lunar space services that could grow and benefit the whole space economy (Wang, 2018). Another concern is that if there is significant investment in the LOPG, the project may detract resources (capital, human, time) from establishing a lunar base and disrupt the timeline presented below in Section 3 (Roadmap). However, the LOPG could also be seen as a complementary mission to future crewed missions to the lunar surface.

It is also important to consider how investing in a lunar base may redirect resources away from pressing problems on Earth. However, as described in Section 2.1.1.3 above, and in Section 2.2.1.2 (spin-offs) below, investing in space directly translates into benefits for people on Earth. Eventually, investing capital in activities that could help solve our planet's issues has always been considered as a valid opportunity cost for lunar exploration missions and any other space activity.

2.1.3 Economic Rationale Summary

In order for governments, private agencies, and non-governmental organizations to work towards returning to the Moon, the economic case has to be sound. While spaceflight requires large upfront investments, the money generated through jobs and industry development throughout all phases of lunar settlement, and lunar resources and services once human presence is established on the Moon make that investment worthwhile. The rationales in this section are summarized below in Table 2.4.

Table 2.4. Summary of Economic Rationale

Rationale for Going	Arguments Against Going	Responses
Growth of markets based on lunar resources utilization: • Water based economy • Lunar launchers • Lunar market for electrical power Growth of lunar services • Refueling • Transportation • Tourism • Materials and manufacturing Economic Growth and Employment	Cost Efficiency: • The possible payouts of a lunar mission do not justify the upfront costs.	The cost efficiency of going to the Moon is much higher today than it was before, and the economic benefits outweigh the cost. In order to reach international goals for space, a lunar settlement is the most cost effective option.
	Opportunity cost: • Alternative projects on Earth or elsewhere in space might be a better investment.	Investing in space missions is a way to bring added value to Earth, which was highlighted in Section 2.1.1 The economic case is sound, and the opportunity to use space related spinoffs to benefit humanity is detailed below in Section 2.2.1.3