INSPIRING EDUCATION
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Professional Master Thesis

in the program
Advanced Master in Technology Innovation Management
(Mastère Spécialisé Management de l'Innovation Technologique)

Which economic value is in the lunar economy?

by

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Defended in October 25, 2022

Declaration

I hereby declare that, the contents and organization of this dissertation constitute my own original work and does not compromise in any way the rights of third parties, including those relating to the security of personal data.

Florian Mahieu

2022

“It’s different, but it’s very pretty out here. I suppose they are going to make a big deal of all this”

Neil A. Armstrong, Commander of Apollo 11

Nomenclature

ISRU	In-Space Resource Utilization
ESA	European Space Agency
CNES	Centre National d'Etudes Spatiales (French Space Agency)
ASI	Italian Space Agency
NASA	National Aeronautics and Space Agency
CSA	Canadian Space Agency
JAXA	Japan Aerospace Exploration Agency
CNSA	Chinese National Space Administration
ROSCOSMOS	State Space Corporation "Roscosmos"
CSLCA	U.S. Commercial Space Launch Competitiveness Act
LEO	Low Earth Orbit
GEO	Geostationary Earth Orbit
VC	Venture Capital
UN	United Nations
BEA	US Bureau of Economic Analysis
OECD	Organisation for Economic Co-operation and Development
PGMs	Platinum Group Metals
ISS	International Space Station
R&D	Research and Development
CLPS	Commercial Lunar Payload Services
GDP	Gross Domestic Product
PwC	PricewaterhouseCoopers
NSR	Northern Sky Research
SLS	Space Launch System
PPP	Public Private Partnership

Abstract

INTRODUCTION: During the sixties, NASA and other space agencies did not need to defend their budget. Now things have changed with the trend towards commercialising space and new ambitions to conquer the Moon offering interesting resources. There is no doubt that the lunar exploration will generate economic value. A need is therefore emerging, whether from institutional actors or from new private actors to measure the economic value of such a space exploration or even space exploitation. Short-term economic impacts of space exploration are already well documented in the literature. However, measuring the economic impacts of space activities is complex, and even more trying to get a return on investment in lunar activities.

OBJECTIVES: This work aims at exploring how the economic valuation of the lunar exploration can be made and improved, where the economic value comes from and could come from. Finally, a further aim is to provide recommendations on how to better assess and discern the lunar economic impact.

METHODS: Literature review

RESULTS: The Moon is full of resources, not all of which are interesting in the short term but the lunar economy can address all sectors of the economy. Measurements of lunar potential economic impacts can be improved with better cooperation between the different stakeholders.

CONCLUSION & RECOMMENDATIONS: The recommendations are mainly based on the creation of an economic framework which can be done with more collaboration on data sharing.

Keywords: Economic value, lunar economy, moon conquest, natural resources

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1 Introduction

1.1 Empirical interest: humanity's return to the Moon

During the sixties and the Apollo missions. An incredibly high amount of money was spent, "the United States spent $25.8 billion on hardware, facilities, and overhead directly associated with Project Apollo between fiscal years 1960 and 1973" (Dreier, 2022, p. 1). These missions were rather a political war between the big countries about who would be the first to put a flag on the Moon. Now, things have changed and the new conquest of the Moon, on top of still being a charismatic war between the different nations is becoming an economic conquest involving new and different actors. The US ARTEMIS program, aiming to bring back humans on the Moon and insure a sustainable lunar human presence marked the beginning of a new era of lunar exploration. While its long-term objective will be to lay the foundations of a lunar economy and establish a step to go to Mars, this program involves different nations and space agencies such as the European Space Agency but also commercial private actors. In total, there are more than 24 big Moon missions planned by both private enterprises and government organizations from multiple countries such as the USA, China, India, Russia, South Korea, UAE, Japan (Buchholz, 2022). This growing global interest in conquering the Moon stems from multiple factors.

First, the Moon is a well-spatially located celestial body with multiple natural resources making this place important for the economy. Secondly, there is an immense need to tackle the next global energy demand which will result from the global evolution in natural resource consumption and the scarcity of those resources (Jaganmohan, 2020). This global demand tends to increase by a factor of six or

eight by the mid-point of the 21st century (Schmitt, 1999). It is, then, an important topic to explore outer space in order to access new resources. Finally, on top of being a big scientific laboratory for space exploration with commercial potential, the interest in exploring the Moon and establishing a permanent presence lies in the fact that lunar exploration innovations will benefit also terrestrial technological progress and help change various sectors including "energy transition, digital hybridization, and inevitable changes in ways of living and working" (Coxam, et al., 2021, p. 74).

1.2 Theoretical interest: economic value paradigm?

As we can observe in the literature, it exists multiple definitions of economic value. Actually, and as mentioned by (Perrin, 2001), thoughts on economic value are nowadays almost absent in economic sciences. Moreover, as we can see in the news, there is a desire to rethink the way the economy is assessed: a previous French president, Nicolas Sarkozy, missioned an international experts commission composed of two Nobel prized economists to work on measuring the economic performance and the social progress with a purpose to develop "a reflection on means to avoid a too quantitative and too accounting approach of the measure of our collective performances" and elaborate new wealth indicators (Perrin, 2011).

The assessment of the economic value depends on the many uses we can have for a resource. As an example, according to (Ward & Michelsen, 2002, p. 428), the definition of the economic value of water "comes from the many uses to which water can be put in satisfying people's needs". Also, forests have an economic value as they are scarce and have multiple economic uses, allowing a variable choice of economic indicators (Adger, Brown, Cervigni, & Moran, 1995). Therefore, there is no fixed economic value general definition.

Still, a proposed definition of economic value by Mrs Mazzucato in her book 'The Value of Everything: Making and Taking in the Global Economy' is that even if it can be defined in different ways, "it is the production of new goods and services" (Mazzucato, 2018). In this study, we will consider this general definition and develop it throughout our findings.

This permeability of the concept of economic value and all the economic criteria that can be used to measure and assess the lunar economy raise the interest in exploring how the Moon exploration and the establishment of a lunar economy can generate economic value.

1.3 Research objectives

Thanks to a literature review, the aim of this work is to, first, explore, synthesize and try to measure the creation of economic value coming from a lunar economy, or at least, better understand where could the value come from. Then, discuss and provide a critical evaluation of economic value assessment.

1.4 Research contributions

First, the definition of the economic value is something complex without a paradigm. Different economic theories exist and we retain the neoclassical theory that we use to detail value creation and extraction. Economic value is hard to measure but can be assessed via economic indicators which need to be appropriately determined depending on the use cases.

Second, boosted by the NewSpace era and the institutional actors, the race to the Moon as started including private and public actors. This rising interest in conquering the Moon, a big scientific laboratory of choice, lies, in addition of being an argument for political power, in the availability of lunar natural resources and this proximity in Space.

Third, measuring Space economy is something quite complex. The lunar economy, for which the data is only prospective for the time being is not an exception. Nevertheless, the economic impacts of the lunar conquest can be already assessed. We considered two timescales, short-term and mid-term, taking into account the progressive evolution of a lunar settlement to study the economic impacts of the lunar conquest. Then, we explore where the economic value comes from and could come from and different indicators to measure lunar economy.

As a conclusion, we propose recommendations for a better economic valuation of the Moon while presenting the limits of this study.

Chapter 2

2 The economic value creation

Before going further into lunar economics, we need to define what is economic value, what are the creators of this value and how we could measure this complex economic value. In the rest of this document, when we refer to value, we mean economic value.

2.1 Words on Economics and Economy

First of all, it is worth it to define economics, economy and detail their key differences. According to one of the oldest and most known learned society, the American Economic Association[1], economics can be defined as "the study of how people use resources and respond to incentives, or the study of decision-making. It often involves topics like wealth and finance, but it's not all about money" (American Economic Association, s.d.). The study of individuals is called microeconomics whereas the study of larger things such as countries' debt is called macroeconomics. In macroeconomics, the global supply and demand is studied and in microeconomics the study is focused on the behaviour of the consumers, enterprises and markets. Economics is not only the study of money, actually, the money can be seen as the tool (Sloman, Garrat, & Guest, 2018). Economics is also the study of:

- the production of goods and services: how much is produced, who produce, what are techniques used and the number of people employed (Sloman, Garrat, & Guest, 2018).
- the consumption of goods and services: the number of people spending money, the distribution of these people, the prices of these goods and services, the people's incomes and other factors (Sloman, Garrat, & Guest, 2018).

In a nutshell, economics is mainly addressing the decisions made on the scarcity of resources for a human whereas economy is an application of the theory of

[1] Learned society which encourages research, publication and discussions around economics. It was founded in 1885 and is composed of more than 23,000 members.

economics and represents a demarcated area such as a country or an industrial or financial sector.

2.2 A definition of the 'permeable' economic value: prices reveal value

As mentioned earlier, economic value can be seen as measuring the benefits derived from goods or services. How these goods and services are produced, shared across the economy and how the earnings coming from their production are reinvested are key questions in defining the economic value (Mazzucato, 2018). Besides, for instance, it is interesting to ask ourselves if the production of a new factory is valuable as it may pollute so much that it could destroy the environment around it. This shows, that economic value may vary regarding the point of view but especially to the economic theory used. Two theories of value concept are predominant in the literature: the classical theory of value and the neoclassical theory of value (Trinh & Sapena, 2018). The first theory considers that the value is proportional to the amount of labour that has been needed to produce it whereas, in the neoclassical one, the value is driven by the consumer's perception of a product's value.

The economic value is naturally different from the market value. In order to simplify this variable and complex definition of economic value, we will consider the economic value in a resource-based theory in order to propose a definition that can be used all along this work. Through a literature review, (Bowman & Ambrosini, 2000, p. 2) found that resources are valuable "in relation to a specific market environment", "if it exploits opportunities and/or neutralizes threats in a firm's environment" or "if it either enables customer needs to be better satisfied".

In other words, most economists tried to make a clear distinction between economic value and market price (Trinh & Sapena, 2018), but there is no clear understanding of what is economic value. It might be blurry, indeed, what is the economic value produced by a trader for example.

More than 300 years ago, François Quesnay, a French economist, was considering that the production of goods and their trades do not produce value except farming (Eltis, 1975). Since then, things have changed and neoclassical economics are considering supply and demand which reveals price. This shows that the trades reveal prices in general. As a common understanding among economists, we can consider that the value of a good or service is driven by the market price, revealing the price that people are willing to pay for it (Trinh & Sapena, 2018).

2.3 Value creators, extractors and beneficiaries

This then begs the questions: what are value creation and extraction? Who are the creators? Who will benefit from this value?

2.3.1 Value creation and value extraction

Regarding value creation, here again, there is not a clear common definition. According to the Italian-American economist Mariana Mazzucato, 'value creation' can be defined as the way "different resources whether human, physical or intangible interact together to produce new goods and services" whereas 'value extraction' corresponds to "activities focused on moving around existing resources and outputs, and gaining disproportionately from the ensuing trade (Mazzucato, 2018).

By value creation, we mean that values are created following a certain process: inanimate resources (such as machines) are purchased and input to the production, and then, people need to take action to create new use values from these acquired resources (Bowman & Ambrosini, 2000). It is the same with less tangible resources such as brands which need to be associated with products or services to generate value (Bowman & Ambrosini, 2000). The company create value for the customer which can, in turn, create value for the firm. This echoes the definition proposed by Mrs. Mazzucato above.

By value extraction, we mean, for a firm, extracting value from the customers by "maximizing shareholder value" (Denning, 2021). It does not mean that people are necessarily producing products but rather an exchange value that can be captured once the product or service is purchased. Thus, we cannot know if a value has been added through that process or not (Bowman & Ambrosini, 2000). This is reflected by the definition from Mrs. Mazzucato above.

Those differences are highlighted in Figure 1 showing the different two divergent paths taken by firms for the past half century (Denning, 2021).

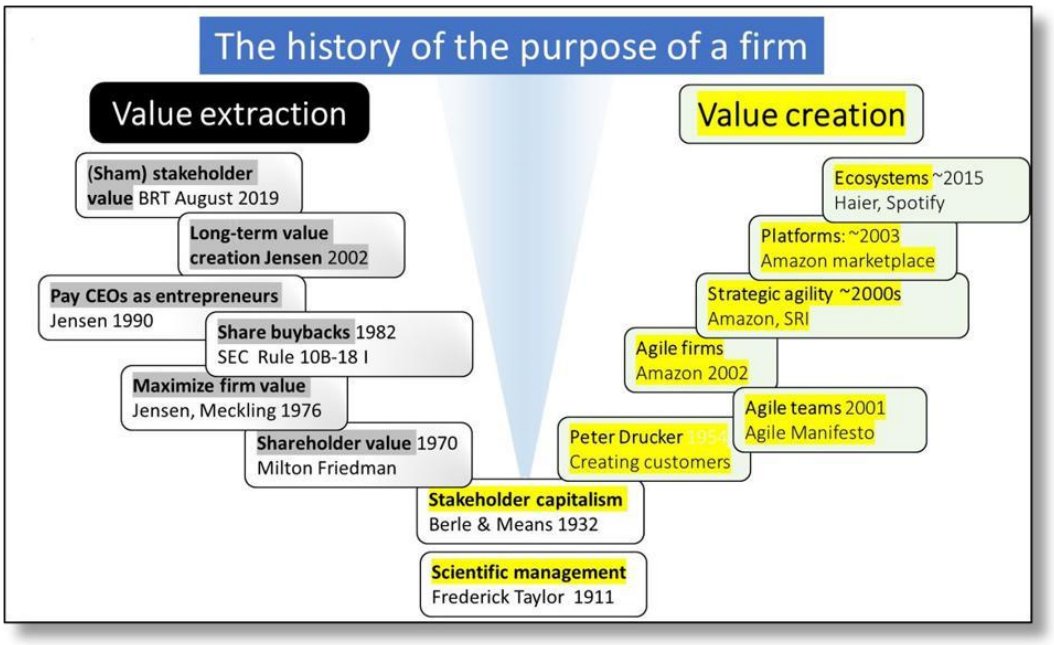


Figure 1: Two divergent paths in the history of the purpose of a firm from Forbes - (Denning, 2021)

As an illustration, with the global increase of market capitalization of firms (Denning, 2021), shown in Figure 2, we can say that we have an ultra-financialized industrial sector where the net income and the profits are not reinjected in production, research and development or human capital training but are reinvested to shares (Mazzucato, 2018).

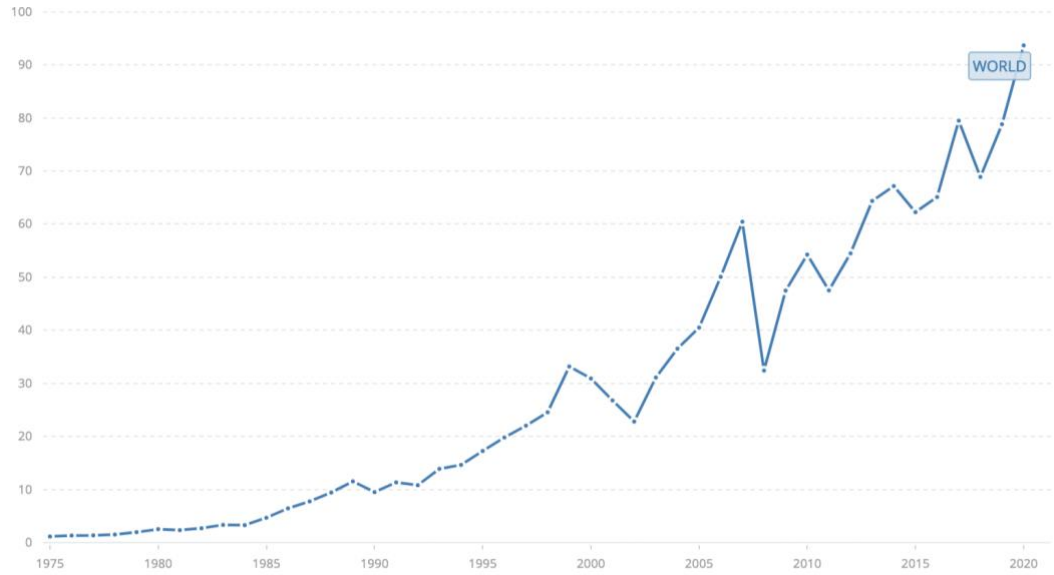


Figure 2: Market capitalization of listed domestic companies in % of GDP (current US$) from (The World Bank, 2022)

In the context of a lunar economy, the question of which path to choose between value creation or value extraction will provide food for thought.

2.3.2 The beneficiaries from economic value

At first sight, it appears clear that economic value can benefit both the customer and the producer. From a value creation perspective, we can say that from a firm and a customer perspective, each stakeholder can benefit from this value because, as a reminder, the process relies on creating value for the customer to get value in return.

In neoclassical theories, economic value rhythms rather with utility value (Trinh & Sapena, 2018) and producing this value needs inanimate, physical or human resources such as people (Mazzucato, 2018). More broadly, economic value can be also linked to other forms of values directly or indirectly linked to the production of goods and services such as employment rate, Gross Domestic Product (GDP) but also other values not linked to economies such as innovative value which can be defined as the evaluation of possible impacts regarding how research "may generate new or improved products, services, processes, or knowledge as compared to traditional approaches" or social value which can correspond to factors such as quality of life, health benefits, environmental benefits, cultural, inspiration among the society… (Johnson, 2019).

Beneficiaries of economic value can be very different through shareholders, firms, customers or even countries and in an important number, whether in the upstream or downstream use of a resource. For example, the trading and use of water impact the country's activity, by reducing farm employment for example (Chong & Sunding, 2006). Environmental impacts can be also observed with the use of water such as salinity and drainage (Chong & Sunding, 2006).

2.3.3 Measuring value in neoclassical economics

Following the neoclassical theory of economy, the one we will keep for this study, we can assume that we can measure the productivity of the workers as well as the value of other resources, just by looking at the prices. It is natural to measure the value of something by the income it earns. Indeed, "you earn income because you are productive, and you are productive because you earn income" (Mazzucato, 2018).

With some assessments already made for the economic valuation of the International Space Station, economic indicators such as "market penetration, revenue generation, cost-benefit analysis, future industry outlook and limitations on accessibility" has been used (Johnson, 2019). Moreover, as detailed in the Updated Benefits for Humanity from the International Space Station paper presentation during the International Space Station Program Science Forum, indicators used to assess the economic valuation of the ISS[2] were around new private actors (such as SpaceX[3] or Orbital ATK), a boost for commercial research, new products, new ventures, new commercial markets… (Brady, et al., 2018; NASA, 2018). Moreover, the indicators such as public investments, commercial revenues, patents or employment can be considered (OECD, 2020).

To put it more simply, economic value can be measured or assessed via indicators which need to be appropriately determined depending on the use cases.

2.4 Evolving indicators to measure the value creation

All that being said, we can summarize useful indicators to measure economic value creation in a non-exhaustively manner. As mentioned by the OECD, "the number and variety of indicators tracking the development and impact of space activities have grown significantly in recent years" (OECD, 2020, p. 3) showing the

[2] ISS: International Space Station

[3] SpaceX: American spacecraft manufacturer, space launch provider and satellite communications provider founded in 2002 with a goal to significantly reduce space transportation costs

unprecise nature of economic value again and the need for more collaboration in the sharing of economic data between all the different stakeholders of an economy.

As an example, the Figure 3 from OECD enumerates economic impacts and associated indicators in the purpose of assessing Space economy. In this schematic, investments are taken as input but this way of identifying indicators could be discussed as well as the associated impacts.

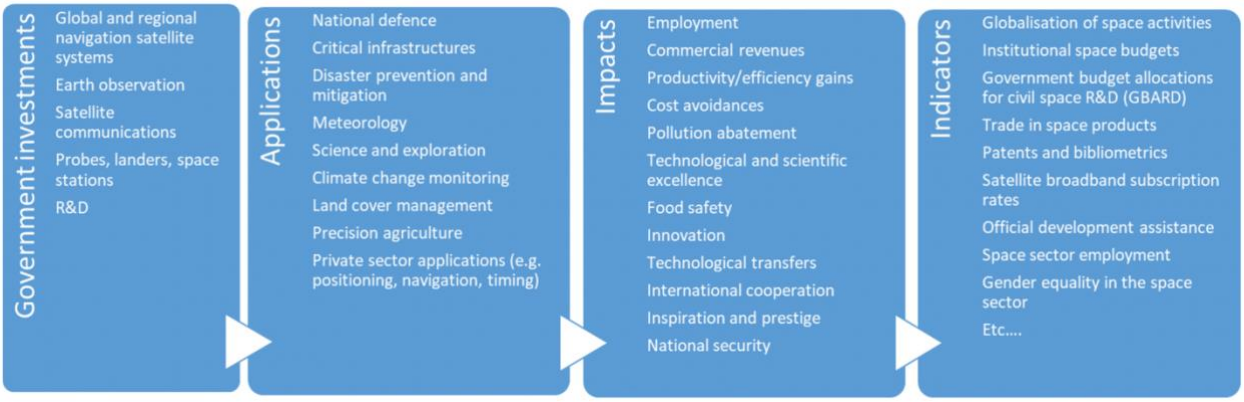


Figure 3: From investments in the space sector to impacts - Source: (OECD, 2020, p. 6)

Finding appropriate indicators and especially, enough reliable economic data, in the space sector at least, is something complex. Recommendations for policymakers, in order to improve the measurement of the space economy, have been stated by the OECD (OECD, 2020). By taking a step back to the topic of economic valuation, we can state that multiple approaches can be put in place to measure economic value. Those approaches can vary from one use case to another and evolve according to the update of the economic data.

Chapter 3

3 The Moon, an interesting and accessible celestial body

The Moon appears as an interesting and accessible celestial body. As a big scientific laboratory of choice, the Moon is also considered as a step to go to Mars and other planets. From Helium-3, trough fuel propellants, materials and volatiles, the Moon is full of resources (Downing, Baxter, & McCullough, 2005). In this section, we describe what are the main assets of the Moon that make it worth exploring or exploiting it.

3.1 Valuable resources on the Moon

The growing interest in the Moon and the emergence of private companies in different areas is mainly aroused by not only interesting resources but also the spatial assets offered.

3.1.1 Lunar natural resources

Indeed, this natural satellite holds a significant number of resources including water and oxygen (extracted from the rocks), precious metals, rocks and rare earths and Helium-3.

The lunar surface can be divided into two main areas: “the ancient, light-coloured lunar highlands, and the darker, generally circular, lunar mare (‘seas’) which fill the large impact basins, predominantly on the nearside” (Crawford, 2015, p. 138). Highlands make up roughly 80% of the lunar surface as we can observe in Figure 4 illustrating the nearside of the Moon.

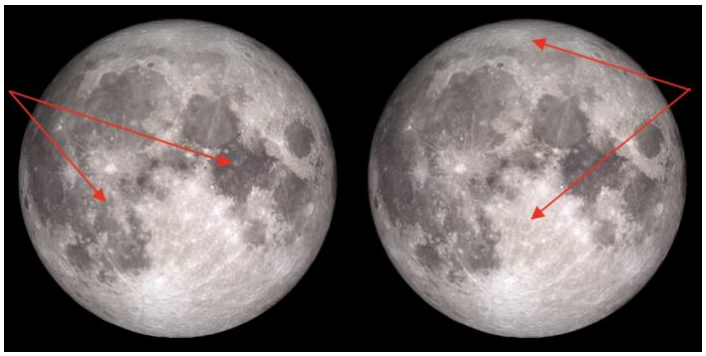
Lunar Maria  Lunar highlands

Figure 4: Photography of the face of the Moon we see from Earth. This image is based on data from NASA's Lunar Reconnaissance Orbiter spacecraft. Credit: NASA/GSFC/Arizona State University

The lunar regolith, i.e., the dust layer covering the lunar surface, is composed of multiple interesting materials and has been characterized thanks to remote sensing missions and sample returns from the Apollo[4] missions. Figure 5 illustrate the distribution of regolith on the lunar surface. Then, different locations on the Moon do have not the same interest.

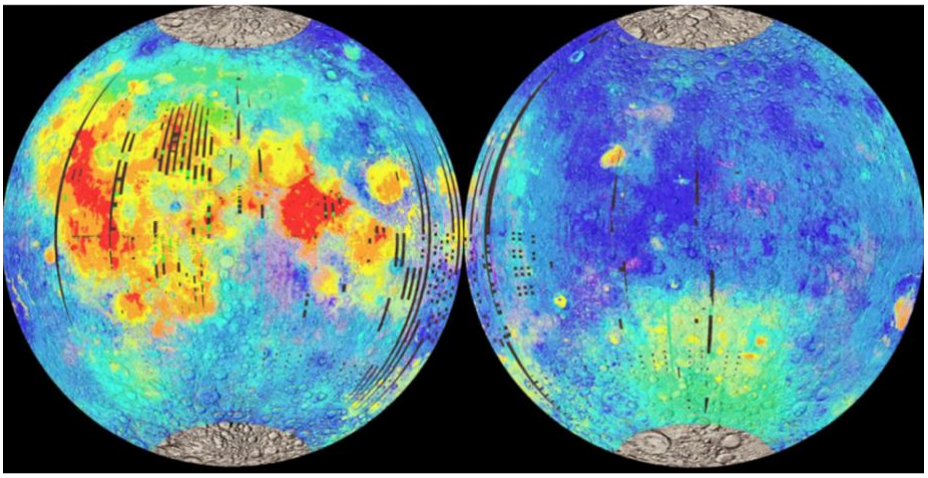


Figure 5: Distribution of regolith compositions on lunar nearside (left) and farside (right) (Crawford, 2015)

Comparing the two figures (Figure 4 and Figure 5), we can conclude that:

- *Highlands* are mainly composed of anorthositic rocks (in blue) which are rich in Calcium, Aluminium, Silicon and Oxygen (Crawford, 2015).

[4] Apollo program is a scientific lunar exploration program carried out by NASA from 1961 to 1972

- *Lunar Maria* are mainly composed of basaltic lava flows (in red) which are richer in Magnesium, Iron and Titanium (Crawford, 2015).

Thanks to different remote sensing missions, partial assessments of the composition of the Moon can be made thanks to different remote sensing observations and surface experiments.

In order to have an overview of the materials and resources available on the lunar surface, we detail the different resources and their interests in a lunar economy in Table 1 below.

Material	**Location and abundance**	**Ease of extraction**	**Applications and interest**
Oxygen	Trapped inside regolith	"20 different possible processes" "eight selected are considered to be the most practical" "All are quite energy intensive"	Life support and rocket propellant
Silicon	Abundant in all rocks (about 20%)	Same extraction process as for Al	Interesting for industrialization of space (production of arrays of solar cells)
Aluminium	Concentration in lunar Highlands regolith (10-18%)	Via magma electrolysis or carbothermal reduction → energy intensive processes	Useful metal for various applications
Carbon	Lunar soil in low concentrations (50 and 90 parts per million by weight)		

Titanium	Concentrated in Lunar Maria (in 5 to 8%), mostly in the mineral ilmenite	Electrochemical processes	Useful metal for aerospace applications. Ti production from ilmenite could make combined Ti/O_2 production one of the more economically attractive future industries on the Moon
Helium	Lunar soil in low concentrations		Rocket fuel and reducing agent for some of the schemes proposed for extracting oxygen and metal from metal oxides
Helium-4	Coming from the solar wind and located in the regolith.	"Quite energy intensive to extract solar wind implanted volatiles" "Most of this solar wind implanted volatiles can be degassed from the regolith by heating it to temperatures of between 300 and 900°C"	"useful addition to terrestrial resources"
Helium-3	Coming from the solar wind and located in the regolith. One million tons of Helium-3 are estimated. It "is actually very rare in lunar soils, having only ppb concentrations" and may probably be lost during transport to Earth or such other operations (Crawford, 2015)"		"Powerful source of fuel for energy on Earth" (Lovegren, 2014) "The energy present in a ton of helium-3 is the equivalent of that present in 6.7 million tons of coal"
Hydrogen	Lunar soil in low concentrations but such a significant abundance on soils at high latitudes has been discovered (50 and 90 parts per million by weight)		Spacecraft propellant, energy source, reducing agent for some of the schemes proposed for extracting oxygen and metal from metal oxides
Sulphur	"lunar soils contain a not insignificant quantity of sulphur"		A range of industrial applications
Neon and Argon	"Small quantities"		

Water	in ice located in lunar poles		"may be valuable in the context of a future in-space economy"
Nitrogen	Lunar soil in low concentrations (50 and 90 parts per million by weight)		Useful breathable air in the field of a long-term human presence

Table 1: Lunar surface materials based on (Spudis, 2011) (Crawford, 2015)

There is an unequal distribution and concentration of these materials. "Light elements such as hydrogen, helium, and nitrogen, are present in the lunar soil in low concentrations, but in enough quantity to permit their extraction and use" (Spudis, 2011, p. 242).

To conclude, these material resources are very interesting for In-Situ Resource Utilization (ISRU), but also to be brought on Earth with the Helium-3 that is, according to (Lovegren, 2014), the only resource that is worth shipping back to the Earth regarding its high energy intake.

It is also important to mention that only 5% of the Moon's surface has been explored so far and the fact that "the lunar crust may contain bodies of locally concentrated 'ores' of economically exploitable materials is still largely unknown" (Crawford, 2015, p. 141).

3.1.2 A strategic space location

The Moon offers not only material resources but also other strategic resources and an interesting space position. First, the Moon is only a 3-day trip from the Earth so it is quite accessible and it is also a 3 light second round trip allowing to perform real-time robotic missions and then making it an interesting space location (Spudis, 2011). Secondly, gravity on the Moon is six times lower than on Earth, presenting a very interesting space location where we can launch objects from the lunar soil to the Moon orbit or also called cis-lunar space or even to other planets such as Mars, with less energy that it would have been needed from Earth (Figure 6). This low gravity can also be of interest in many industrial processes that could be carried out in the field of a lunar settlement (Lovegren, 2014).

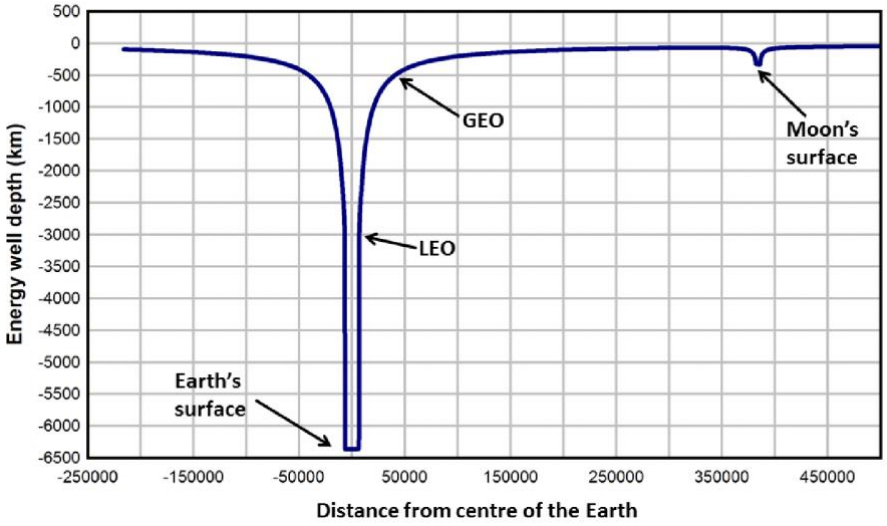


Figure 6: Orbital and potential energies in the Earth-Moon system from (Crawford, 2015, p. 155)

"It requires 22 times less energy to escape from the Moon as from the Earth). Note that all locations in cis-lunar space, including low Earth orbit (LEO) and geostationary orbit (GEO), require far less energy to access from the surface of the Moon than from the surface of the Earth (Crawford, 2015, p. 155). Also, the Moon is "nearly perpendicular to its orbit around the Sun" some areas are in near-permanent light, so it is very interesting for energy production purpose (Spudis, 2011, p. 242).

Finally, on top of being a safe and operational laboratory where we can experiment with the use of space resources (Spudis, 2011), it also presents innumerable orbits for a variety of operations:

- Low Lunar Orbits (close to the surface and excellent for remote sensing)
- Distant Retro-Grade Orbits (far from the Moon but quite easy to reach from Earth)
- Halo Orbits (fuel-efficient orbits revolving around Earth-Moon neutral-gravity points)
- Near-Rectilinear Orbit Halo Orbit (NRHO: which will be the Lunar Gateway[5] orbit as it has very interesting properties).

[5] The Lunar Gateway is a small space station that will orbit the Moon and that will serve as a lunar outpost for deep space exploration. This project, currently in development, has been proposed in 2017 by NASA and has commercial partners and three other space agencies (CSA, JAXA, ESA) supporting it.

To summarize, even if it is difficult to "identify any single lunar resource that will be sufficiently valuable to drive a lunar resource extraction industry on its own" (Crawford, 2015, p. 137), it seems that the association of the different material or immaterial resources of the Moon have an economic interest for a sustainable human settlement on this Earth-satellite and, in a further future, for the use of lunar resources on Earth.

3.2 Lunar In-Situ Space Resources Utilization (ISRU) applications

Indeed, when thinking about a lunar economy, it makes sense to think about the use of local resources locally, also called, Lunar In-Situ Space Resources Utilization as this economy is mainly driven by the cost of sending resources from Earth to the Moon.

First, it is important to mention that a Lunar ISRU needs some conditions, on top of establishing a short-term economic model that will not need a long-term establishment of a lunar infrastructure:

- A mapping of the different lunar resources (Le Cadre Loret, et al., 2021) including the Moon surface, but also the subsoils which are not yet well documented.
- "Developing technologies and installing the necessary infrastructures" (Le Cadre Loret, et al., 2021, p. 84) that will be needed for all the processes required to extract the different resources and manufacture equipment and systems.

Involvement and technological development of public and private space and non-space companies seems to be inevitable for an efficient and circular Lunar ISRU (Le Cadre Loret, et al., 2021). All these local resources will be able to serve many different publicly or privately oriented applications such as life support, propellant production, manufacturing equipment and building ground infrastructure (Scatteia & Perrot, 2021). ISRU activities will have to be deployed step by step, as the settlement on the Moon will be progressive, driven by the ISRU technology advances and the private and public actors' level of engagement. A roadmap (Figure 7) proposed by (Scatteia & Perrot, 2021), outlines the main chronological steps regarding ISRU.

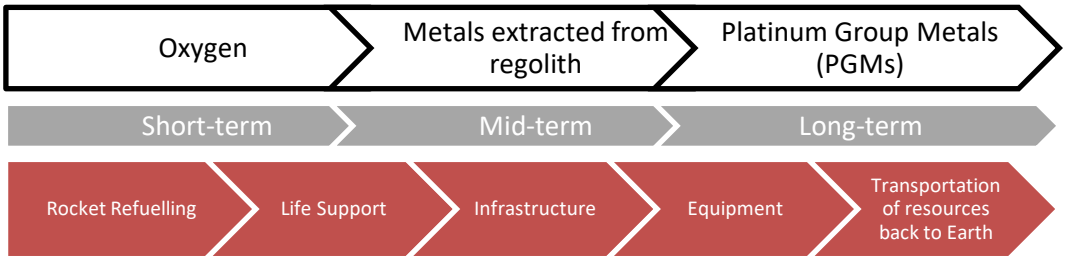


Figure 7: Roadmap on Lunar ISRU and used resources from (Scatteia & Perrot, 2021)

First, oxygen is very present in the regolith and will be able to be used for space transportation purposes. Then, it can be used for life support as well as the water mainly located on poles. Infrastructures could be made from the lunar regolith with 3D printing for instance. The use of other materials such as titanium could serve the manufacturing of equipment locally. Finally, we can envisage the transportation of these resources back to Earth such as the Helium-3 which is very powerful for nuclear fusion and useful for cryogenics, quantum computing and MRI[6] lung imaging purposes (Vidal, 2022). To summarize, Lunar ISRU ranges from supplying consumables for manned missions to serving a lunar human colony and leverage industrial infrastructure.

3.3 The rising interest and the still existing legal gap

The interest in exploiting space resources, and specifically the Moon as it is one of the most accessible celestial body has already been shown a couple of times with space agreements signature regarding the appropriation of celestial bodies.

The applicable international law regarding that matter is still uncertain and specifically regarding the exploitation and ownership of celestial bodies (Geldenhuys, 2015).

Table 2, below, shows some major treaties that aimed at creating a legal framework for the exploitation and ownership of celestial bodies such as Moon, Mars and beyond. We summarize the private dimension included by those agreements:

Agreement	Date	Commercial space orientation

Outer Space Treaty[7]	1967	The use of outer space is granted to governments and private actors but with certain limitations. (Geldenhuys, 2015) and some things are not regulated and can be permissible.
Moon Treaty[8]	1979	Introduction of the concept of common heritage. The goal of this agreement was to regulate activities such as private investments. Limited to the only countries that have signed it.
CSLCA[9]	2015	Signed by president Barack Obama and stating that any US company (private or public) or citizens that extract resources from celestial bodies shall have rights to "possess, own, transport, use and sell" those resources (Obama, 2015) This encourages commercial space activities but complexify the international common ownership of space resources.
The UAE Space Law	2019	United Arab Emirates Space Law address the interest of the private companies in outer space (UAE Government, 2019). It states that space activities and ownership of space objects or resources are regulated by the UAE Space Agency[10]
Encouraging International Support for the Recovery and Use of Space Resources	2020	Executive order signed by the President of the USA (Trump, 2020). That policy stresses that the current regulatory regime — notably, the 1967 Outer Space Treaty — allows the use of such resources. This treaty was already mentioning national ownership, leaving the doubt regarding private ownership.

[7] Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies

[8] Agreement Governing the Activities of States on the Moon and Other Celestial Bodies

[9] U.S. Commercial Space Launch Competitiveness Act

[10] Space agency of the United Arab Emirates

Law of 15 December 2020 on Space Activities	2020	Luxembourg law enhancing the legal framework of space activities (Chamber of Deputies of Luxembourg, 2020)
Law for the Promotion of Commercial Activities Related to the Exploration and Exploitation of Space Resources	2021	Japan Act allowing people to exploit outer space resources under certain conditions. (Japan Parliament, 2021) Definition of "space resources" as water, minerals and other natural resources present in outer space.

Table 2: Major treaties regarding international outer space activities

We can see that the legal framework tends to evolve with the context of commercial space activities as there is a need to regulate private activities but also to encourage this commercialisation. There is still a lot of legal work to perform to regulate activities on the Moon. As the UN Outer Space Treaty prohibits every country to claim territory in Space, it seems inevitable that new treaties and agreements will have to be created in order to avoid a power struggle, once a first installation on the Moon or the use of resources will be performed.

3.4 Factors influencing lunar exploration: PESTEL analysis

Some factors impact the interest in conquering the Moon. Those factors will also drive the economics of the Moon. In order to describe the business environment around the Moon conquest, we performed a Political, Economic, Socio-cultural, Technological, Environmental and Legal analysis also called PESTEL analysis. This analysis allows us to understand the tendencies of the Moon exploration driven by those different factors and then, to give more insights into the influence on Moon economics. This assessment, based on two criteria which are uncertainty and impact is based on personal knowledge acquired mainly through academic research.

	Factor	Uncertainty	Impact
Political	Increase of Space Exploration political interest	M	H
	International charismatic warfare	M	M
	Increase of efforts from Space agencies	L	H
	Lack of international cooperation on Moon exploration	M	H

Economic	Increase of investments in Space	M	H
	Commercialization opportunities for private players	L	H
	Highly risky and costly missions	M	H
	Non-space industries interest and collaboration with space industries	M	M
	Non-existing economic framework to measure economic impacts of space	H	M
Social	Increase of space exploration popularity	M	H
Technological	3D printing	M	H
	Operational delays for Moon missions	L	H
	Reduction in cost of spacecraft manufacturing	H	H
	Increasing cargo payload capacity	M	H
	New ISRU applicable technologies	H	H
	Increase of robotic operations capabilities	L	H
Environmental	Lack of terrestrial resources and rise of global energy demand	L	M
	Waste Management	L	L
	Environmental policy	L	L
Legal	Lack of international legal framework	M	L
	National legal measures put in place	M	L

Table 3: PESTEL analysis of lunar exploration

This analysis allows us to have more inputs to synthesise and forecast the economic impacts of this lunar conquest 2.0.

Chapter 4

4 Economic valuation of the lunar conquest 2.0

As it is obvious, a net present value calculation or even a cost-benefit analysis about going back and forth to the Moon again have not been done yet and this is not about to happen. As already seen earlier, economic value is not always about price as it is difficult to measure environmental impact, technological innovation, new knowledge, and potential applications that could be real outputs of the lunar exploration. In order to analyse the economic value behind the new upcoming lunar conquest, we will first study the potential economic impacts of it and after a description of the lunar environment and its resources, we propose relevant indicators to assess this economic value.

4.1 A practical definition of the lunar economy

First, the Organisation for Economic Co-operation and Development[11] (OECD) defines the space economy as "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" (OECD, 2020, p. 5). It is the most easily found definition of the space economy. In a direct way, we can deduce that a definition of the lunar economy is similar except that it addresses the Moon. A definition of lunar economy used by practitioners and proposed by the consulting firm PricewaterhouseCoopers is "A lunar economy encompasses all general economic activity associated with the production, use and exchange of lunar resources on the Moon's surface, in lunar orbit and on Earth" (Scatteia & Perrot, 2021, p. 3). This definition corroborates the neoclassical definition of economic value retained above (Section 2.2), and this is a general definition that we will consider for the rest of our study.

[11] The Organisation for Economic Co-operation and Development is an international organization for whose purpose is to foster economic progress and world trade.

4.2 The Moon, on its way to become a new economic ISS favoured by the NewSpace era?

4.2.1 The economic value of the International Space Station

The ISS, in its economic model, could be compared to the next Moon exploration. The Station's main purpose is to serve as an in-orbit giant research facility to conduct biological or technical research in a low-gravity environment. Moreover, even if it is not the main purpose, the ISS is also used for commercial purposes as we can see with the Airbus Bartolomeo Platform allowing access to Low-Earth Orbit (LEO) (L'Usine Nouvelle, 2020). The areas of economic impact are depicted in Figure 8 below. It shows the diversity of economic impacts.

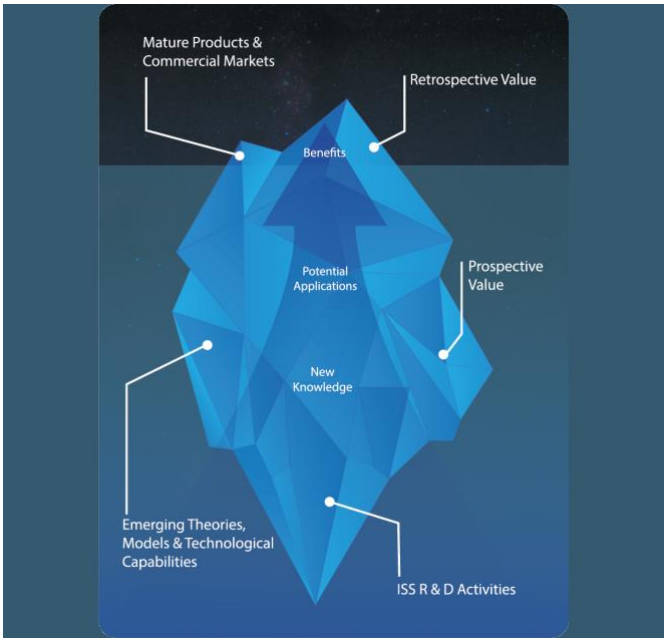


Figure 8: Generating value from research endeavours - Credits MAPI/NASA

An economic evaluation of the ISS has been performed with the support from Navigant Consulting, Inc. in 2018 by the members of the ISS Program Science Forum (PSF) which includes the National Aeronautics and Space Administration (NASA), Canadian Space Agency (CSA), European Space Agency (ESA), Japan Aerospace Exploration Agency (JAXA), State Space Corporation ROSCOSMOS (ROSCOSMOS), and the Italian Space Agency (ASI). This economic valuation has shown tangible economic outputs and benefits from some selected ISS activities through three dimensions of value innovative, humankind/social and economic which can be retrieved in Figure 8. We do not remember here that it is indeed difficult to measure once again the economic impacts of technologies and also social value. It is also important to mention that most of the research projects on the

ISS have been selected for their scientific interest rather than their commercial one (NASA, 2018), showing that its economic impact would or could be even greater. The scientific value brought by the ISS is quite significant: “In total, space station researchers have generated over 2,000 peer-reviewed publications (as of Sept. 2021) representing the work of more than 4,000 research investigators” (NASA, 2022).

As the lunar conquest tends to be first concerning the building of infrastructures to sustain a permanent human presence, mainly driven by institutional actors and, secondly, a commercial expansion fostered by the access given for private actors in lunar infrastructure and by the huge number of assets offered by the Moon (Section 3.1) (Downing, Baxter, & McCullough, 2005), we should think of the Moon as an ISS in its model.

4.2.2 A favourable NewSpace era for space economic development

With wide policies fostering entrepreneurship in the space sector led by space agencies such as the National Aeronautics and Space Administration (NASA), the European Space Agency (ESA) and the Centre National d’Etudes Spatiales (CNES), the space sector has seen an important increase in the number of start-ups that “increased nearly fivefold over a 10-year span” (Cloitre, Dos Santos Paulino, & Theodoraki, 2022, p. 5). This so-called ‘NewSpace’ era which corresponds to the emergence of new private actors in the space industry (Sorge, Morin, & Wilson, 2019) such as new big LEO[12] constellations like Starlink or OneWeb, has generated an important number of private investments and an associated economic value. The increase of new entrants in the space market (space and non-space companies) is quite in line with the increase in the number of private investments. In the U.S “$1.5 billion were invested annually in space startups during the period 2010-2015” (Vernile, 2018, p. xxvi). As we have seen earlier, the partnerships between the different companies will be one of the keys for sustainable business models, as institutional actors such as the space agencies are moving towards a public-private partnership approach of the lunar conquest, meaning that they are keen to partner with private companies such as startups or non-space industries (Dos Santos Paulino, et al., 2021).

In a nutshell, the economic value produced by this NewSpace context are: “Innovative industrial approaches, market disruption solutions, substantial private investment, new industry verticals and space market and new innovative public procurement” (Vernile, 2018, p. xxii).

[12] Low Earth Orbit is an orbit around Earth where most of the artificial objects in outer space are in orbit. The altitude is around one-third of the radius of the Earth.

This enthusiasm in shooting for the Moon can be seen in Figure 9 illustrating a mapping of some companies that are or can be involved in this lunar conquest. This helps to understand what associations might be possible, especially in terms of complementary capabilities and mutual interests.

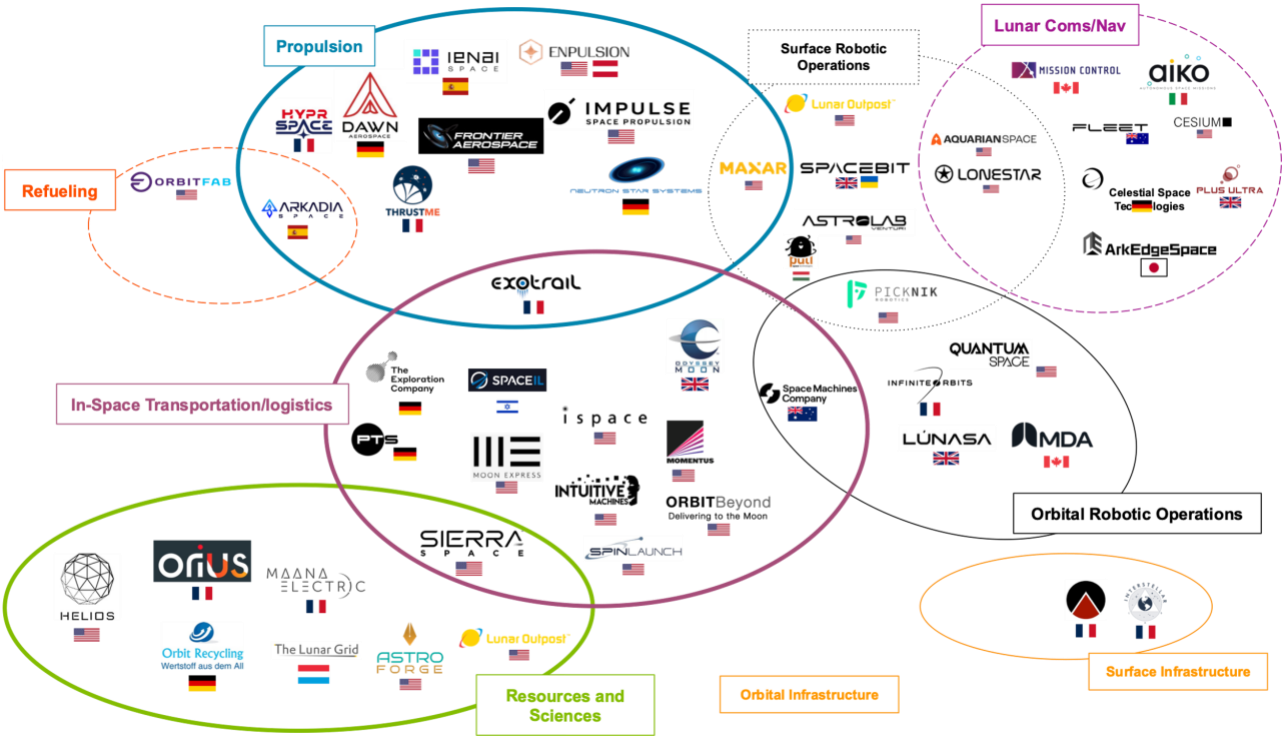


Figure 9: Mapping of some lunar companies - Source Author

4.3 Global economic impacts of the new lunar conquest

Before exploring the different indicators that could measure the lunar conquest economic impacts, we study the different economic impacts generated by different lunar market segments.

As well as the space economy overall, lunar exploration not only has or will have impacts on commercial revenues but also far beyond in other segments of the economy such as agriculture, transport, energy, health, gas industry or mining industry.

We can remember that the general economic impact of space has already been assessed by a multitude of stakeholders such as the OECD, the U.S Bureau of Economic Analysis (BEA), NASA or independent consulting firms such as PricewaterhouseCoopers or Euroconsult (OECD, 2022; Nathalie P. Voorhees

Center for Neighborhood and Community Improvement at the University of Illinois at Chicago, 2020; Highfill & MacDonald, 2022; Crane, Linck, Lal, & Wei, 2020).

Regarding the lunar conquest, in the case of a permanent presence on the lunar soil, the environment is very different from what has been observed in sectors of space applications so far. Indeed, the space activities that have been conducted until now encompasses Satellite communications, Space Transportation, Earth observation, Science, Space technologies and Space exploration (OECD, 2022). However, by now, the Space exploration sector does not include the other possible activities that a permanent lunar presence could permit, such as the lunar ISRU or sending the resources to Earth, manufacturing, or in-orbit refuelling.

In order to have a better view of what are the different economic impacts of a potential lunar economy, we decided to split these impacts into two timescales 'short-term' and 'mid-term'. The short-term one which corresponds to the Space Transportation and Infrastructure & Logistics capabilities that will enable the construction of a lunar exploration infrastructure with all the logistics required. The other one which corresponds to Science & Resources and Life Support that will refer to a permanent settlement on the Moon with the conduct of experiments and diverse operations. We decided to put Transport and Infrastructure & Logistics markets in the short-term need as it is clear that a lunar economy will rather only be established when an Earth-Moon lunar transportation system is put in place, either to transport terrestrial resources to the moon or to bring lunar resources on Earth.

Long-term need						
Science & Resources				**Life support**		
Remote sensing	Research station	Water/Fuel production	Prospection	Human Habitat	Food production	
Short-term need						
Transport			**Infrastructure & Logistics**			
Lunar Orbit Access	Surface Access	Crew Transport	Lunar Communications & Navigation	Surface Mobility	Power Supply	In-Situ Construction

Table 4: Lunar Economy Market Segmentation and capabilities for the Short and Long-term need

4.3.1 Short-term impacts: Transport and Infrastructure & Logistics

The market change will be first on the Space Transportation market segment which has already seen an expansion. The areas encompass Launch from the Earth, transportation to the moon orbit and cis-lunar space and then landing/access to the

lunar surface. Launching things into space and, especially on the Moon has a significant cost which will be the main driver for establishing a permanent infrastructure on the lunar soil. Different capabilities are needed to access the lunar surface which is not only accessing the lunar orbit with a traditional rocket but also having orbital transfer capabilities, landing capabilities and may also require refuelling capabilities. The Space Transportation market exist since we have been launching things into space. The impact of the lunar conquest would expand the market and accelerate the development with a first goal, which seems obvious, which is to reduce the costs of sending payloads to the Moon and get it back in the mid/long-term. Mobility capabilities on the lunar soil will be also another goal. As of today, some private companies are positioned to offer transportation capabilities for lunar missions such as SpaceX with their Starship rocket, Airbus Defence and Space and Lockheed Martin with the Orion spacecraft or even companies such as Astrobotic, iSpace or Intuitive Machines, which are offering lunar mobility services. The rising number of lunar missions planned encourages new actors to emerge whether from the space sector or the non-space sector (Scatteia & Perrot, 2021; Dos Santos Paulino, et al., 2021). According to a report on the lunar market from PwC[13] which provide a lunar transportation market forecast based on the different moon missions planned "between 2020 and 2040, the payload mass to be transported on the Moon will reach around 187 tons with a corresponding transportation market size of 79 $Bn (Scatteia & Perrot, 2021, p. 12). This corresponds to a compound annual growth rate of 11%.

Then, in order to allow a sustainable presence on the Moon, the need for infrastructure and resources is inevitable. As a comparison, the ISS needed more than 40 missions to be built and the station is still evolving (ESA, 2022). At the moment, 40 trips to the Moon seem too far expensive regarding the current cost to send something to the Moon (See Appendix A – Costs estimation of Earth-Moon cargo). Lunar cargo costs are on their way to being reduced and the payload capacity is increasing. But there is a radical difference with the ISS as we can envisage building the needed infrastructure using Lunar ISRU capabilities thus reducing the payload mass to be sent contrary to the ISS which is in orbit. This first step will drive the Science & Resources segment we will study next.

In a nutshell, thanks to different sources including (Scatteia & Perrot, 2021; OECD, 2022; OECD, 2020; Crane, Linck, Lal, & Wei, 2020; Hertzfeld, 1998), we synthetise the different impacts and the associated factors the lunar exploration has and may have on the Space Transportation segment:

[13] PricewaterhouseCoopers

Factors	Direct Impacts	Induced Impacts
Emerging programmes around lunar transportation such as the CLPS[14] from NASA ARTEMIS program	• Creation of new startups providing capabilities for an end-to-end Earth-Moon Transportation system including lunar soil mobility	• Increase of employment • New R&D[15] projects
A first lunar infrastructure/habitat put on the Moon	• Increase in the need of lunar/earth cargo and reduction of associated costs	• Increase of employment • New R&D projects • Technology spin-offs and spin-ins
Legal initiative to foster the exploitation of the Moon	• Rise of new private actors • New projects	• Increase of employment • New R&D projects • Technology spin-offs and spin-ins
Interest of non-space industries in lunar exploration (Mining, automotive and energy industries)	• Increase in the need of lunar/earth cargo • Capture more investments in lunar projects	• Technology spin-offs and spin-ins • Increase of employment • New R&D projects • New businesses

Table 5: Impacts of Space Transportation and Infrastructure & Logistics activities

These impacts are quite the same as the ones coming from the ISS and the Space Economy (NASA, 2018). The accent is put on reducing costs, accompanied by global rising interest in exploiting the Moon. Anchor customers, i.e., the states, act now as customers to private clients, which boosts the commercial aspect of this segment (Dos Santos Paulino, et al., 2021, p. 100).

4.3.2 Long-term impacts: Science & Resources and Life Support

In the late phase of developing the Moon, human lives will have to be supported as well as "lunar resource production and scientific projects" (Downing, Baxter, & McCullough, 2005, p. 2). Also, if actions are taken by governments to boost commercialization and industrialization of the Moon, we would see a significant commercial expansion attracting more and more investments and expanding the various industrial sectors with the development of dual-use technologies (Benaroya, 2001) but also in tourism, advertising and entertainment (Downing, Baxter, &

[14] Commercial Lunar Payload Services
[15] Research and Development

McCullough, 2005). New long-term projects addressing far different sectors of what we would never have thought of are emerging such as the use of blockchain (Bratu, 2022) and the tokenization of lunar payloads with the CopernicSpace[16] startup. An increased demand in human habitat is expected and "the evolution of inflatable habitats could have implications for the colonisation of the Moon and Mars" (Vernile, 2018, p. 57) and may establish news business relationships such as with the startup InterstellarLab[17] whose biological habitats can also be used on Earth.

Factors	Direct Impacts	Induced Impacts
Economic, legal and institutional framework	• Democratization of space exploration • Potential colonisation of the Moon and other planets such as Mars	• Technology spin-offs and spin-ins • Increase in employment on various sectors • New R&D projects • Population's migrations • New businesses
Pollution of Earth and lack of resources	• Potential colonization of Moon and other planets such as Mars	• Increase in employment on various sectors • New R&D projects • Population's migrations • Change in economic development
Easier access to lunar assets for private actors	• Creation of regulatory • Development of new sectors	• Increase in employment on various sectors • New businesses
Interest of non-space industries in lunar exploration (Mining, automotive and energy industries)	• Capture more investments in lunar projects • New customers of the lunar economy	• Technology spin-offs and spin-ins • Increase of employment • New R&D projects • New businesses

Table 6: Impacts of Sciences & Resources and Life Support activities

[16] https://copernicspace.com/

[17] InterstellarLab is working on designing controlled-environment modules for crop cultivation on Earth and life-support in space: https://interstellarlab.com/

As we can observe, the induced impacts are substantially the same except the ones that would be generated with an already well established commercial lunar infrastructure, Earth-Moon transportation services and legal, institutional and economic framework (Downing, Baxter, & McCullough, 2005). Moreover, considering that this will happen in the mid/long-term, induced impacts would be accelerated with new factors such as the scarcity of terrestrial resources, the pollution of Earth, the habitability of Earth (Benaroya, 2001).

4.4 Relevant indicators and approaches for economic valuation of the lunar exploration

In light of 'Measuring the Space Economy: Estimating the Value of Economic Activities in and for Space' (Crane, Linck, Lal, & Wei, 2020), the OECD Handbook on measuring space impact on the economy (OECD, 2022) and the book chapter 'Space as an investment in Economic Growth' (Hertzfeld, 1998), we study macro-economic and micro-economic criteria which we judge relevant for assessing the economic impact of this new lunar conquest. It is important to note the difficulty to differentiate activities, goods or services that are linked to space in general and those that are induced by lunar exploration.

4.4.1 Macro-economic indicators

The Gross Domestic Product (GDP) is the indicator that comes first to our mind. This indicator provides the total value of goods and services produced in the economy. Thus, this indicator can be compared to the government budget allocation in the lunar exploration (OECD, 2022) to have an assessment of what are the tendencies of governments regarding lunar exploration. The commercial sale of goods and services produced in space can be used to evaluate the impact of lunar exploration on sales. Again, this indicator should be adjusted to rely on the lunar economy.

All these activities have generated and will generate changes in the labour market. Those changes can be assessed through metrics such as labour income, and the number of jobs and can be linked with the number of employees involved in R&D projects.

In the long term, the need for having a detailed measure of the lunar exploration impact will complexify the task as many sectors will be implied. This raises the need to have an economic measurement framework able to give fairly accurate information regarding a 'return on investments'.

Finally, as shown throughout this work, the lunar economy will indirectly impact other segments of the economy, specifically with R&D investments which

generate technology spin-offs or spin-ins. These initial investments for space R&D, often lead to new investments needed to transfer technologies to other sectors, to manufacture and sell them (Hertzfeld, 1998).

4.4.2 Micro-economic indicators

More micro-economic indicators associated with extensive cooperation between economic data might be the key to a better assessment of those economic impacts. As detailed by Chase Econometrics which was commissioned to redo NASA economic impacts study: “further attention should be focused in the future on the examination of effects at a more micro level. Industry case studies (for which much data already exists) and interindustry studies would be mutually complementary and should provide significant new insights” (Hertzfeld, 1998, p. 426).

Attention needs to be put on private investments received by startups emerging from space agencies programmes for instance. This could be considered as an indirect impact of space agencies’ initiatives to fund new projects around lunar exploration.

Finally, microeconomics is interesting and may need to be linked with macroeconomics. Besides, the distinction between the two has been narrowing over the past few decades (Blanchard, Dell’Ariccia, & Mauro, 2010), Also, the potential rising of blockchain technologies and the use of cryptocurrencies, using microeconomic indicators could allow us to better understand lunar economic flows.

4.4.3 Discussions on economic approaches

The question of the approach to be taken is hard to answer. Measuring impacts is something complex as a lot of outputs are not quantifiable such as the technological progress (OECD, 2022).

The Input-Output analysis seems to be a good general approach to first extract the indirect and induced impacts and then measure all these outputs. As we can see in history, a lot of other methods have been applied (Hertzfeld, 1998), but we can deduce, and this agrees with the OECD (OECD, 2020), that the imprecision and lack of data, also lack of data sharing is one of the major issues in measuring value.

4.5 The beneficiaries of the Moon exploration

All that being said, we may wonder who will be the beneficiaries of such a lunar economy. If the space agencies are customers of the lunar exploration, but also

almost totally providing their own funds, can we call that a real lunar economy? Apart from generating technology spin-in of spin-offs, what would be the commercial value generated? In this part, we will try to understand what would be the customers, the provider of services in a lunar economy.

In the short-term, it seems clear that the customers will be governments which are going to put the first infrastructure on the Moon. Then, once infrastructures will be established and investments facilitated via industrial and economic strategies such as Public-Private partnerships (PPP) (Downing, Baxter, & McCullough, 2005; Dos Santos Paulino, et al., 2021), new actors from space or non-space industries will be able to 'enter' this lunar economy and take the business opportunities offered. This sends us back to the measurement of the economic impacts, actually it appears that it might be too early to try to assess the commercial benefits but even if the lunar conquest has not physically started, the rising interest from enterprises and the different space programmes initiated already create value via the different investments towards the different actors (startups, universities, researchers…) and also only with the interest it arouses leading to academic research, working groups…

As an illustration of the benefits that could come from such space exploration projects, we can in Figure 10 the technological progress issued from the Apollo program.

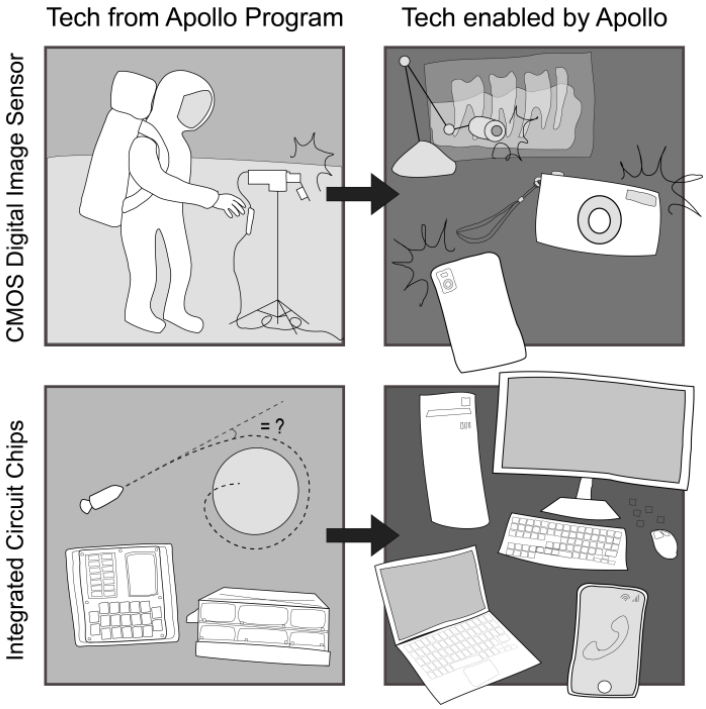


Figure 10: Examples of technologies that proliferated thanks to the Apollo project from (Rota, 2020)

Not only space agencies will benefit from the lunar exploration, but the entire planet that will be driven by the achievements of institutional actors to build infrastructures on the Moon with the help of various actors through Public-Private partnerships.

Chapter 6

5 Conclusion and recommendations

A paradigm for a definition of economic value has not been found but most economists agree that economic value is related to market value. The rising interest in the Moon associated with the rise of private, smaller actors and the need for space agencies to save money by subcontracting to private actors are paving the way to establish a human presence on the Moon and create new potential businesses. However, there is a need for every stakeholder, government, policymaker, commercial actor to measure economic value and benefits. Even if the number of indicators to measure the space economy is constantly increasing, there are still big challenges to tackle in order to better measure the lunar economy to allow more actors to invest and create new projects. The lunar exploration will have impacts on various segments of the economy and also create business opportunities for the space and the non-space industry. But it remains difficult to assess the technology and social values from such an exploration. Next, we detail recommendations in this direction.

5.1 Recommendations for a better economic valuation

There is a need to create an economic and industrial framework that will allow us to better evaluate the economic impact of such an exploration. To make it short, this will give more visibility and willingness to investors. There is a need for a strategy to better measure lunar economy globally but especially the impact on non-space industries (gas industry, mining industry…) and integrate technological, social and environmental values in the assessment.

Collaboration between governmental and private enterprises at an international level will make the economic assessment easier. As seen with the ISS, the lack of international cooperation on economic data sharing makes economic evaluation even more difficult.

Microeconomics and macroeconomics indicators should be carefully selected and initiatives on how to bring the two together should be put in place. Even only ambitious goals in space exploration are generating investments and economic

growth overall as we have seen with the ISS case. This interest is mainly driven by the space exploration programmes from the governments. This adds another variable to the economic assessment as these projects can be conducted in a sparse manner.

5.2 Limits

The still legal gap in the exploitation of celestial body, the uncertainty of private companies may generate change in the overall lunar economy. We are not sure yet of the form of this economy. Some lunar markets may be developed and others not at all (Human habitat for example). This uncertainty is therefore reflected in the economic evaluation.

As demonstrated, the economic value is something that is not clearly fixed and where the value can be relative to what it is studied. Even economists do not all agree in the existing value concepts. The fact that the lunar economy is a different ecosystem where many of resources will be used locally, and potentially traded locally between the different countries, it questions the fact of considering a different economic value on the moon than the one on the Earth.

There is no doubt that the lunar economy is a very prospective economy where a lot of assumptions are made. This hypothetical nature of this economy is reflected in a couple of lunar market reports from practitioners such as PwC, NSR…

5.3 Further research

Further research could continue on how to use other method of economic evaluation such as the Mars to Moon[18] (M2M) program one made, how to make the different actors collaborate on their economic data sharing.

Also, the economic property of the Moon could be studied in details. Can the Moon be considered as a tax haven? What about creating a monetary system on the Moon? How could this be governed?

How could an international organization could be in charge of assessing and establishing insights on the lunar economy? Are there ways to assess, or create a framework, to assess innovative, social values in order for companies and government to see better what would be the benefits in terms of money?

[18] Mars to Moon program

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7 Appendix A – Costs estimation of Earth-Moon cargo

Before talking about a commercially viable economy on the Moon, it is important to have an idea of what is the cost of launching goods and services to the Moon. The "cost of sending small payloads to the lunar surface" with different spacecraft (Crane, Linck, Lal, & Wei, 2020)

Spacecraft	Purpose	1st Mission Cost	Cost after 20 utilizations
HLS: Two-stage Human Landing System (Crewed)	NASA intends to use this crewed Spacecraft for roundtrips mission between the Lunar Gateway and the lunar surface. A variant of the Starship launcher capable of transferring astronauts from lunar orbit to the surface of the Moon and back	1457 $M	309 $M
NASA SLS[19] + Orion[20] spacecraft + HLS	SLS for the launch from earth and Orion for orbital transfer	Cost of: SLS launch 1 $Bn Orion launch 0.85 $Bn HLS operation 1457 $M **Total: 3.3 $Bn**	**Total: 2.159 $Bn**

Table 7 – Combined cost for crewed missions from Earth to lunar surface. Source STPI calculations (Colvin, Crane, Lindbergh, & Lal, 2020)

[19] NASA Space Launch System (SLS): super heavy-lift expendable launcher used in NASA's Artemis program

[20] Orion spacecraft: partially-reusable crewed spacecraft to be used in NASA's Artemis program Lockheed Martin and Airbus Defence & Space

The transportation cost is very high and should be compared with the potential lunar economic activities these cargo and crewed missions will generate such as Lunar ISRU in order to assess the commercial viability of such a model.

But this cost tends to decrease and the number of private companies in the transportation market is increasing. With the arrival of new private actors such as SpaceX with their Starship HLS (see Table 7), but also Astrobotic, iSpace or MoonExpress, the cost of lunar transportation overall should decrease. Moreover, we can consider that in a context of a circular lunar economy, the resources will be, in the first decades of moon conquest mostly sent from Earth but will progressively be extracted and used locally with the technological progress and the terrestrial resources that will be already sent.

According to a report on the lunar market from PwC which provide a lunar transportation market forecast based on the different moon missions planned "between 2020 and 2040, the payload mass to be transported on the Moon will reach around 187 tons with a corresponding transportation market size of 79 $Bn (Scatteia & Perrot, 2021). This corresponds to a compound annual growth rate of 11%