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Master of Science in Petroleum Engineering

Master Thesis

ENERGY ANALYSIS OF A CIS-LUNAR PROPELLANT PRODUCTION SYSTEM

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Dedication and Acknowledgements

This thesis is dedicated to my beloved family, Walid, Rytta, and Christopher who have always been a constant source of support and encouragement during the challenges of my whole academic life. Their good examples have always taught me to work hard for the things that I aspire to achieve.

I have to thank them for their love and support throughout my life. Thank you for giving me strength to reach for the stars and chase my dreams. My aunties, uncles and cousins whom I feel grateful having by my side, deserve my wholehearted thanks as well.

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Big thanks to my friends for their understanding and encouragement in many moments of crisis. Your friendship makes my life a wonderful experience. I cannot list all the names here, but you are always on my mind.

Thank you, Lord, for always being there for me.

I believe this thesis is only a beginning of my journey.

Abstract

With the increasing of space exploration activities and the expansion of human presence, the use of resources in space is a critical step to allowing the development of sustainable future missions. A practice called in-situ resource utilization (ISRU) enables the generation of products from local materials in space exploration. As the Moon is found to possess raw resources like ores and water, and is located at relative vicinity to Earth, and possess decades of scientific study, it provides the potential ground and platform for the development of technologies and methods for ISRU activities. Water is an important resource present on the Moon that can be critical for human activities for example hydrolysing it into oxygen and hydrogen, for producing rocket propellant highly used in efficient rocket propulsion engines.

Observation missions of the Moon were made, giving in terms of ISRU potential and promising results suggesting some ice-bearing source locations to contain estimations between 3.5% and 30% of water ice by mass to be mixed with dry regolith and suitable to mine.

By utilizing this water resource and transforming it to fuel to be served at a Low Lunar Orbit level, the mass of materials and fuel carried from Earth can potentially reduce significantly the mission cost, thus allowing future missions to be reconsidered as more feasible.

This study addressed the issue by investigating through an energy analysis a system design that can achieve a production and eventually storage of 1,640 mT propellant, identified as the annual lunar-derived propellant demand. This amount would necessitate the extraction of 2,450 mT of lunar water through a lunar mining revolutionary concept that sublimates the ice before transporting it to the processing facility.

The system consisted of four main functional blocks and an analysis of the energy allocated in each subsystem was calculated. The blocks evaluated were respectively related to transportation of equipment from Earth, lunar mining, lunar propellant production, and finally transportation and storage on Low Lunar Orbit. Even with technical and logistical constraints and limitations, the study has found that the system consumed a total energy of 128,628 GJ (mostly by the production block) to produce the annually propellant demand corresponding to a useful energy of 31,816 GJ once employed in propulsion.

This study thus discuss the energetic balance of establishing a LLO propellant refuel station and provides suggestions and recommendations to interested entities in space for future work.

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List of Acronyms

BFR	Big Falcon Rocket
CO2	Carbon Dioxide
ESA	European Space Agency
ISCPD	In-Space Cryogenic Propellant Depot
ISRU	In-Situ Resource Utilization
IWP	Ionomer-membrane Water Processing
LCROSS	Lunar Crater Observation and Sensing Satellite
LEO	Low Earth Orbit
LH2	Liquid Hydrogen
LLO	Low Lunar Orbit
LOLA	Lunar Orbiter Laser Altimeter
LOX	Liquid Oxygen
LRO	Lunar Reconnaissance Orbiter
LS	Lunar Surface
MT	Metric Ton
NASA	National Aeronautics and Space Administration
NERL	National Renewable Energy Lab
OPEX	Operating Expenses
PPP	Public-Private-Partnership
PSR	Permanently Shadowed Regions
RMD	Rover Mounted Drill
SLS	Space Launch System
SEV	Space Exploration Vehicles
SSME	Space Shuttle Main Engines
ULA	United Launch Alliance

1. Introduction

"I think we are going to the moon because it's in the nature of the human being to face challenges. It is by the nature of his deep inner soul… We are required to do these things just as salmon swim upstream.'' -Neil Armstrong' answer on challenges during Apollo 11's pre-flight news conference.

Mankind has always been interested in space and it is impossible to exactly date when astronomy started to influence humanity as astronomical elements were incorporated by ancient religions and cultures for as far as historical records go back. In the past century, humanity overcame almost impossible challenges. Stepping foot on the Moon was one of the most noticeable challenges faced by humans. Since then, technological developments and the commercialisation of space resources have made complex missions less complicated. Space science and technology have been developed even more with the increase of entrepreneurial capital in the private sector. With the growing interest of Public-Private-Partnerships (PPPs), significant cost reductions are nowadays possible and would consequently play notable roles especially through OPEX contributions resulting in more sustainable space projects.[1] Accordingly, missions in space have now evolved and consider not only focusing on the Moon but going even further.

With Mars as the next planet along others to be explored, challenges arise to be able to transport people and achieve missions across the 34 million miles of space that stretches the Red Planet from Earth. Any kind of mission have limitations related to budget constraints which is strongly associated with the amount of fuel needed. The transportation of humans and payloads in space involves the use of vast amount of propellant. More propellant implies more weight, and more weight implies the need of even more propellant. The fuel demand is one of the most eminent hurdles to make deep space travel possible and requires decent engineering design to overcome such obstacle. It is hence necessary to develop a cislunar to deep space transportation strategy that allows sustainable, operable, and effective transportation.[2]

With the increasing space exploration activities and the expansion of human presence, the use of resources in space is a critical step to allowing the development of sustainable future missions. A practice called in-situ resource utilization (ISRU) enables the generation of products from local materials. The use of resources in space is a practical and affordable way for significantly decreasing the need of same resources that were to be carried from earth. With fuel as the most promising space commodity, ISRU has been considered for drastically reducing the amount of propellant that must be launched from Earth. According to NASA, through minimization of materials from Earth, in-situ resource utilization will make extra-terrestrial exploration and operations affordable.[3] As the Moon is found to be abundant with available resources, is present to relative vicinity to Earth, and possesses decades of scientific study, it provides the ideal ground and platform for the development of technologies and methods for ISRU activities that facilitates deeper space missions.

However, although it is evident that lunar ISRU will have a significant potential for human lunar missions and beyond, it has never been fully demonstrated or proven feasible enough before in space. To validate its relevance and check its feasibility, an international collaboration would be necessary to understand the lunar resources available, demonstrate and prove feasible the extraction of such resources in the environmental conditions applied, and perform the capabilities of these ISRU at a relevant mission scale. The most relevant use of ISRU after oxygen would be rocket propellant which is mainly produced by processing polar water ice through electrolysis.

The aim of this project is to develop and assess an energy balance of a lunar operation design defined by its functional requirements to prospect, extract, process, transport, and store enough rocket propellant products on a Low Lunar Orbit (LLO) level to make future deep space missions more feasible. It further investigates the proper functional flow conditions allowing extraction of water ice present on the surface of the moon to produce liquid Oxygen and liquid Hydrogen, the lunar derived rocket propellant once cryogenically stored.

In this report, the reader will find the development of an engineering design that undergoes a thorough energy analysis for each functional block followed by a sensitivity analysis. Subsequently, the analysis will be evaluated highlighting limitations and challenges to the proposed operation system followed by recommendations for future study and research.

2. Lunar Background Research

This chapter will document some basic theoretical background important to this study. The aspects to be discussed will help the reader understands the landscape, environment, geology, and resource characterization of the Moon. Firstly, section 2.1 discusses the lunar landscape traits by explaining its topography and surface features. Section 2.2 will briefly outline the geology of the moon. Section 2.3 covers the characteristics of the lunar environment. Section 2.4 delves in the resources present on the Moon with the focus on water for the purpose of our study.

2.1 Lunar Landscape

When we speak about landscape, we refer to the surface shapes and features that a physical body have. The features that the astronomical body has helps lunar scientists and astronomists to understand its geologic history and composition. Hence come the use of topology which is the science that studies these shapes. Using different methods such the use of laser altimetry and stereo image analysis, the Moon topology has been able to be measured.

One of the most known science labs orbiting from an altitude of 50 kilometres around the moon to study the lunar topography is the Lunar Reconnaissance Orbiter (LRO) that NASA designed The instrument would apply laser pulses to characterize topography and surface reflectance as well as identify permanent sunlight/shadow through analysis of surface elevation[4]. Attached to the LRO, the Lunar Orbiter Laser Altimeter (LOLA) is a supplementary equipment that is employed to give precise lunar topographic maps using laser altimetry[5].

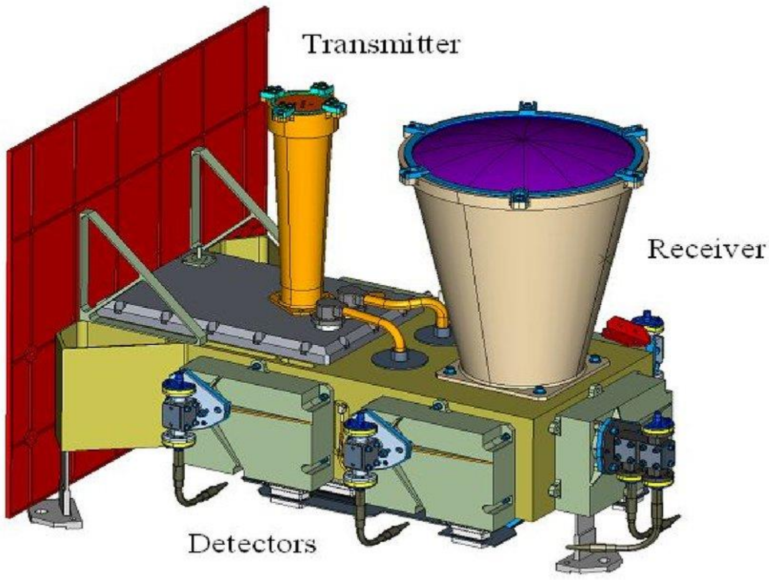

Figure 1: LOLA Instrument Diagram[5]

With this technology used (see figure 1), high resolution maps of the moon were created portraying the shape of the moon from different angle that would later help in understanding its geology. Figure 2 shows how the surface of the moon is composed of two main aspects: highlands and lunar mares. The mentioned aspects have the distinction between the bright zones for highlands(orange and red in the fig.2) and the dark zones for mares(blue and purple in fig.2) which corresponds to the moon's higher and lower elevations respectively. Lunar Highlands are the oldest rocks and are mainly composed of anorthosite rocks whereas the mares of basalt materials.[4]

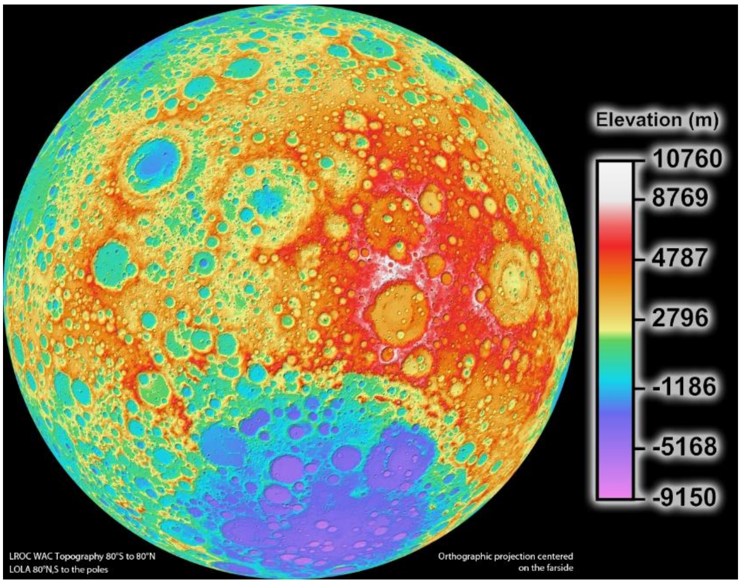

Figure 2: High resolution lunar topographic map[6]

The figure also represents various topographic views of the moon showcasing the distribution of highlands and mares on the Moon's poles. It is worth mentioning that both the north and south poles are dominated by low-lying mare areas, with the Aitken Basin as the largest and deepest feature on the Moon.

2.2 Lunar Environment

We need to emphasize the importance of understanding the hostile environment of the Moon to successfully study and analyse any design. Analysis of lunar samples helped in factualizing the recorded lunar conditions as well as helped in forming hypothesis about parameters that would later act as basis for space scientists and aerospace engineers to found on.

Contrary to the perception of many, the Moon has an atmosphere yet very thin. The latter is composed of gases that envelops the moon and would practically make the surrounding a vacuum-like body with an atmospheric pressure of 3×10^{-15} bar or 0.3 nPa. [7]

As for its temperature, the Moon has surprisingly a wide range of temperatures variation on its surface. Responsible for covering the entire lunar surface, is the LRO that for the purpose of mapping the temperature of the moon, also have an operative instrument attached to it called the Diviner Lunar Radiometer.

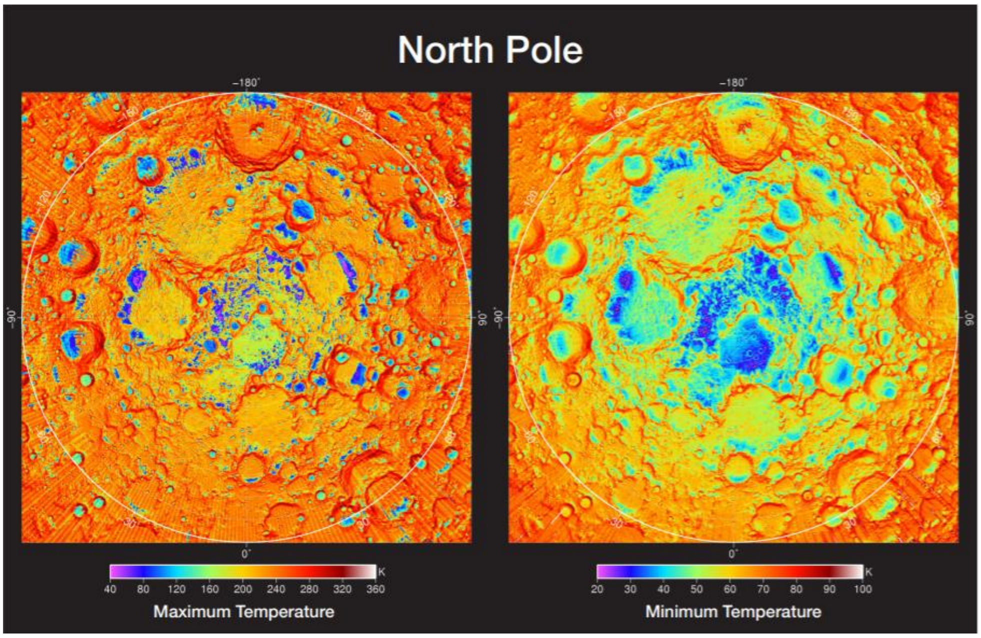

Figure 3: Temperature Variation on the Moon[8]

Figure 5 displays maximum and minimum temperatures recorded on the North pole by the Diviner while operating on the orbiting LRO. It reveals the extreme cold and hot conditions the lunar environment unfolds.

Over time, more data were generated to build a global map of lunar temperatures covering an entire lunar day during which temperature recordings ranged near the lunar equator between 140 K (-130 ºC) and 400 K (120 ºC). Additionally, data gathered on the poles revealed interesting aspects of the colder temperature map: remarkable regions were to be observed. Temperatures recorded on the poles ranged between 25 K (-250 ºC) and 220 K (-50 ºC)[9]. The coldest measured temperature was found at the bottom of several craters near the lunar south pole that would be called Permanently Shadowed Regions (PSRs).

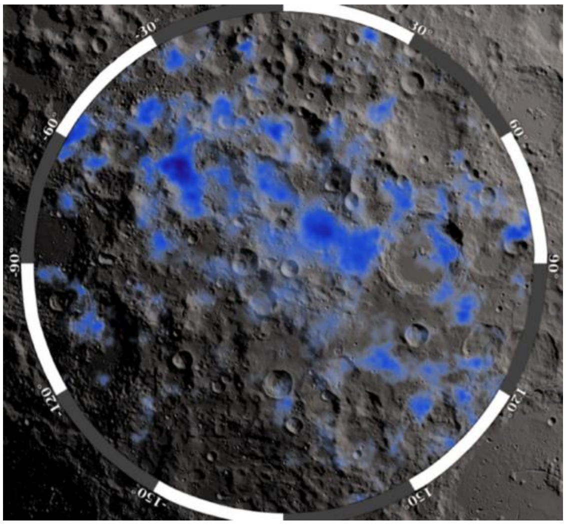

Figure 4: Permanently Shadowed Regions on the Moon[10]

These areas are basically craters that never get sunlight due to the tilted axis of the Moon from the ecliptic plane preventing direct solar radiation[11]. Receiving no sunlight into the PSRs craters, astronomers have consequently hypothesized that low temperatures can essentially make them cold traps for volatiles such as water to settle and be deposited.[10]

This study will focus greatly on these regions of interest as they suggest the best place to locate the polar water ice for ISRU and from which produce eventually the desired rocket propellant.

2.3 Lunar Geology

As complicated as it gets, the Moon consist of ever discovered minerals and materials that has been formed and modified by different combination of processes. The most significant processes noted were impact cratering and volcanism.

The body differentiation of the Moon is composed of geochemically distinct crust, mantle, and core. While a substantial portion of the planet's surface has not yet been explored leaving numerous questions unanswered; geological studies were based on analysing results of Earth-based telescope explanations, measurements from orbiting instruments, collection of lunar samples, and acquirement of geophysical data.

Beginning with the Apollo 11 that landed on the Moon in 1969 and followed by many others, samples collected during the missions reported back direct knowledge about the composition of the lunar surface interior. The lunar crust was found to be largely anorthositic in composition: intrusive phaneritic igneous rock composed of mostly plagioclase feldspar with a minimal mafic component[12].

Within the broader lunar crust term which averages about 50 km thick, we focus mainly on two portions within each other. Firstly, the lunar regolith which generally ranges between 4-5 m of thickness in mare areas and 10-15 m in highlands areas. Then the lunar soil which is the finer fraction of the regolith (1cm in diameter)[13]. The latter is the source of all our information since all physical and chemical measurements of lunar material, whether from rocks or soil were made from it.

Although water is considered the material focused upon on this study, it will be discussed fully at a later stage. First, it is worth mentioning other present materials spread throughout the Moon and see how rich it is. In terms of elements, it is rich among others in Oxygen(O), Silicon (Si), Iron(Fe), Magnesium(Mg), Calcium(Ca), Aluminium(Al), Manganese(Mn), and Titanium(Ti) with an abundancy by weight of Oxygen the most (45%) followed by Iron and Nitrogen[14]. As for the chemical composition, table 1 shows the most common compounds present and their location distribution on the lunar surface[15].

Table 1: Lunar Surface Chemical Composition and Distribution

Compound	Formula	Composition	
		Maria	Highlands
silica	SiO_2	45.4%	45.5%
alumina	Al_2O_3	14.9%	24.0%
lime	CaO	11.8%	15.9%
iron(II) oxide	FeO	14.1%	5.9%
magnesia	MgO	9.2%	7.5%
titanium dioxide	TiO_2	3.9%	0.6%
sodium oxide	Na_2O	0.6%	0.6%
		99.9%	**100.0%**

All these natural well-defined chemical compositions, when present in solid form with a specific crystal structure create the presence of an abundancy of minerals that are spread all over the Moon. Among many, the most common lunar minerals composed from the underlying elements are the following: Plagioclase feldspar, Pyroxene, Olivine, and Ilmenite.

	Plagioclase	Pyroxene	Olivine	Ilmenite
Highland rocks				
Anorthosite	90%	5%	5%	0%
Norite	60%	35%	5%	0%
Troctolite	60%	5%	35%	0%
Mare basalts				
High-titanium	30%	54%	3%	18%
Low-titanium	30%	60%	5%	5%
Very-low titanium	35%	55%	8%	2%

Figure 5: Approximate Mineral Abundances in Moon Rocks[16]

Figure 7 reports the distribution of minerals the Moon rocks have by percentage and location. These mentioned materials whether found in volatiles or minerals assure a substantial possession the Moon has of potential natural resources that could be exploited and used in the future.

2.4 Lunar Resource Characterization and ISRU

Engaging with a resource quest in the vast extraterrestrial space depends merely on developments of space exploration technologies. With the recent renewed interest in the resource rich lunar environment; space agencies such as NASA and ESA alongside private owned companies (Deep Space Industries, Moon express, Shackleton Energy Company to name a few), have established the aim of exploiting lunar resources[17]. As more incentives are being targeted in the interest of identifying, understanding, and exploiting resources present, more sustainable utilization can be discovered and eventually maintained.

Information from orbit and sample-returned missions paved the way through determining the availability of resources. In this section, we will be listing some of the resources found on the Moon.

With the previously mentioned thorough description of the Moon, it is now clear where and what could be depicted from its potential environment. Approximately two weeks of daylight are followed by two weeks of night and the lunar poles regions are illuminated almost all the time except inside the interior of the craters consequently creating the previously discussed PSRs[18]. This condition allows suggesting that solar power (generated from solar arrays) could be an eminent resource being both sustainable and useful, possibly of great use in locations for lunar operation facilities. To foster its resourcefulness, we should emphasize the fact that solar cell production could be eventually produced from materials already present in lunar soil. Of the primary materials needed to produce such technology, Silicon, Aluminium, and glass are found in high concentration(due to the vacuum-environment allowing direct deposition of thin-film materials) and hence can be exploited for its production[19].

Oxygen is another elemental resource available in large quantity as it is estimated to be present at 45% by weight. Lunar sample-return missions have never returned free oxygen; however, the rock and soil samples contained oxygen in oxides form due to its combination with metals or nonmetals. Extraction oxygen methods are also known and valid through different methods, with basically origins from ilmenite, basalt, soil, and volcanic glass. Of the most mature technologies, the use of hydrogen as reducing agent in reduction processes can be used to result in the release of high oxygen yield in the form of water vapor. The latter is the product of a reduction process performed on lunar iron minerals[20]. The basic equation of the chemical reaction is the following:

$$FeO + H_2 \rightarrow Fe + H_2O$$

The ISRU of oxygen on the Moon provides more applications in life support systems as well as fuel and power systems once used with hydrogen that could drastically reduce the payload launched and carried from Earth.

NASA's Lunar Reconnaissance Orbiter (LRO) spacecraft has observed and indicated deposits of hydrogen-bearing molecules especially in crater slopes near the poles. Being a volatile material (easily vaporized), hydrogen may be in the form of water or hydroxyl molecules bound to the lunar surface; where two hydrogen atoms bound to an atom of oxygen forms a water molecule or one hydrogen to one oxygen forming a hydroxyl molecule[21]. Within the solar system, the Moon is subjected to impacts of comets and asteroids that contains amounts of water. Accordingly, there are many possible sources for hydrogen presence on the Moon. Of which, the solar wind can implant protons on the surface thus forming the hydrogen atom[22]. Nevertheless, the questions remain to whether much of it would diffuse in the surface, escape in space, or diffuse in cold traps near the poles.

Among other metal resources found on the Moon Iron, Titanium, Aluminium, Silicon, Calcium, Magnesium and Helium-3(a rare-earth element) once exploited could provide multiple uses for aerospace, engineering, technology, and other relevant applications and mostly to achieve advances in space exploration.

3. Water resource on the Moon

Water is yet another important resource present abundantly on the Moon. Ever since the previously mentioned Apollo samples were returned, it was clear that volatiles were present on the surface and in the subsurface of the Planet. These volatiles were referred to enhancements of hydrogen that have been measured and detected by orbital spacecrafts sensing their existence. Two particular missions launched in 2008 and 2009, NASA's Lunar Crater Observation and Sensing Satellite (LCROSS) and the Indian Space Research Organization's Chandrayaan-1 orbital spacecraft, confirmed the presence of eminent amount of water ice deposits masked under significant hydrogen deposits at both lunar poles[10]. The measured readings were mainly in plumes detected in over 40 permanently shadowed craters near the Moon's polar regions showing material containing $5.6 \pm 2.9\%$ H_2O by mass.[23]

As for the origins of this resource, astronomers had always theorised that water may have been delivered through regular bombardment of water-bearing comets, asteroids, and meteoroids over geological timescales[24]. Another source to it could be its local production on the planet by hydrogen ions coming from solar wind that would eventually impact oxygen-bearing materials.[25]

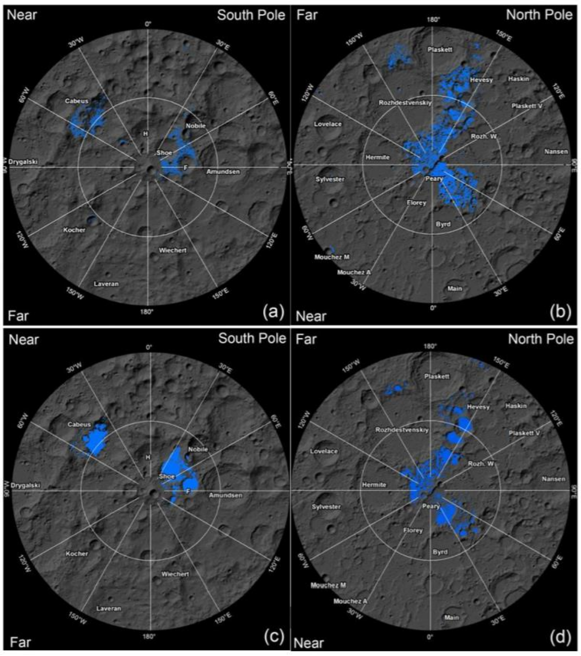

Figure 6: Detection of Hydrogen Presence in the South [(a) and (c)] and North [(b) and (d)] Poles of the Moon.[23]

The quantitative estimates of hydrogen that support and provide the direct evidence attributed to water vapor and ice presence would hence be indicated in and around PSRs as shown in figure 8. The PSRs due to being permanently shaded from sunlight, will allow the natural trapping and collection of water molecules in the form of ice pieces distributed and coated on the regolith and on ice grains. These observations of concerned areas were made by gathering data from LRO using the Lunar Orbiter Laser Altimeter's (LOLA) infrared spectrometer. The latter have measured topographies and slopes at both poles, giving in terms of ISRU potential promising results that suggest some ice-bearing source locations to contain estimations between 3.5% and 30% of water ice by mass to be intimately mixed with dry regolith and suitable to be mined in the future[26]. The mining and extraction methods will be discussed in section 5.2 that will highlight the ideal extraction scenario for effective and efficient yield.

4. ISRU for rocket propellant

In relation to ISRU, once extracted and recovered, water will be sought for multiple uses. Applications consist of direct use either in life support (drinkable water, food growth, breathable oxygen supply) or in other chemical productions processes. The latter will be our focus in this study that will directly investigate the processing of water into cryogenic rocket propellant. By utilizing this indigenous water resource and transforming it into a product very much needed for space missions, the mass of materials and fuel carried from Earth will be significantly reduced, thus making potential reduction in space mission costs and even allowing future missions to be reconsidered as more feasible.

The biproduct of processing water in terms of fuel would be the production of a rocket propellant type called cryogenic propellant. There are mainly three widely used types of rocket propellant: solid propellant, liquid propellant, and hybrid propellant. Although they differ in state, they all operate under the condition that a fuel and an oxidizer must be combined to burn and produce the thrust of hot gases created needed to propel the rocket. Figure 9 quickly illustrates the difference between liquid-fuel and solid fuel rockets.

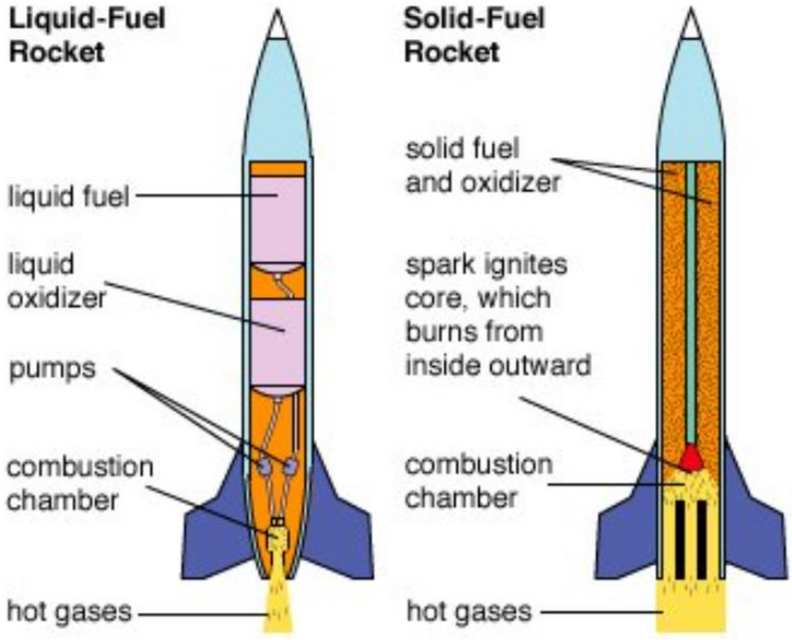

Figure 7: Cross Section Representation of Liquid and Solid Rockets.[27]

Briefly, liquid propellants consist of two tanks that store separately the fuel and the oxidizer and are combined within an engineering design to a combustion chamber where the actual thrust is created once burned. Typical fuels would be alcohol, kerosene, hydrazine, and liquid hydrogen while oxidizers include nitrogen tetroxide, nitric acid, liquid fluorine, and liquid oxygen[28].

In the recent past, oxygen/hydrogen combination has gained interest in the studies for new generation propulsion systems particularly for upper stages, liquid booster stages, and in-orbit transfer stages. To evaluate the performance of a propellant (ability to increase the delivered payload mass), the specific impulse (I_{sp}) and the propellant bulk density will be judged. The specific impulse will measure how effective the exhaust velocity is or the change in momentum per unit mass for the fuel used, thus the higher it is, the more push a rocket can get for the fuel burning out. Judging by the propellant density, a lower density material is a disadvantage as it needs to occupy more volume than lighter fuels, thus increasing the vehicle's overall dry mass by basically requiring larger fuel tanks and pumps. In figure 10, specific impulse and bulk density of 4 different propellant combinations are plotted against the oxidizer to fuel mass ratio.[29]

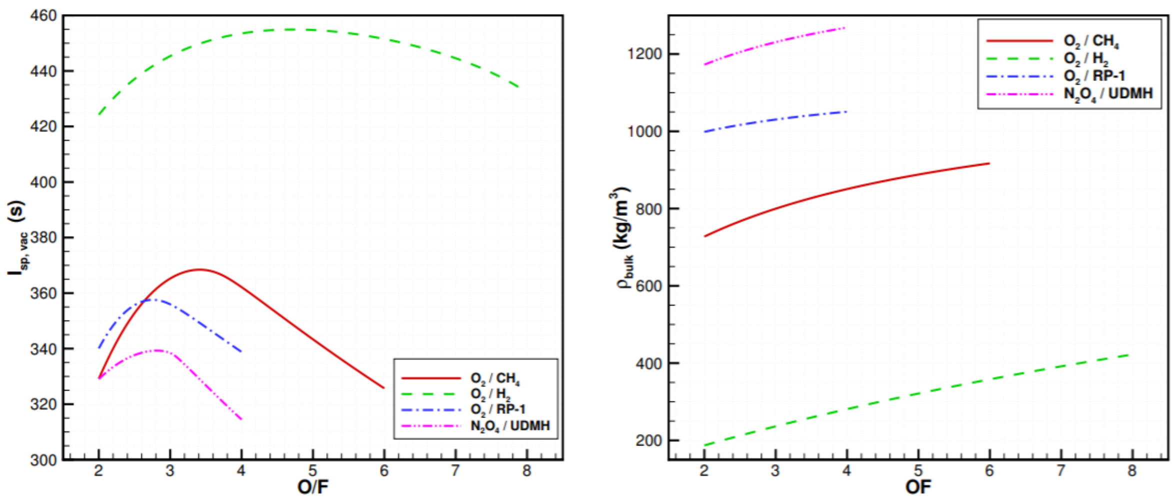

Figure 8: Performance Comparison of Different Propellant Combinations

Among oxygen/hydrogen, oxygen/methane, oxygen/kerosene, and nitrogen tetroxide/unsymmetrical dimethylhydrazine, the O_2/H_2 combination although with lowest in bulk density which necessitates larger tanks for storage, it gives the richest performance in regard to specific impulse. Through the in-situ propellant system on the Moon, this capability will facilitate and be of use for further space exploration applications.

As the target of our study will be the use of water resource as a rocket fuel, we will focus the investigation on the propellant type of liquid oxygen as oxidizer and liquid hydrogen as fuel – the final product of processed lunar water.

Water on the moon would be subjected to electrolysis; a process used to electrically decompose water molecules into releasing oxygen and hydrogen gas, hence producing the required elements for a chemical liquid propellant. However, to be used in the rocket tanks, the released gases from the electrolysis would need to be cryogenically cooled and eventually stored in cryogenic tanks. These tanks are disposed to handle a liquified gas requiring very low temperature conditions to stay in its liquid state. Most frequently, space navigation agencies use liquid hydrogen LH_2 as fuel and liquid oxygen LO_2 or LOX as oxidizer. For their use in high efficiency main engines of spacecrafts, LOX/LH_2 should be stored in a way that maintain hydrogen below -253 °C and oxygen below -183 °C[30]; hence making it a difficult process to store them and it requires further investigations and enhancements for whether it would be possible storing them via In-Space Cryogenic Propellant Depot (ISCPD). Once produced from lunar water, propellant storage is a critical function for the ISRU to support propellant customers interested in cislunar space. In order to obtain a functional orbital propellant depot there will be a need to develop subsystems like reusable space tugs, Moon shuttles and refuelling stations that would undeniably play a role in successfully creating a commercial lunar propellant architecture.[31]

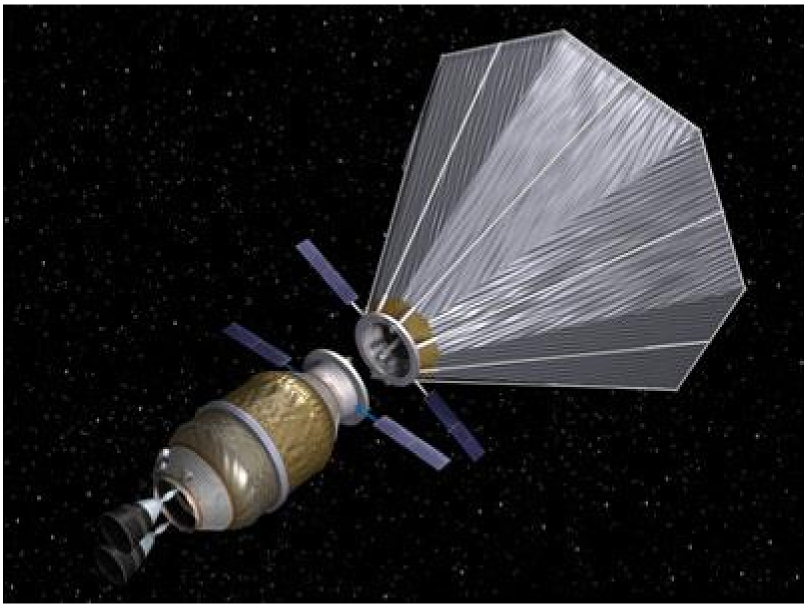

Figure 9: Cis-Lunar Propellant Depot Design by ULA[32]

However, due to budget constraints to support the development of technologies and infrastructures responsible for storing and refuelling propellants in space, there are no defined or yet proven in space system that showed functionality and reliability over fuel transfer and storage. Nevertheless, space agencies are stepping in to bring more cutting-edge technologies in spaceflight. With the support of commercial public-private-partnerships like SpaceX as example, NASA and other agencies are performing thorough studies to solve the fuel storage and transfer challenges and put together propellant depot development strategies.[33]

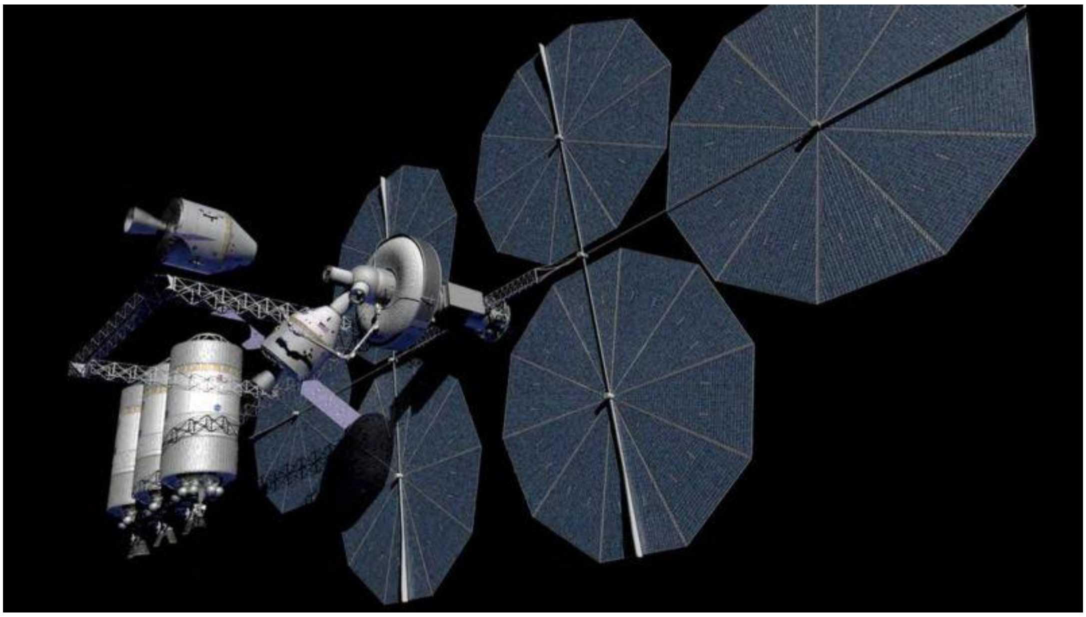

Figure 10: NASA concept for In-Space Cryogenic Propellant Depot[33]

Decades from now and with endeavours as such, the technological maturity for space depositing system would be reached allowing to perform in space refuelling. Some of the abilities obtained from orbital depositing for refuelling stations consist of employing smaller vehicles with higher flight rate launched from Earth eventually reducing exploration costs as they are dominated by the cost of transportation. Additionally, having a space "pit stop" facilitates scientific and economic activities in the so called cis-lunar space as well as future missions elsewhere in the solar system, take Mars as the next destination.

To better understand how the Moon by being a viable source of water and subsequently of LO_2/LH_2 propellant presents itself as the ideal in-space place to support activities beyond Low Earth Orbit (LEO), it is important to understand two inter-reliant scientifical notions: the rocket equation and the map of cislunar space.

The rocket equation also called Tsiolkovsky rocket equation or classical rocket equation comes in handy as we study the requirements and behaviour of spacecrafts or basically any vehicle that can apply acceleration to itself by thrusting and expelling part of its mass with extremely high velocity. The conservation of momentum is thus applied to rockets exerting the spew of gas burned out of nozzles to move the rocket and the attached nozzles in the opposite direction. Understanding how the equation works is key for best comprehension of the subsequent energy analysis.

Tsiolkovsky's equation is written: $\Delta V = v_e \ln(\frac{m_i}{m_f})$; and has three variables, the change in rocket velocity or delta V, the energy available in the used rocket propellant or specific impulse I_{sp}, and the propellant mass fraction(the amount of propellant needed compared to the dry total rocket mass)[34]. For interplanetary missions, delta V depicts the spacecraft flight dynamics and depends on the starting and ending point of the travel which. Once the equation is solved for a propellant energy and a specific route, it takes an exponential behaviour where farther travel will require an ever-increasing rate of propellants. It is for that reason that far space missions expect to consist of big spacecraft like the size of Saturn V or the SLS currently in development. The following chart illustrates this situation by showing the relationship between the performance of a rocket vehicle and its mass through plotting a rocket's mass ratio versus its final velocity.

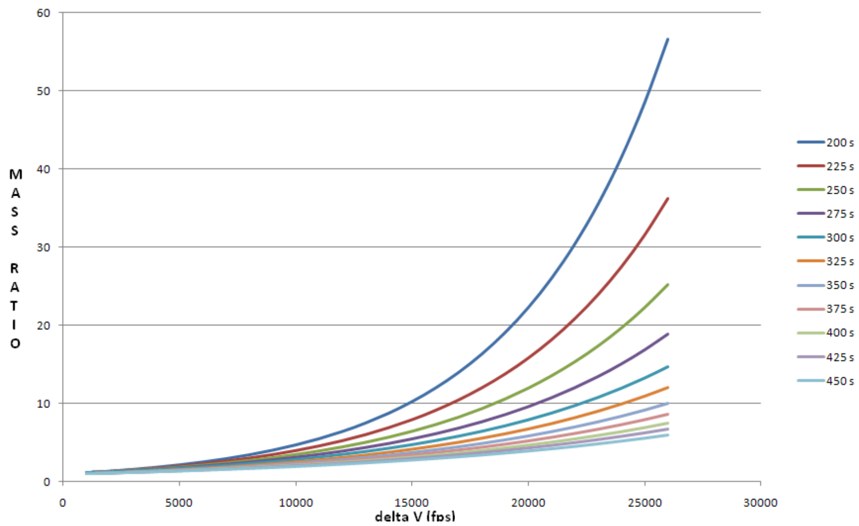

Figure 11: Effect of Isp on Mass Ratio for Different Delta V[35]

On another hand, the cis lunar map holds value for representing the delta V corresponding to different trajectories or route taken for space travel. It hence depends only on the desired trajectory and not on the space vehicle mass, thus giving estimations of the total change in velocity required to perform any specified propulsive manoeuvre. To move between different space destinations, scientists use tables of the delta-V required to conceptually plan a sp ace mission.

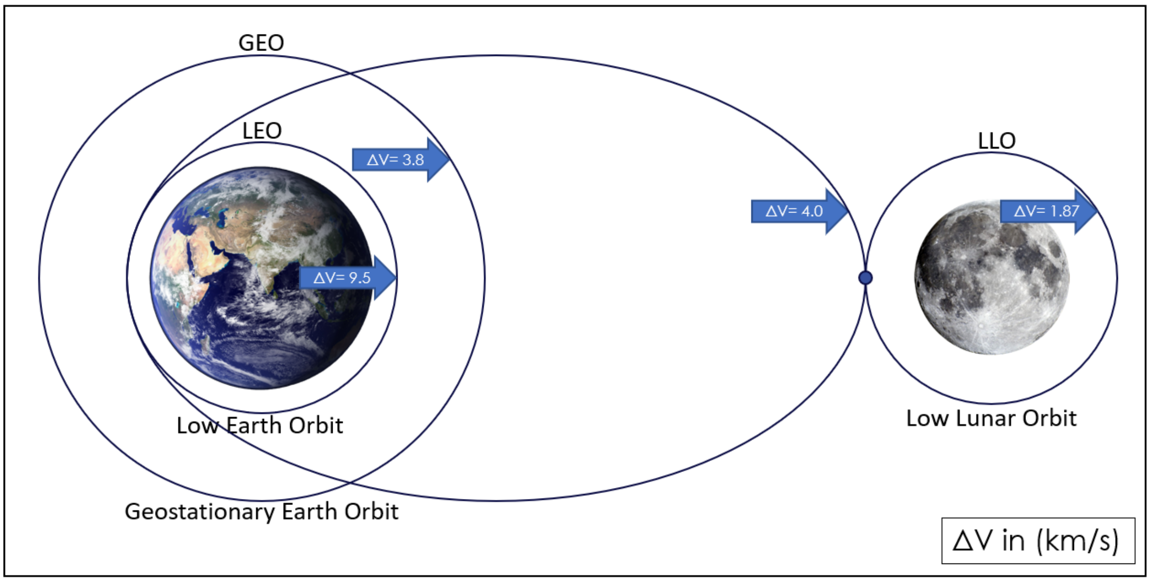

Figure 12: Delta V Map of Cis-Lunar Space

Figure 12 clearly shows that escaping earth gravity well requires a delta V of 9530 m/s which means a lot of propellant used. Comparing to the latter is escaping the Moon's gravity well from the Moon's surface with 1,870 m/s of delta V needed which is much easier with a factor of five less than from Earth.

Once escaped from LEO, the moon is the closest source of fuel outside Earth's gravity. It would intuitively be beneficial to have a refuellable space architecture somewhere around the Low Lunar Orbit (LLO). A space refuelling station would take advantage of the propellant resource present on the Moon to support missions launched from Earth that already lost lots of fuel escaping the Earth's orbit and thus need their replacement to continue traveling beyond or return back to Earth.

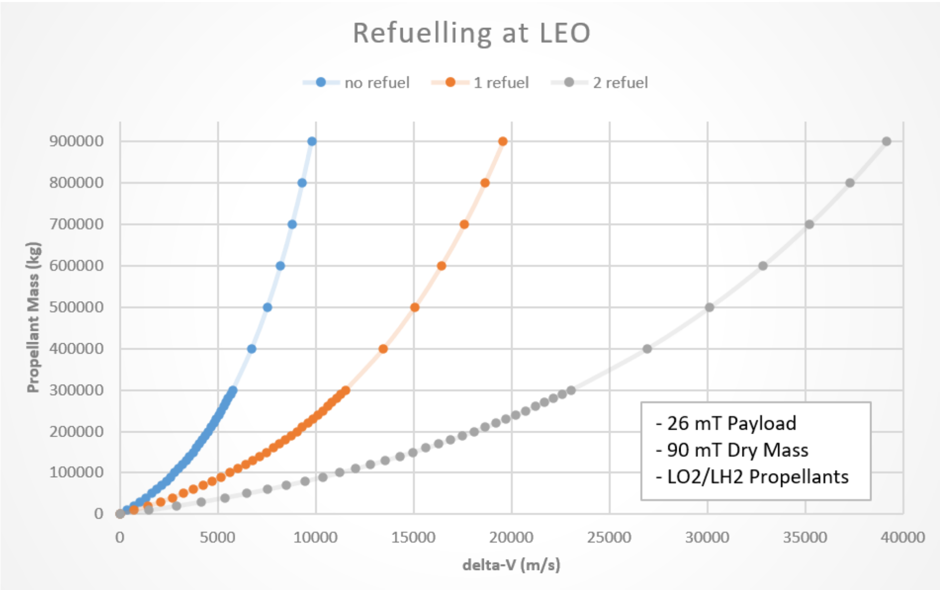

Figure 13: Benefits of Refuelling With Lunar Sourced Propellants[36]

Refuelling enroute and reusing propulsion systems with multiple refuellings can break the tyranny of the rocket equation previously discussed where the relationship between the distance travelled and the propellant mass becomes more linearized, thus reducing propellants for a given Delta-V . Figure 13 shows this advantage for one and more refuellings resulting in significant mission cost cuts by reducing the propellant required to achieve a given delta-V or by consequently reducing the size of the spacecraft. This benefit was proved in the plot by simply applying the rocket equation (Equation 1) for assumed configuration (payload mass, dry mass, and fuel type).

Equation 1: $\Delta v = -I_{sp} \times g_0 \times \ln(`1 - \frac{m_p}{m_0})$

Where the specific impulse is assumed to be 460 m/s, gravity 9.80665 m/s^2, m_p the propellant mass which will be increasing at a 10,000 kg increment, and m_0 the lift of mas. The latter includes the payload mass assumed to be of 26 mT (2% payload fraction), the dry mass of the spacecraft (here assumed 90 mT), and the mass of the propellant mass at each stage added. Delta-V is hence calculated until reaching its corresponding exponential limit.

A no refuel-scenario plot was compared with one refuel and multiple refuels. Each scenario was plotted where simulations of different trends were done; by increasing the propellant mass input parameter continuously until reaching the exponential ‘’limit’’ each scenario possibly can reach accordingly. It is hence clear how any space mission beyond the Low Earth Orbit can benefit from a lunar propellant refuelling station located at a relative proximity to the Earth.

5. Study Description

Chapter 5 describes based on all the research done at the start of the study, the working method towards the energy analysis of an architecture design for a lunar propellant production by first elaborating in section 5.1 the system's required need and in section 5.2 the chosen design able to meet this demand through a functional flow diagram. Then, section 5.3 describes each defined functional requirement that all together provide the necessary elements to provide the infrastructure allowing to trace the flow of ice from its source, through processing, and all the way to the final storing location. After which, some assumptions and ground rules that justify decisions affecting transportation, mining, and processing will be introduced and discussed in section 5.4. Once the overall system is defined and explained, the reader will find it simpler to comprehend the energy and sensitivity analysis developed in the chapters to come.

5.1 Propellant needs

As all the space transportation agencies like NASA and ESA would want to reduce the cost of launch from Earth and still desire further reach in space, having a supply of lunar propellants in the vicinity of the Moon is so favourable. A fuel supply station in orbit of the Moon can make many missions affordable and more sustainable. Not only would it support deeper Mars missions by providing a staging location for Mars departures but can yearly provide great help when refuelling reusable vehicles for crewed lunar missions rather than delivering from Earth new systems and fuel supply as well as refuel vehicles orbiting the Moon on non-lunar missions[37]. Once a commercial lunar propellant production is established, demands of different projected customers must be estimated. Early customers for a base of lunar derived propellant may well be within commercial launch industries; companies like SpaceX, Blue Origin, and ULA as well as governmental space transportation agencies like

NASA and ESA would be the first in the market to request and demand amounts of propellant. To satisfy all the demands from initial lunar propellant customers estimated at start while accounting for the propellants(to be burned) needed to transport the supply fuel; a collaborative study of lunar propellant production sponsored by the National Renewable Energy Lab (NERL) demonstrated a yearly demand of 1,640 MT of lunar propellant produced on the surface of the Moon, corresponding to 2,450 MT of lunar water yearly processed[31]. The annual propellant amount of 1,640 MT will be the final product of the designed system the study will assess and analyse.

5.2 System Boundaries

Before we dive deep in the details of every subsystem, this section will provide an overview of the global system design or architecture that will later undergo an energy analysis. It can be used to look back on whenever the reader gets lost with the flow of operations that supports the proper functionality order. The study goal and the course of what the work will look like is also defined in this section.

The goal of the study is to investigate and analyse the energy allocated in a system that can produce and store enough LO_2/LH_2 propellants from polar lunar ice for deeper space missions. The system chosen in this study, comprises operational subsystems allowing proper flow of actions to achieve this goal.

The functional requirements to establish a lunar propellant production are captured in the functional flow diagram below that represents a simple overview of the system workings.

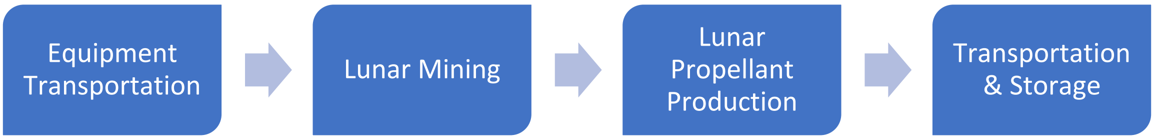

Figure 14: Functional Flow Diagram for Lunar Propellant Production

5.3 Functional Block Description

For better understanding the proper functional phases the system is composed of before investigating energies flow, this section briefly explains each block/phase visualized in figure 14 and describes them in terms of goals required for the completion of each phase. The diagram in figure 15 visualizes briefly the appropriate sub-goals further clarified in the sections that come after.

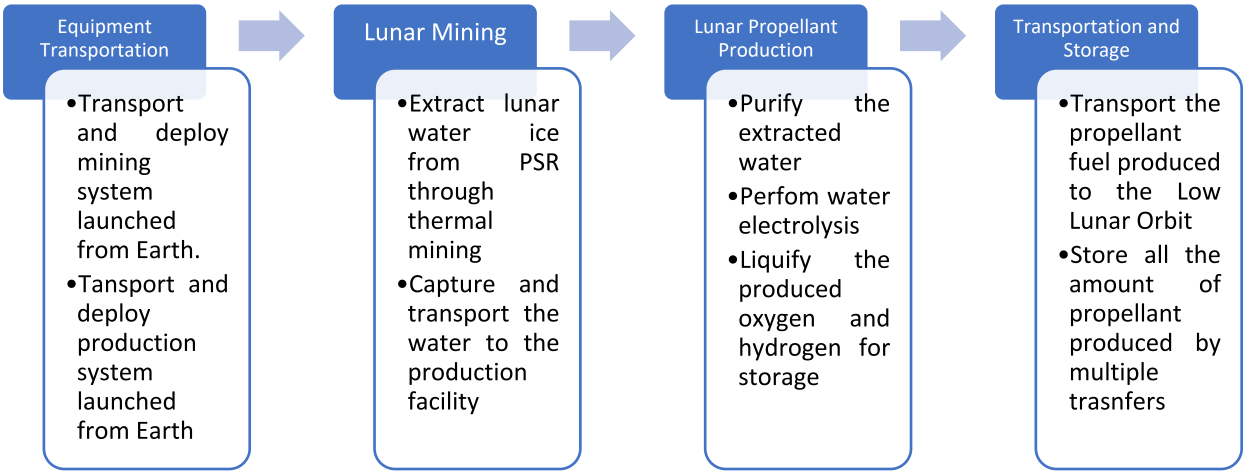

Figure 15: A diagram of the System Blocks and Their Goals

5.3.1 Phase 1: Equipment Transportation

Based on previous studies that worked on assigning the essential apparatus for the proper functioning of the mentioned operations while suggesting a system design able to establish a production mission of the stated demands, it was therefore possible to assemble all the needed equipment.

The equipment needed will be launched from Earth and deployed on the Moon in order to operate and maintain production once started. The components deployment will depend on their functions. As discussed, it is obvious that the Permanently Shadowed Regions (PSRs) which have areas of high-water distribution will be the location for deployment. However, within these regions, subsystem components are to be allocated differently as each location (crater, crater rim) can give access to different functionality. For the purpose of sticking with the description of each phase at a time, the deployment lunar locations will be discussed at a later stage in the study.

The following table displays a subsystem component list proposed by a study from the Colorado School of Mines who investigated a thermal mining method operation on the Moon. The suggested equipment are to be transported from Earth with an average mass of 26 mT[38]. It is to be mentioned that for the scope of our study, a brief functionality description will be given for only some of the component and in a later section under the block it will be used in.

Subsystem	Mass (kg)
Capture tent	2000
Cold traps	900
Ice haulers	1500
Secondary optics	1200
General purpose vehicle	1000
Purification & electrolysis system	5000
Liquification system	3000
Solar energy system	7500
Power system	4000
Communication system	100
Total	26,200

Figure 16: Suggested Subsystem Masses[38]

Choosing the spacecraft able to send this amount of payload will be out of the scope of the study. However, spacecraft configurations similar to the Space Launch System (SLS) were found to be available that can offer a cargo mass up to 27 mT to be send to the Moon and thus making the load delivery possible[39].

5.3.2 Phase 2: Lunar Mining

The mining for the water resource is a subsystem of the overall lunar production facility for propellants. Many methods for mining the ice distributed on the Moon have been suggested. Some of them consider active extractions techniques such as RMD (Rover Mounted Drills) or subsurface heating. Another technique would include passive extractions that either extract ice from the ground as a bulk physical material or through sublimation allowing the regolith to remain.

This study will use the so-called thermal mining method that considers sublimating the icy regolith to extract the water. The latter avoids many drawbacks of the other excavation methods in regards of transporting, handling, and providing the required power to handle the large volumes of regolith and thus exploit the sublimation by being efficient and scalable hence providing a feasible excavation method.[31]

The mining operation consists of applying heat directly to the frozen regolith within the PSRs allowing the sublimation of the volatiles water. The engineering architecture proposed allows heat to be applied in the form of concentrated sunlight from crater rims nearby that will be redirected to hit the inner surface of capture tents positioned in ice-rich fields. Heliostats can be deployed on craters rims in different locations and used to adjust sunlight and hit secondary optics above the tents to better warm the crater floor surface.

Figure 17: Thermal Mining Concept Showing functionality of Heliostats and Capture Tents[31]

Once the water is sublimated into vapor, it will be captured inside the tent placed over. The vapors obtained will migrate from the tent's inner surface through openings and refreeze the water inside 'cold traps' to be collected. The following figure illustrates in a simplified manner how the water sublimation and extraction will be performed.

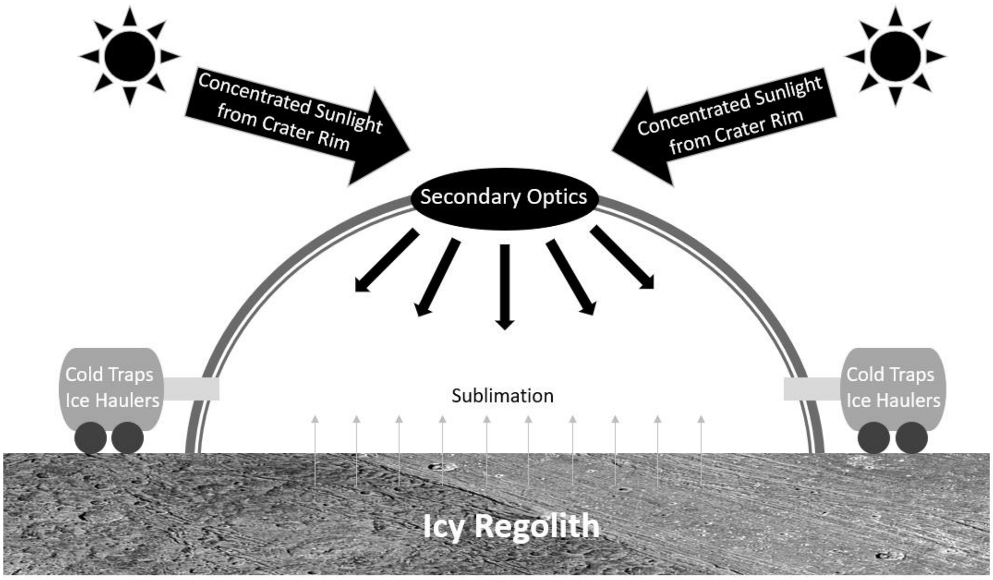

Figure 18: Thermal Mining Concept

Mining the chosen regolith area goes on until the surface becomes depleted of water volatiles and then the tent gets allocated to another location[31].Throughout the operation, the 2,450 mT of water inside the filled cold traps will be transported and emptied in the neighbouring processing facility where the propellant gets produced (see next section).

5.3.3 Phase 3: Lunar Propellant Production

This block has a function of processing the vapor collected and frozen from the extraction block into producing the resource-derived propellant of LO_2/LH_2. Once the ice haulers deposit the ice in the processing facility, a series of processes will be done all inside this facility.

As the volatiles captured within the cold traps contain other contaminants and not only water molecules, the water entering gets compressed and undergoes purification through a membrane distillation architecture called Ionomer-membrane Water Processing (IWP)[40]. The purified water will then be condensed, polished, and transferred to an electrolyser. The latter utilizes an electric current to decompose water molecules into oxygen and hydrogen. Once the gases are generated, they are separated, dried, and liquified independently, ready to be transferred as ISRU-derived fuel into other storing containers. Figure 19 shows a brief representation of the flow of water being processed passing through all functional subsystems.

Figure 19: Propellant Process System Flow

5.3.4 Phase 4: Transportation and Storage

The block focuses on the two purposes of stocking the created LO_2 and LH_2 and transporting them to the refuelling station within the cislunar space depots (see figure 19). Due to the strict storing conditions, the propellants require heaters to prevent freezing and cryocoolers to eliminate any boil-off risk.

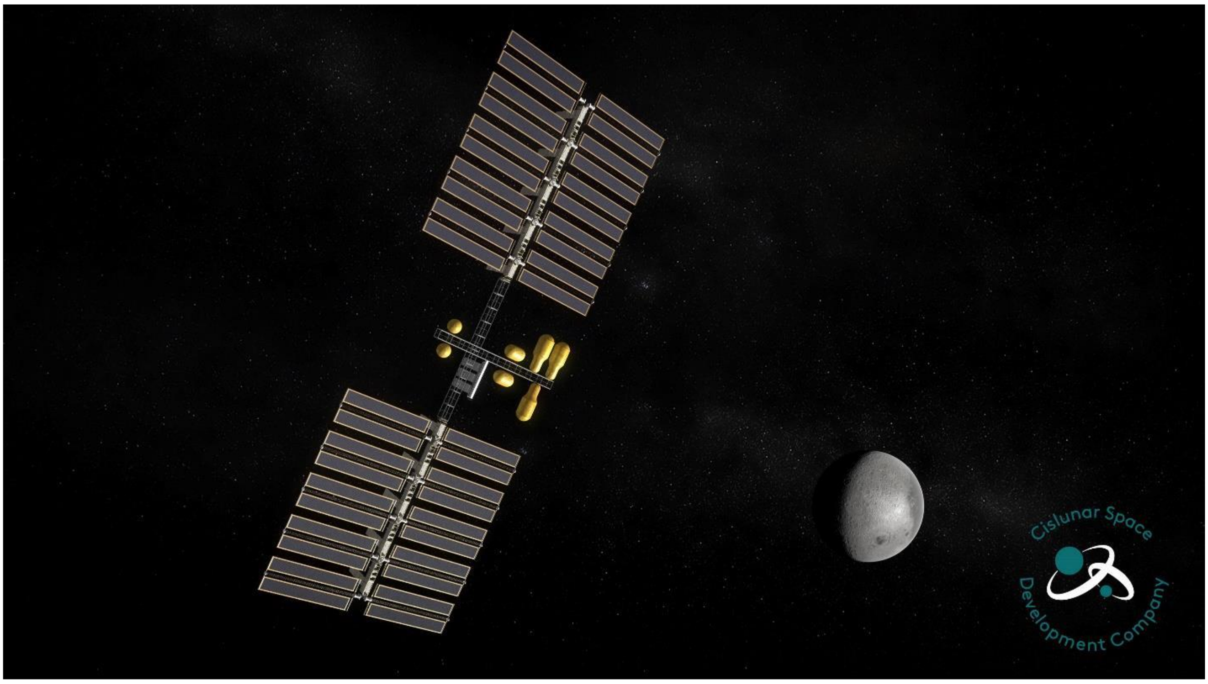

Figure 20: Lunar Orbit Propellant Station

To achieve this, storage tanks would need to maintain the proper thermal conditions with the help of good insulation and other heating technologies to support successful storage of massive propellant amounts. Although no technology is already operating at this moment, agencies are working on testing capabilities of cryogenic propellant depots to be placed and used in space as a fuel station[41]. Once the depots are stationed in Lunar Orbit and enough fuel is produced, delivery shuttles would move the propellants directly from the facility on the Moon Surface to the orbiting fuel depot where rockets could dock and refuel. Transporting the propellants will be done through multiple load deliveries of 150 mT tankers to successfully store annually the 1,640 mT of propellant produced. The latter are the focus in development within a work in progress Big Falcon Rocket (BFR) design from SpaceX that can carry payloads up to 150 mT[42].

5.4 Assumptions and Ground Rules

The energy analysis will be investigated based on a set of assumptions and criteria that were defined during this study for the purpose of performing a possible realistic evaluation as there are still unknowns in regards of the science state. The data implemented were researched for space and Moon context to be coherent within the set model and concede a practical analysis of the entire defined system. Common assumptions and rules are:

- The analysis will exclude major infrastructure elements related to the robotic, communication/navigation, and power systems.
- The analysis evaluates the system operation of one full year.
- No interruption of process during the entire year.
- Mining operations consider a fixed scale tent architecture.
- Solar power plants located outside PSR will rely on sunlight and will power different operations.
- The study only considers technology developed or in development.
- Spacecraft mentioned would depend solely on liquid oxygen and liquid hydrogen as propulsion fuel.
- The energy analysis will only consider the active operation and not the energy needed to develop, deploy, and maintain the infrastructure.

Further process related assumptions will be mentioned within the energy analysis of each block under the energy analysis chapter below.

6. Energy Analysis

Along the intended operating patterns to achieve the final goal of the study, the energy analysis will be performed block by block following the system functional flow course of actions.

6.1 Energy Analysis of Equipment Transportation

As discussed earlier, the system model we are evaluating in this phase will be only considering the transportation of equipment from Earth to the Moon through a spacecraft with configurations similar to that of the Space Launch System (SLS), capable to deliver the payload needed of equipment that weighs approximately 26 mT (see section 5.3.1).

To deliver this payload from Earth to the Moon surface, the adopted spacecraft will be assumed to run on liquefied oxygen and hydrogen as used in the highest efficient main engines of space shuttles. [30]

The energy basically required in this phase to perform its function, would be the energy accounted when the spacecraft burns the propellant fuel along the entire delivery trajectory. Therefore, it is mandatory to indicate the amount or mass of propellant used to deliver the payload.

To calculate the amount of propellant used, we need to go back on the rocket equation, as it represents the only mathematical method to approximately and scientifically approximate the amount of propellant needed. However, to solve the rocket equation for the mass of propellant, we account for the other inputs that depend on the engineering design of the spacecraft to be used and the trajectory its following consequently.

It is essential here to elaborate on the notion of payload fraction which helps us know what the spacecraft engineering configuration is (mainly interested in its lift off mass). A payload fraction can reveal the efficiency of an engineering configuration where it is calculated by dividing the weight of payload carried by the take-off mass (or initial lift-off mass) of the spacecraft, including its fuel which takes most of the weight.

$$Payload\ Fraction = \frac{Payload\ Mass}{Lift\ Off\ Mass}$$

Based on the payload fractions of different launch vehicle that are designed to fly spacecrafts in outer space and transport heavy cargo, we can assume that the average payload fraction of a launch vehicle for such operation would range between 1% and 7%.

Assuming that the spacecraft employed in our model use a 2% payload fraction, the initial lift off mass for a payload of 26 mT, would be equal to 1,300,000 kg or 1,300 mT (see calculation below).

$$Initial\ Lift\ Off\ Mass = \frac{Paylaod\ Mass}{Payload\ Fraction} = \frac{26{,}000\ kg}{0.02} = 1{,}300{,}000\ kg$$

Also, it is important to indicate the type of rocket engine used to specify the propulsion system's specific impulse that is going to be used throughout the evaluation. Engines will be assumed like the Space Shuttle Main Engines (SSME) that burn liquid hydrogen and liquid oxygen during the ascent and along the flight, with a specific impulse (I_{sp}) of 460 s[43].

It is to be mentioned that the space travel of this phase will require an estimate of different delta-V budget to move between different space venues. The delta-V of each trajectory will also be an input to solve the rocket equation for the propellant mass in study. The following table is generated based on available online sources that approximate almost identical ranges of Delta-V between various locations[44], [45]; however, it only presents the delta-Vs of location venues of interest to our study.

Table 2: Cis Lunar Delta-V Budget

Delta-V from / to (km/s)	Low Earth Orbit (LEO)	Low Lunar Orbit (LLO)	Lunar Surface (LS)
Earth Surface	9.5	-	-
Low Earth Orbit (LEO)	-	4	-
Low Lunar Orbit (LLO)	-	-	1.87

Now that all the inputs regarding our model are available, we can manipulate Tsiolkovsky's equation in sort to calculate the propellant mass. Hence another notion to add in this context is the propellant mass fraction (ζ), which is given by the ratio between the propellant mass (m_p) and the initial mass (m_0) of the vehicle.

$$\zeta = \frac{m_p}{m_0}$$

<u>Where:</u>

- ζ is the propellant mass fraction.
- $m_0 = m_f + m_p$ is the initial mass of the vehicle.
- m_p is the propellant mass.
- m_f is the final mass of the vehicle (also considered as dry mass).

The mass fraction is an important notion in the rocket equation which now can be modified to the following:

$$\Delta v = -I_{sp} \times g_0 \times \ln(\frac{m_f}{m_0})$$

$$\Delta v = -I_{sp} \times g_0 \times \ln(`1 - \frac{m_p}{m_0})$$

With inputs of:

- I_{sp} = 460 s
- g_0 = 9.80665 m/s^2
- m_0 = 1,300,000 kg
- ΔV (From Earth Surface to LEO) = 9500 m/s
- ΔV (From LEO to LLO) = 4000 m/s
- ΔV (LLO to Lunar Surface) = 1870 m/s

The propellant mass corresponding to each trajectory is calculated (considering that for each trajectory a new initial mass m_0 is obtained as propellants were burned):

- From Earth Surface to LEO: m_{p1} = 1,141,748 kg (with $m_{01} = 1{,}300{,}000\ kg$)

- From LEO to Low Lunar Orbit: m_{p2} = 93,051 kg (with $m_{01} = 158{,}252\ kg$)

- From Low Lunar Orbit to Lunar Surface: m_{p3} = 22,126 kg (with $m_{01} = 65{,}201\ kg$)

➔ $m_{p\ total}$ = 1,256,925 kg

Combining all the propellant mass obtained from the trajectories, it is found that 1,256,925 kg of propellant is going to be used/burned to transport the 26 mT payload to the surface of the Moon.

To evaluate the energy employed by burning these fuels, we need to consider the energy density equivalent to this propellant combination.

$$Energy\ consumed\ in\ this\ block = 19.4 \frac{MJ}{kg} \times 2{,}513{,}849\ kg = 24{,}384{,}345\ MJ$$

The calculated total propellant mass would require the energy equivalent of 24,384,345 MJ or 24,384 GJ. Accordingly, this energy would be considered as a fixed value for any amount of propellant to be produced at any other scale than the 1,640 mT desired. The reason behind this, is that it considers delivering all the necessary equipment (a payload of 26 mT) responsible for a functioning propellant production infrastructure to be employed, regardless the production outcome. The energy to transport 1kg of payload would be equal to 937.85 MJ/kg-payload. In terms of 1kg propellant produced and for a total yield of 1,640 Mt propellant, the energy needed in this phase compared to 1kg propellant produced would be of 14.85 MJ/kg-propellant.

6.2 Energy Analysis of Lunar Mining

Since the surface of the moon is within an extreme sub-zero temperature environment of the range of 25 °K and 220 °K at the poles, water ice present inside the regolith need to be warm enough to sublimate as volatile. The thermal mining extraction system is positioned in the ice-rich locations and adjusted as sort to enable heating from the constant sunlight rays when hitting the tents.

Ice is mostly found at temperature of 40 °K and is kept stable and undisturbed. It has been found that to have an adequate rate of vapor diffusing out of the porous surface through sublimation, temperatures need to be risen above 220 °K[46]. So, to sublimate the amount of water needed (2,450 mT) and assuming that the water ice is uniformly distributed within the lunar soil, the heating energy to warm the lunar soil should bring the temperatures from 40 °K to 220 °K. It is to be mentioned that after experimentations on sintered lunar soil samples, the specific heat capacity the lunar soil can be approximated to 1,843 J/kg.K[47].

As different water distributions are present on the surface of the moon, this study will assume the regions where 4 wt% of water will be subjected to heating.

The following calculation provides the heating energy (Q) needed that would result in heating the soil responsible for sublimating the 2.450 mT of water as present inside the soil pores:

$$Q = 2{,}450{,}000\ kg\ \times (220 - 40)\ K \times 1{,}483 \frac{J}{kg}.K = 654{,}003\ MJ$$

However, this energy takes into consideration only the amount of water and not the entire regions of soil being heat targeted, thus extrapolating based on the 4 wt% region distribution the heating energy needed for all the regions(multiple capture tents) responsible to sublimate the 2,450 mT of water instead:

$$Q_{regions} = \frac{654{,}003\ MJ}{0.04} = 16{,}350{,}075\ MJ$$

Another critical energy input needed in this block is for the transportation of tents from position to another. This would include the energy requirements for transporting the capture tent, ice haulers, and cold traps accounting for around 3000 kg. Based on average available technologies, a 3000 kg scale Space Exploration Vehicles (SEV) have electrical power ranges between 50 kW and 200 kW that can operate under solar energy recharging around the crater rims where sun hits(recharge energy considerations are not in the scope of this study)[48].

Since on average a lander using solar arrays to power up could receive close to permanent light 80% of the time operating yearly, the operating time of an assumed 150 kW rover will be 7008h per year.

The power annually required for maintaining and transporting the infrastructure (calculation below) would be equal to 1,051,200 kWh with an energy equivalent of 3,784,320MJ.

$$Energy\ consumed\ by\ the\ SEV = 150\ kW\ \times 7{,}008\ h = 1{,}051{,}200\ kWh = 3{,}784{,}320 MJ$$

Summing up the main input of energies consumed to achieve the extraction of water from the lunar soil by thermal mining would leave us with a total needed energy of 20,134,395 MJ. In terms of basing the unit of propellant produced at the end of the year, the energy would be of 12.28 MJ/kg-propellant.

6.3 Energy Analysis of Lunar Propellant Production

As described in section 5.3.3, the process of water into propellant products of liquid oxygen and liquid hydrogen consists of several subsystem inside the production facility. To perform an energy analysis for the entire facility, the power required of each subsystem component is approximated based on available scientifically feasible engineering solutions or calculated below.

It is to be mentioned that due to lack of sunlight inside the craters during the year, the power system from which the facility is being supported is either a wired power transmission system or a power beaming system both to be located around the crater rims where enough sunlight (7,008h/year) is converted through photovoltaics into electricity. Thus, we can evaluate the power and energy consumed from each subsystem component depending on its power description.

Table 3: Energy Needed by the Propellant Production Facility per Subsystem Component

Subsystem	Description	Power	Energy
Compressor	See calculation below	38 kW	266,304 kWh = 958,694 MJ
IWP[49]	Heater power: 458W Blower power: 416W	874 W	6,124 kWh = 22,049 MJ
Condenser	See calculation below	1,698,564 kWh or 242.375 kW	6,114,830 MJ
Transfer pump	See calculation below	0.00191 kW	48,122 kJ
Electrolyser[50]	237 kJ/mol water or 13.17 kJ/g or 13,166 kJ/kg	-	32,256,700 MJ
Separators/Dryers[51]	2 kW	14,016 kWh	50,457 MJ
Oxygen Liquefiers[52]	0.9 kWh/kg	1,260,000 kWh	4,536,000 MJ

Hydrogen Liquefiers[52]	16.4 kWh/kg	3,936,000 kWh	14,169,600 MJ
TOTAL			**58,156,452 MJ** = 16,154,570 kWh or **35.46 MJ/kg-propellant**

The previous table explicitly labels and indicates for each subsystem its energy required that combined with the other subsystems, will eventually support the lunar propellant production of 1,640 mT as mixture of LO_2 and LH_2.

Calculations evaluate the power consumption of some of the subsystem components the facility use during water processing.

Depending on the technology to be used, some inputs assumptions were chosen carefully to be adequate with available engineering hardware, the lunar environment, and the required function.

The power consumption of the compressor is assessed with this equation:

$$P_1 = 2.31 \frac{k}{k-1} \frac{T_{disch} - T_{suct}}{M} Q_m$$

Where:

- P_1 = Power (kW)
- T_{suct} = Inlet temperature of the compressor (K) = 40 K
- T_{disch} = Outlet temperature of the compressor (K) = 250 K
- M = Molar weight of gas (g/mol) = 18 g/mol
- Q_m = Compressor throughput (t/h) = 0.35 t/h
- K = Gas isentropic coefficient = 1.31

$$P_1 = 2.31 \frac{1.31}{1.31-1} \frac{250 - 40}{18} 0.35 = 38\, kW$$

The power consumption or heat released when condensing the gases is assessed with this equation[53]:

$$Q_{ht} = h_e \times M_s$$

Where:

- Q_{ht} = Heat transfer (kW)
- h_e = Specific evaporation enthalpy of steam = 2,493 kJ/kg[54]
- M_s = Steam flow rate = 350 kg/h = 0.09722 kg/s

$$Q_{ht} = 2{,}493 \times 0.09722 = 242.365 \frac{kJ}{s} \ (kW)$$

The power consumption for pumping water into the electrolyzer is assessed with this equation[55]:

$$P_2 = \frac{q \times h \times \rho}{6{,}116 \times 10^3 \ \mu}$$

Where:

- q = Flowrate (L/min) = 5.833 L/min
- h = Head (m) = 2m
- ρ = Density of water (kg/m^3) = 1000 kg/m^3
- μ = Pump efficiency = 1

$$P_2 = \frac{5.833 \times 2 \times 1000}{6{,}116 \times 10^3 \times 1} = 1.91 \times 10^{-3} \ kW$$

After combining all the consumed power within the subsystem components of this phase, it was evaluated that the total energy required to produce the lunar propellant would be equal to 58,156,452 MJ which in terms of propellant mass is 35.46 MJ/kg-propellant.

6.4 Energy Analysis of Transportation and Storage

Similar to section 6.1, the energy evaluation for this block accounts for the propellant burned when delivering the produced propellants from lunar surface to a lunar orbit space station venue. Due to unavailable adequate information regarding orbital propellant depots, the analysis will only consider the delivery process by focusing on the amount of energy expected.

Tankers with a design infrastructure supporting the delivery payloads of 150 mT would need to perform multiple roundtrip deliveries to assure the complete transport of 1,640 mT propellants annually. To achieve this, 11 roundtrips are required and will be energetically assessed.

It is reasonably assumed that spacecraft launchers whose function solely consist of transporting the propellant to orbit have a payload ratio of 49%. This fraction also corresponds to lunar ascent and descent modules that are launched and landed with a low gravity environment.

Therefore, the initial lift off mass for each propellant delivery of 150 mT to a Low Lunar Orbit level, would be equal to 306,122 kg or 306.122 mT (see calculation below).

$$Initial\ Lift\ Off\ Mass = \frac{Paylaod\ Mass}{Payload\ Fraction} = \frac{150{,}000\ kg}{0.49} = 306{,}122\ kg$$

Using the rocket equation, we can determine the amount of propellants needed to complete a trip of 150 mT batch delivery and return to the lunar surface, ready for another delivery.

<u>With inputs of:</u>

- I_{sp} = 460 s
- g_0 = 9.80665 m/s^2
- m_0 = 306,122 kg
- ΔV (From Lunar Surface to LLO) = 1,870 m/s

- ΔV (LLO to Lunar Surface) = 1,870 m/s

The propellant mass corresponding to each trajectory is calculated (considering that for each trajectory a new initial mass m_0 is obtained as propellants were burned and the cargo delivered):

- <u>From Lunar Surface to Low Lunar Orbit:</u> m_{p1} = 103,883 kg (with $m_{01} = 306{,}122\ kg$)

- <u>From Low Lunar Orbit to Lunar Surface:</u> m_{p2} = 17,727 kg (with $m_{01} = 52{,}239\ kg$)

➔ $m_{p\ total}$ = 121,610 kg

To account for the all trips supplying annually the energy station with 1,640 mT of lunar-derived propellant, the total mass of propellant needed would be 1,337,710 kg. Converting the obtained amount into energy value, this block requires 25,951,234 MJ to achieve its function and accounts for 15.82 MJ/kg-propellant produced.

7. Sensitivity Analysis

The developed energy analysis above has focused on choosing a fixed set of what normally is varying. That includes all the inputs used to formulate and reach the calculation results for each functional block, respectively. For a greater focus on minimizing uncertainties and its propagation, the process followed in this section search for different relying or sensitive input parameters and simulate multiple models that are affected by the iteration of the based parameters.

The process of recalculating outcomes under alternative assumptions and/or calibrations seeks to identify relevancy of blocks in respect to the overall model. It also seeks to examines to which factors or parameters the energy sum required to allow an on orbit ISRU-derived propellant energy station is most sensitive.

7.1 Equipment Transportation

The calculation for the energy required in this block is based on the same one used in the energy analysis chapter relative to this phase. However, the sensitive parameters in this block would be related to the payload fraction earlier explained and we would thus see how its possible variation affects the outcome.

Looking at the rocket equation with its fixed inputs for specific impulse(460 m/s), gravity and known delta-V budget we can revaluate the energy needed to transport the 26 mT payload of equipment considering the change in payload fraction for its lowest value of 1% and its highest of 7%.

Assuming the configuration of a different spacecraft and accounting to a possible payload fraction of 1%, the initial mass of a spacecraft launcher vehicle consisting of the 26 mT payload would be equal to 2,600,000 kg (see calculation below).

$$Initial\ Lift\ Off\ Mass = \frac{Paylaod\ Mass}{Payload\ Fraction} = \frac{26{,}000\ kg}{0.01} = 2{,}600{,}000\ kg$$

Using the rocket equation based on the new parameters would result in:

$$\Delta v = -I_{sp} \times g_0 \times \ln(`1 - \frac{m_p}{m_0})$$

<u>With inputs of:</u>

- I_{sp} = 460 s
- g_0 = 9.80665 m/s^2
- m_0 = 2,600,000 kg
- ΔV (From Earth Surface to LEO) = 9500 m/s
- ΔV (From LEO to LLO) = 4000 m/s
- ΔV (LLO to Lunar Surface) = 1870 m/s

The propellant mass corresponding to each trajectory is calculated (considering that for each trajectory a new initial mass m_0 is obtained as propellants were burned):

- <u>From Earth Surface to LEO:</u> m_{p1} = 2,283,497 kg (with $m_{01} = 2{,}600{,}000\ kg$)

- <u>From LEO to Low Lunar Orbit:</u> m_{p2} = 186,100 kg (with $m_{01} = 316{,}503\ kg$)

- <u>From Low Lunar Orbit to Lunar Surface:</u> m_{p3} = 44,252 kg (with $m_{01} = 65{,}201\ kg$)

➔ $m_{p\ total}$ = 2,513,849 kg

Combining all the propellant mass obtained from the trajectories, it is found that 2,513,849 kg of propellant is going to be used/burned to transport the 26 mT payload to the surface of the Moon.

To evaluate the energy employed by burning these fuels, we need to consider the energy density equivalent to this propellant combination.

$$Energy\ consumed\ in\ this\ block = 19.4 \frac{MJ}{kg} \times 2{,}513{,}849\ kg = 48{,}768{,}670\ MJ$$

The calculated total propellant mass would require the energy equivalent of 48,768,670 MJ or 48,768 GJ. Hence, in terms of basis units the energy to transport 1kg of payload would be equal to 1.875 GJ/kg-payload. In terms of 1kg propellant produced as the final yield of our system, the energy needed would be of 29.73 MJ/kg-propellant.

To understand the energy flexibility of this block we shall calculate the energy required for the other upper limit of payload possibly used by a different engineering configuration for transporting the 26 mT payload of equipment to the Moon.

For the upper limit, a 7% payload fraction will be evaluated leading to the calculation of energy needed in this block.

The initial mass of a spacecraft launcher vehicle corresponding to a 7% payload fraction and consisting of the 26 mT payload, would be equal to 371,428 kg (see calculation below).

$$Initial\ Lift\ Off\ Mass = \frac{Paylaod\ Mass}{Payload\ Fraction} = \frac{26{,}000\ kg}{0.07} = 371{,}428\ kg$$

Using the rocket equation based on the new parameters would result in:

$$\Delta v = -I_{sp} \times g_0 \times \ln(`1 - \frac{m_p}{m_0})$$

<u>With inputs of:</u>

- I_{sp} = 460 s
- g_0 = 9.80665 m/s^2
- m_0 = 371,428 kg
- ΔV (From Earth Surface to LEO) = 9500 m/s
- ΔV (From LEO to LLO) = 4000 m/s
- ΔV (LLO to Lunar Surface) = 1870 m/s

The propellant mass corresponding to each trajectory is calculated:

- From Earth Surface to LEO: m_{p1} = 326,213 kg (with $m_{01} = 371{,}428\ kg$)

- From LEO to Low Lunar Orbit: m_{p2} = 26,586 kg (with $m_{01} = 316{,}503\ kg$)

- From Low Lunar Orbit to Lunar Surface: m_{p3} = 6,321 kg (with $m_{01} = 65{,}201\ kg$)

  ➔ $m_{p\ total}$ = 359,120 kg

Combining all the propellant mass obtained from the trajectories, it is found that 2,513,849 kg of propellant is going to be used/burned to transport the 26 mT payload to the surface of the Moon.

To evaluate the energy employed by burning these fuels, we need to consider the energy density equivalent to this propellant combination.

$$Energy\ consumed\ in\ this\ block = 19.4\frac{MJ}{kg} \times 359{,}120\ kg = 6{,}966{,}928\ MJ$$

The calculated total propellant mass would require the energy equivalent of 6,966,928 MJ or 6.96 GJ. Hence, in terms of basis units the energy to transport 1kg of payload would be equal to 267.9 MJ/kg-payload. In terms of 1kg propellant produced as the final yield of our system, the energy needed would be of 4.248 MJ/kg-propellant.

The following table shows the result of changing the sensitive parameters (payload fraction) on the propellant mass needed as well as the propellant mass and energy needed to transport 1kg payload to the Moon.

Table 4: Result Outcomes of Possible Payload Fractions

	Payload Fraction		
	1%	**2%**	**7%**
Total Propellant Mass	2,513,849 kg	1,256,925 kg	359,120 kg
Total Energy of Propellant	48,768 GJ	24,384 GJ	6,966 GJ
Propellant Mass per 1kg payload	96.7 kg	48.44 kg	13.8 kg
Energy per 1kg payload (total of 26 mT)	1.875 GJ/kg-payload	937 MJ/kg-payload	268 MJ/kg-payload
Energy per 1kg propellant produced (with a demand of 1,640 mT)	29.73 MJ/kg-propellant	14.86 MJ/kg-propellant	4.247 MJ/kg-propellant

7.2 Lunar Mining

The lunar mining operation on the moon is still under development and still awaits research to identify requirements and correct course of conduct to achieve water ice extraction in its best manner possible. As we have unavailable data for this conceptualized extraction method, some sensitive parameters were not able to be included. However, some parameters were to be mentioned that could influence the overall energy outcome of this block and eventually affect the overall system energy.

The sensitive parameters evaluated in this section are the water ice distribution (in percentage by weight) and the different power configuration of the space exploration vehicle.

The first one varies among regions found on the moon which were identified by lunar orbital sensing and that fluctuates between regions having a 4wt% ice distribution and others up to 30wt%. Each region would thus result in different ice yield and consequently on the energy needed to heat/warm the regolith for water extraction. In short, regions with higher ice distribution gives off more ice decreasing regions to be mined and eventually requiring less energy in contrast to lower ice distribution regions to extract the 2,450 mT of water.

Another sensitive parameter considered in this section analysis is the possible available variation in space exploration vehicle power. Since it is not yet sure what best configuration (able to transport and handle 2000-4000kg mass of various use equipment) would be present by the time space mining is available, the analysis evaluates a range of power requirement based on present configurations of 50-200 kWh.

After assigning the most relevant parameters of this functional phase, we can start revaluating the energy outcomes they correspond to.

For lunar regions of 4wt% ice (minimal distribution needed for extraction and what was considered in the system design), the required energy to extract 2,450 mT is calculated in section 6.1 and is 16,350,075 MJ or 9.97 MJ/kg-propellant.

For lunar regions of 30 wt% ice, the energy required to heat and eventually extract the mentioned amount of water is:

$$Q = 2{,}450{,}000\ kg\ \times (220 - 40)\ K \times 1{,}483 \frac{J}{kg}.K = 654{,}003\ MJ$$

However, this energy takes into consideration only the amount of water and not the entire regions of soil being heat targeted, thus extrapolating based on the 30 wt% region distribution:

$$Q_{regions} = \frac{654{,}003\ MJ}{0.3} = 2{,}180{,}010\ MJ$$

The heating energy needed for all the regions (multiple capture tents) responsible to sublimate the 2,450 mT of water is 2,180,010 MJ or 1.33 MJ/kg-propellant.

Next is the evaluation of different power configurations accounting to different outcome.

The lowest acceptable power to sufficiently function is of a 50 kWh rover vehicle. The latter would require an annual power for maintaining and transporting the infrastructure (calculation below) of 350,400 kWh, corresponding to 1,261,440 MJ.

$$Energy\ consumed\ by\ the\ SEV = 50\ kW\ \times 7{,}008\ h = 350{,}400\ kWh = 1{,}261{,}440\ MJ$$

A limit for the highest limit of power configuration a vehicle can also possibly have is of 200 kWh. This corresponds to an annual power of (see calculation below) 1,401,600 kWh and corresponding to 5,045,760 MJ.

$$Energy\ consumed\ by\ the\ SEV = 200\ kW\ \times 7{,}008\ h = 1{,}401{,}600\ kWh = 5{,}045{,}760\ MJ$$

Table 4 displays the analysis results of various possible scenarios, considering the geological aspect of regions to be mined and the engineering configurations of different rovers used.

Table 5: Energy Results for Different Mining Scenarios Based on Sensitive Parameters

	4 wt% region	**30 wt% region**
50 kWh vehicle	17,611,515 MJ or 10.74 MJ/kg	1,261,440 MJ or 2.1 MJ/kg
150 kWh vehicle	20,134,395 MJ or 12.28 MJ/kg	5,964,330 MJ or 3.64 MJ/kg
200 kWh vehicle	21,395,835 MJ or 13.04 MJ/kg	7,225,770 MJ or 4.4 MJ/kg

7.3 Lunar Propellant Production

The energy sensitive parameters in this functional block are ultimately within each subsystem used along the propellant production process. Due to inaccurate or unavailable data on proposed values of the parameters, we shall force in this section's sensitivity analysis a ±10% level of energy variability to each subsystem, respectively calculating their corresponding change in the output. The results will thus present an energy fluctuation between a lower and higher limit corresponding to the overall energy required for the production facility.

The following table accounts for both limits and show the outcome of all the sensitive parameters considered.

Table 6: Sensitivity Analysis Result of the Propellant Production Facility

Subsystem	Energy (-10%)	Energy	Energy (+10%)
Compressor	862,824 MJ	958,694 MJ	1,054,563 MJ
IWP	19,844 MJ	22,049 MJ	24,254 MJ
Condenser	5,503,347 MJ	6,114,830 MJ	6,726,313 MJ
Transfer pump	43.309 MJ	48.122 MJ	52.934 MJ
Electrolyser	29,031,030 MJ	32,256,700 MJ	35,482,370 MJ
Separators/Dryers	45,411 MJ	50,457 MJ	55,502 MJ
Oxygen Liquefiers	4,082,400 MJ	4,536,000 MJ	4,989,600 MJ
Hydrogen Liquefiers	12,752,640 MJ	14,169,600 MJ	15,586,560 MJ
TOTAL	**52,340,806 MJ or 31.91 MJ/kg-propellant**	**58,156,452 MJ or 35.46 MJ/kg-propellant**	**63,972,096 MJ or 39.02 MJ/kg-propellant**

As shown in table 6, the total energy required in this block accounting for a variation of +10% of the normal case scenario would be equal to 63,972,096 MJ. Dividing that number by the 1,640 mT propellants produced yearly, the energy required to produce 1 kg of propellant is equal to 39.02 MJ. In contrast, a -10% sensitivity margin would necessitate that the production facility requires 52,340,806 MJ and 31.91 MJ/kg-propellant, hence a total possible energy sensitivity of 7.11 MJ/kg-propellant.

7.4 Transportation and Storage

Similarly, calculating this section's required energy consist of figuring out the amount of propellant needed to deliver all the 150 mT loads of propellants to the Low Lunar Orbit with multiple roundtrips.

The sensitive parameter of interest in this functional block is again the payload fraction, whose small variability proves significant effect on outcomes. Payload fraction's is a parameter related to the configuration of spacecrafts to be used and in the case of cis-lunar propellant transportation exclusively, the range of payload fractions is found to be between 45% and 50%. As seen in section 6.4, a 49% payload fraction was used to conduct the calculations. However; to prove its influence over the entire block, we will try to evaluate what the 45% and 50% limits results on the energy outcome.

Assuming a 45% payload fraction, we can determine the amount of propellants needed to complete a trip of 150 mT batch delivery and return to the lunar surface, ready for another delivery. The Initial mass needed in this chosen configuration is 333,333 kg.

$$Initial\ Lift\ Off\ Mass = \frac{Paylaod\ Mass}{Payload\ Fraction} = \frac{150{,}000\ kg}{0.45} = 333{,}333\ kg$$

<u>With inputs of:</u>

- I_{sp} = 460 s
- g_0 = 9.80665 m/s^2
- m_0 = 333,333 kg
- ΔV (From Lunar Surface to LLO) = 1,870 m/s
- ΔV (LLO to Lunar Surface) = 1,870 m/s

The propellant mass corresponding to each trajectory is calculated (considering that for each trajectory a new initial mass m_0 is obtained as propellants were burned and the cargo delivered):

- <u>From Lunar Surface to Low Lunar Orbit:</u> m_{p1} = 113,117 kg (with $m_{01} = 333{,}333\ kg$)

- <u>From Low Lunar Orbit to Lunar Surface:</u> m_{p2} = 23,828 kg (with $m_{01} = 70{,}216\ kg$)

➔ $m_{p\ total}$ = 136,945 kg

To account for the all trips supplying annually the energy station with 1,640 mT of lunar-derived propellant, the total mass of propellant needed would be 1,506,395 kg. Converting the obtained amount into energy value, this block requires 29,224,063 MJ to achieve its function and accounts for 17.82 MJ/kg-propellant produced.

Now for a 50% payload fraction, we can determine the amount of propellants needed to complete a trip of 150 mT batch delivery and return to the lunar surface, ready for another delivery. The Initial mass needed in this chosen configuration is 333,333 kg.

$$Initial\ Lift\ Off\ Mass = \frac{Paylaod\ Mass}{Payload\ Fraction} = \frac{150{,}000\ kg}{0.5} = 300{,}000\ kg$$

<u>With inputs of:</u>

- I_{sp} = 460 s
- g_0 = 9.80665 m/s^2
- m_0 = 300,000 kg
- ΔV (From Lunar Surface to LLO) = 1,870 m/s
- ΔV (LLO to Lunar Surface) = 1,870 m/s

The propellant mass corresponding to each trajectory is calculated (considering that for each trajectory a new initial mass m_0 is obtained as propellants were burned and the cargo delivered):

- <u>From Lunar Surface to Low Lunar Orbit:</u> m_{p1} = 101,806 kg (with $m_{01} = 300{,}000\ kg$)

- <u>From Low Lunar Orbit to Lunar Surface:</u> m_{p2} = 16,354kg (with $m_{01} = 48{,}194\ kg$)

➔ $m_{p\ total}$ = 118,150 kg

To account for the all trips supplying annually the energy station with 1,640 mT of lunar-derived propellant, the total mass of propellant needed would be 1,299,650 kg. Converting the obtained amount into energy value, this block requires 25,213,210 MJ to achieve its function and accounts for 15.37 MJ/kg-propellant produced.

The outcome resulted from the variation of the payload fraction is represented in the table below.

Table 7: Payload Fraction Effect on Propellant Mass and Required Energy

	Payload Fraction		
	45%	**49%**	**50%**
Propellant Mass to transport 1,640,000 kg (round trips included)	1,506,395 kg	1,337,710 kg	1,299,650 kg
Energy needed to transport 1,640,000 kg	29,224,063 MJ	25,951,574 MJ	25,213,210 MJ
Energy needed per 1kg propellant transported	17.82 MJ/kg-p	15.82 MJ/kg-p	15.37 MJ/kg-p

This block thus is evaluated to have a maximum energy difference of 2.45 MJ/kg-propellant when considering the lowest and highest values of energy needed per 1kg propellant produced, transported, and stored.

8. Results and Discussions

This chapter summarises the most important findings from the conducted energy analysis the study provides when employing and operating all operations for a lunar propellant production system. It also shows the observations and conclusions that can be drawn from it. The system results are visualised in subsequent figures and are discussed below.

It is now clear how an energy space station is key to developing capabilities to live and work in space. The production and storage of lunar resources if properly incorporated into mission plans, will provide a transition from reliance on Earth-supplied fuel to self-sufficiency of propellant from and on the moon. ISRU-derived propellant, basically from the abundant water resource present as ice on the surface of the moon and within its regolith, is now demonstrated to be of interest for all agencies investing into deeper space missions and possible alternative life in space. It is only questions of feasibility and technical viability that are slowing down the incorporation process of scaled up plants and facilities to get constructed and fully operative on the Moon. However, as the benefits of having a cis-lunar energy station are well acknowledged and perceived, research is key to developing the best design to base and service the infrastructure and logistics of a lunar outpost.

In this study, this entire infrastructure design allowing an operable infrastructure to deliver and store annually 1,640 mT propellants at a lunar orbit level was looked upon based on an energy evaluation approach. The latter eventually examined and dissected each functional block contributing to the entire system and allowed the recognition of the most influencing phases and/or parameters. Thus, shedding light on further needed research to discover best solutions.

As per the focus of assessing the energy involved to make this outpost available, identifying the methods used in equipment/cargo transportation, thermal mining, water processing and the final product needed to be obtained were key to performing this energy analysis.

After assessing and evaluating each block's energy requirement, the study was able to identify the most influential phase on the overall energy consumption that can be tracked while respecting the established system boundaries and made assumptions.

The following table summarizes all the numerical results that were obtained after thorough calculations on the following blocks with the order mentioned: Equipment Transportation – Lunar Mining – Lunar Propellant Production – Transportation and Storage.

Table 8: Summary of Energy Analysis Results Per Block

	Block 1	Block 2	Block 3	Block 4	Total
Energy Required per kg Propellant Produced	14.85 MJ/kg-p	12.28 MJ/kg-p	35.46 MJ/kg-p	15.82 MJ/kg-p	78.41 MJ/kg-p
Total Energy Required	24,384 GJ	20,139 GJ	58,154 GJ	25,952 GJ	128,629 GJ
Energy Contribution	18.93%	15.66%	45.22%	20.17%	100%
Contribution (Lowest Energy Conditions)	7.92%	3.92%	59.5%	28.66%	100% (53.627 MJ/kg-p)
Contribution (Highest Energy Conditions)	29.84%	13.1%	39.17%	17.88%	100% (99.61 MJ/kg-p)
Possible Energy Range	[4.247-29.73] MJ/kg-propellant	[2.1-13.04] MJ/kg-propellant	[31.91-39.02] MJ/kg-propellant	[15.37-17.82] MJ/kg-propellant	N/A
Energy Variation Range	25.48 MJ/kg-p	11 MJ/kg-p	7.11 MJ/kg-p	2.45 MJ/kg-p	N/A
Key Sensitive Parameter	Payload fraction	Ice distribution - Rover Power	Technical efficiency uncertainty	Payload fraction	N/A

8.1 Block 1 Equipment Transportation

The same analytical reading of results done for block 1 can be followed to understand the numbers illustrated in table 8 above, which summarizes the values per block for the energy needed per kg propellant produced, the block-total energy required, and the possible energy range considering each block's key sensitive parameters.

Results obtained from block 1 show a total energy requirement of 24,384 GJ for a chosen payload fraction of 2%. As for a 1,640 mT desired propellant produced, block 1 has a rate of 14.85 MJ for each kg LO_2/LH_2 propellant eventually produced and in contrast to the total energy of this block, this rate is directly influenced by the final product amount. A higher amount produced would require an energy rate lower than 14.85 MJ.

After performing a sensitivity analysis over what could be the most sensitive parameter affecting the energy outcomes of this block, it was found that the payload fraction (dependant on the engineering configuration of spacecrafts) fluctuates between 1% and 7%. A higher payload fraction is obviously favoured as it results in less propellants used to transport the equipment; however, this parameter solely depends on the efficiency of a particular spacecraft design. Its effect over the block's performance results in a possible outcome range of [4.247-29.73] MJ/kg-propellant, hence a variation of 25.48 MJ/kg due to its key sensitive parameter, the payload fraction.

The share of contribution this block has on the total energy requirement of the system is found to be of 18.93% within the system boundaries chosen. Depending on the spacecraft engineering configuration to be used, its share could alter between a low 7.92% portion and a relatively high 29.84% portion of the total energy exerted.

8.2 Block 2 Lunar Mining

Regarding the analysis of the lunar mining block, the total energy obtained was 20,139 GJ which were dissipated from the technologies and infrastructure design analysed, that is the energy to power rovers and heat the surface for water extraction.

In order to eventually produce 1,640 mT propellant from the extracted 2,450 mT water, the subsystem utilises 12.28 MJ for every 1kg liquid oxygen/liquid hydrogen mixture produced.

The results of this analyses exist only for the heat mining solution, assuming that is the method to be employed on the moon with highest efficiency and lowest complications. However, due to lack in accurate data over lunar resource explorations it is required to develop evidence confirming the distribution of ice in both qualitative and quantitative aspects. The distribution of water on the Moon is still unknown and can affect the conduct of mining the ice. Additionally, it is unclear how deep the ice goes, at what temperature below the surface it is preserved, and what exact thermal conductivities the regolith might have which could affect the overall heating or energy used.

The same remark applies to the efficiencies of the rovers operating alongside the mining operation taking care of transportations and logistical applications. The study assessed an assumed rover design that can possibly operate with a power range of [50 kWh – 200 kWh] while getting the required deliverability in return. However, a focal investigation should be run on the surface environment to assess complications of transporting equipment around as well as transporting the ice to design and develop an efficient mining system.

Both ice distribution content as well as the rover's specifications were key parameters in the sensitivity analysis conducted and created different design combinations (see table 5), resulting in an energy range to produce one 1kg propellant of [2.1 MJ/kg – 13.04 MJ/kg].

After using different assumption scenario combinations to analyse energy requirement in the lunar mining block, it was found that its contribution to the total energy was the lowest compared to the other blocks of our system for around 15.66% which means that it is the least energy consuming. When different scenarios apply the energy range fluctuates between 3.92% and 13.1% maintaining its position as the lowest contributing block.

8.3 Block 3 Lunar Propellant Production

After thoroughly analysing each subsystem within the lunar propellant production facility, the study found that this block exerted an energy of 58,154 GJ which constitutes the most compared to all other blocks. Its share comes at a 45.22% portion of the total energy requirement and thus consumes the most.

This energy comes from all different technologies employed to transform the water ice brought to the facility into liquified oxygen and liquid hydrogen. It is important to point out that the electrolyser component accounted for the highest consumption within the production facility for around 32,256,700 MJ or 35.46 MJ to produce 1kg propellant. The remainder subsystem components like compressors, condensers, dryers, and transfer pumps were evaluated to have relatively lower energy consumption. More problematic than oxygen, hydrogen requires additional engineering controls to ensure its safe handling as well as complex storage technologies, thus requiring its liquefiers to consume more energy than the oxygen liquefiers as proved in the analysis.

Due to the lack of available data regarding technologies and engineering hardware solutions, no definite sensitive parameters were to be set. Instead, the conducted sensitivity analysis considered a threshold of ±10% on all subsystem components as technical efficiency uncertainties which potentially describes the possible change in performance and energy consumption. A possible variation of energy rate was found to be of [31.91 MJ/kg – 39.02 MJ/kg] giving a margin of 7.11 MJ/kg-propellant.

This block is responsible of producing annually 1,640 mT as proposed at the start in the demands section. In terms of energy potentially obtained from the propellants produced from the suggested system design, this mass corresponds to an energy (Energy OUT) of 31,816 GJ (see calculation).

$$Energy\ OUT = 19.4 \frac{MJ}{kg} \times 1{,}640{,}000\ kg = 31{,}816\ GJ$$

8.4 Block 4 Transportation and Storage

Lastly, block 4 was evaluated to consume a portion of 20.17% equating to 25,952 MJ (or 15.82 MJ/kg-propellant) following normal system boundary conditions. Similarly, to block 1, the energy was consumed as a result of burning the propellant mass while delivering the 1,640 mT of produced propellants to be stored on lunar orbit level.

The payload fraction is again the sensitive parameter considered to be most influential over the block's energy consumption. Due to different available spacecraft designs, exclusively used to transport and store the propellants, it was found that the payload fraction could slightly affect the energy rate of production from a lower limit of 15.37 MJ/kg-propellant to 17.82 MJ/kg-propellant.

8.5 Overall Results

Furthermore, we were able to show the energy contribution of each block after calculating all energies required within the chosen system boundaries for the scope of the study.

This is clearly illustrated in figure 21 where it depicts the biggest share of energy of 45.22% allocated to the block responsible for the propellant production operations and the lowest of 15.66% to the lunar mining block.

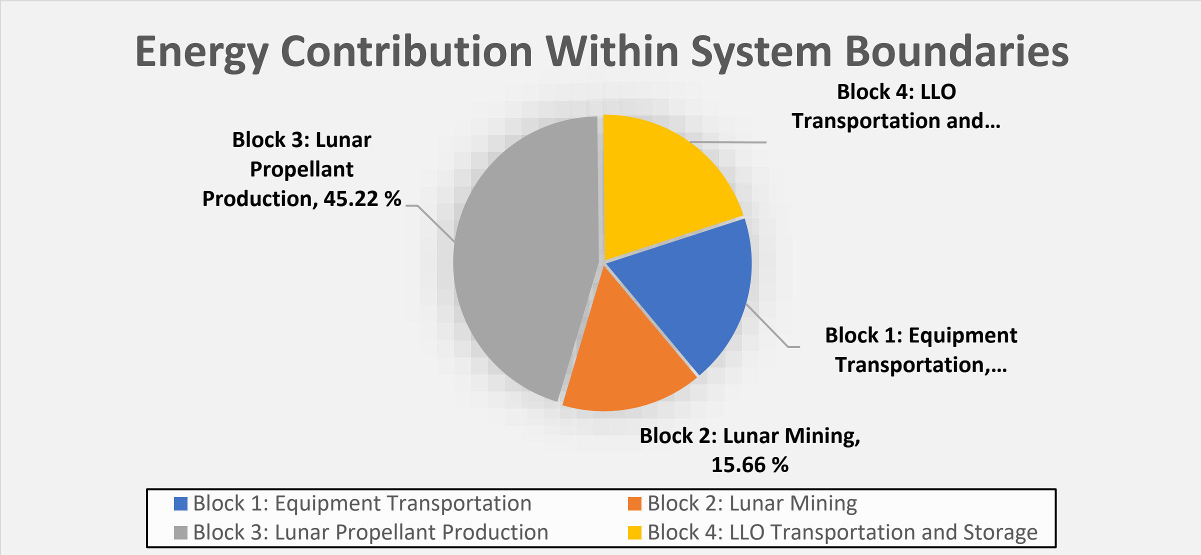

Figure 21: Energy Contribution Within System Boundaries

This diagram shows the different blocks energy repartition allowing us to identify the influence of each block over the total energy outcome of the design. Seen in grey colour, the production phase constitutes the biggest part due to its complex design that involves high energy dependent subsystems allowing the production of the desired 1,640 mT propellants.

Another interesting aspect to consider, is the energy needed per block responsible of producing 1 kg of propellant. Figure 22 presents the energy requirement for each functional block over a set of assumptions considered as normal system boundaries conditions.

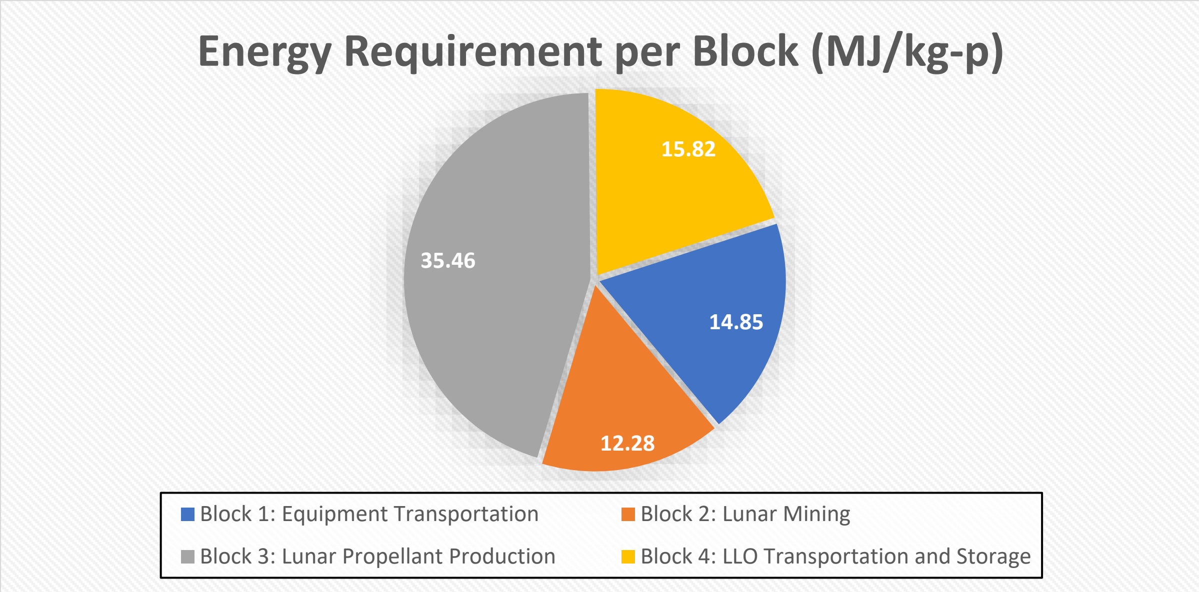

Figure 22: Energy Requirement Rate per Block

After conducting the sensitive analysis that took into consideration all relevant key parameters affecting the outcome per block and eventually determining new portion allocations of energy each block has. Figure 23 shows a detailed view of each bock's contribution in regard to the condition the study was evaluating: normal system boundary conditions – lowest energy condition – highest energy contribution. Noting that the lowest energy condition considers all possible applications of key parameters at their lowest needed energy performance and the highest energy condition the opposite.

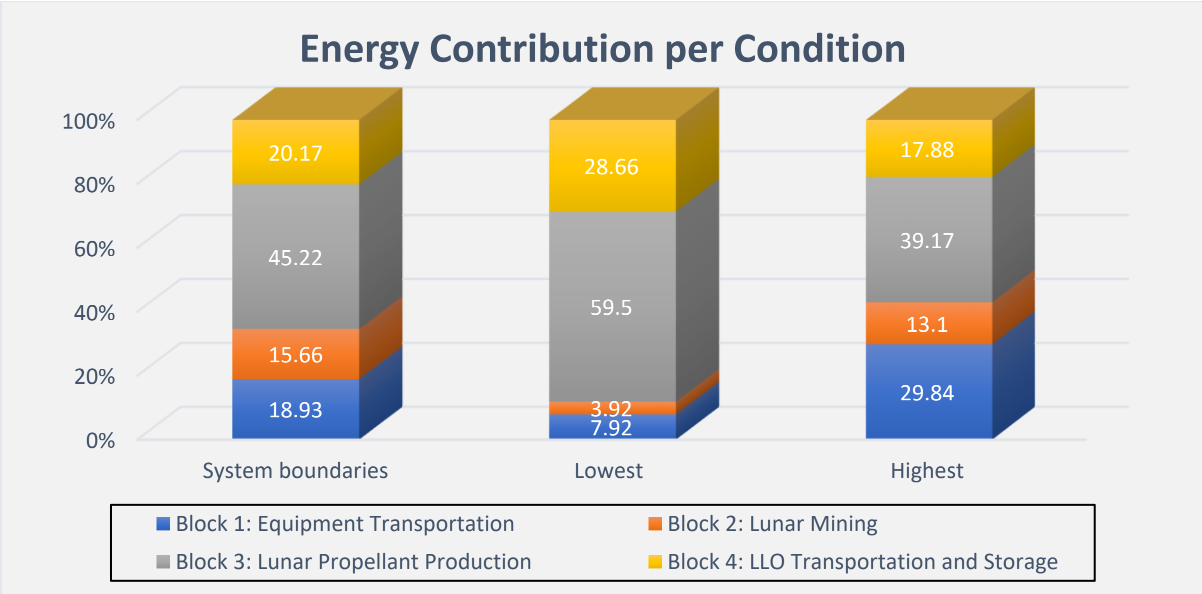

Figure 23: Energy Contribution per Energy Condition

After considering different energy conditions, it is remarkable to note that although the propellant production phase remained the most energy consuming block, the other blocks showed different allocated contributions. For example, as illustrated in figure 23 the energy contribution of the block 4 in the lowest energy condition is 28.66% coming second highest compared to third highest after block 3 and block 1 in the highest energy condition.

Another focal comment to add is on the possibility of attaining very low energy output rate for each of the blocks 1 and 2. As depicted in the illustration, a 3.92 % and 7.92% represent an energy rate of 2.1 MJ/kg-propellant and 4.247 MJ/kg-propellant respectively. It would be of great importance since these two blocks energy can be scaled down eventually cutting cost and energy.

Comparing the relative importance of key variables presented in the sensitivity analysis, figure 24 provides a graphical representation through a tornado diagram showing the degree to which the overall system is sensitive to what block the most.

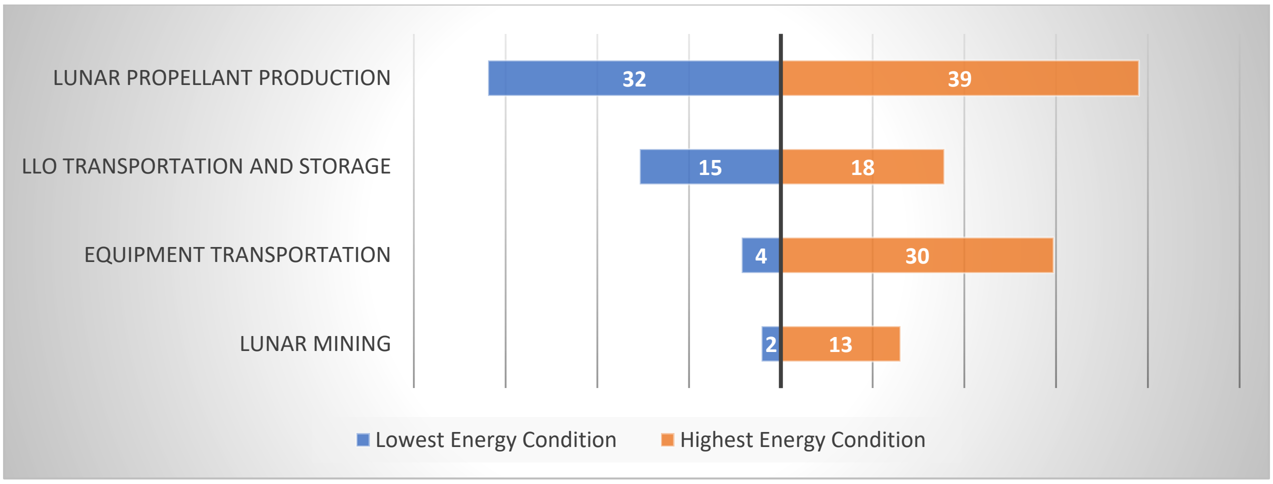

Figure 24: Sensitivity Tornado Plot for Overall System Energy (units being MJ/kg-propellant)

The underlying tornado diagram visually explains and identifies the blocks one should focus on by order where the top bar represents the block that contributes the most to the variability of energy outcome. It is therefore clear that the functional block responsible for all the lunar propellant production operations is identified as most energy consuming and thus a valuable target for energy reduction efforts.

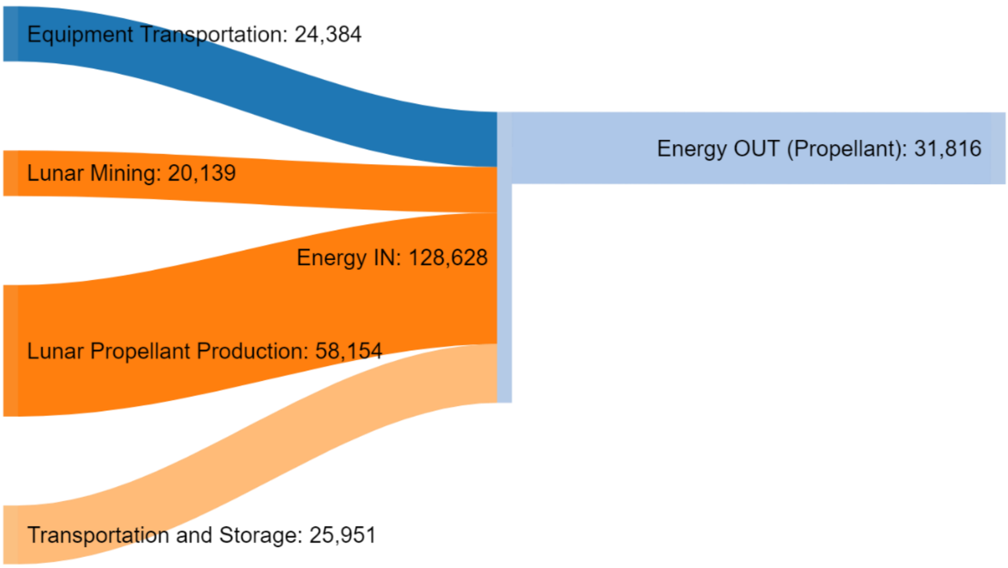

Figure 25: Illustration of The Energy Allocation Through the System

Although a quantitative comparison (see figure 25) between the total energy consumed by the system (128,622 GJ) and the potential energy provided from it corresponding to the 1,640 mT propellants (31,816 GJ) might look energetically unprofitable, the rational to value this outcome is critical. When tackling the energy flows, the valuation logic here is further enhanced by focusing upon the benefits from the useful energy obtained which is the actual available energy after final conversion for its respective use. In our case the 1,640 mT converses in a useful energy of 31,816 GJ, thermodynamically holding the ability to perform the valuable physical work of generating propulsion of space vehicles into deeper space. Hence one can say that it is worthy "wasting" energy through all the functions and operations to eventually create this valuable and useful energy.

9. Conclusions

This chapter presents the most valuable findings from the conducted study. A summary of the research outline and a quick report of the analysis results are briefed in section 9.1. Section 9.2 discusses important limitations to this study and presents suggestions for its improvements. Lastly, section 9.3 gives several recommendations for future work related to the goal targeted in this study and contribute to further space developments.

9.1 Findings

During the next decades, the international space community will be more and more prone to investing in developing and utilizing space resources as they are key to a sustainable future in space. In-Situ Resource Utilization (ISRU) of lunar resources will allow humans to plan with less cost and achieve scientific and deeper-space exploration missions not possible otherwise.

This study showed based on recent data from Clementine, Chandrayaan-1, LCROSS, and LRO, the discovery of abundant water ice quantities found in permanently shadowed regions within lunar polar craters. Being the closest and most accessible resource in space, lunar water not only has the economically viable use of giving oxygen for life support but also can provide via electrolysis liquid oxygen and liquid hydrogen, a very efficient rocket propellant.

The benefits of establishing a commercial lunar propellant supply station in orbit of the Moon was also demonstrated and the yearly projected estimations for demands were found to be 1,640 mT of lunar-derived propellants, corresponding to 2,450 mT of lunar water processed.

The study explained a possible overall functional design or structure targeting the production of lunar propellant from surface and near subsurface ice. The latter was found to be under a set of plausible assumptions about different aspects reliant enough to allow the extraction and processing of water, the production of propellants, and eventually the transportation and storage of the amount needed in orbit level. The system was comprehensively elaborated to define the details of each functional element. The functional flow developed was sequentially as follows, a function that considers the transportation of all equipment necessary to be deployed for logistical and operational applications throughout the entire system, a function responsible for the extraction of water ice through a thermal mining method, a function accounting for the lunar propellant production facility and operation, and a final function to deliver and store the produced propellants on a Low Lunar Orbit level.

Afterward, an energy analysis was conducted followed by a sensitivity analysis. The first one evaluated the energy consumed within each functional block achieving the desired propellant production. The outcome is best illustrated in figure 25 and shows the different allocated energies per block as well as the total energy consumed (Energy IN) by the system of 128,628 GJ and the energy potentially gained from the propellants of 31,816 GJ (Energy OUT). The latter is best thought of as the useful energy our propellant refuelling system provided, able to generate valuably the added propulsion of space vehicles into deeper space and feasibly to Mars.

Last in the study, a sensitivity analysis was performed to identify first the key parameters affecting each block and eventually the energy outcome and then, quantitively evaluated their influence on previous outcome over different energy condition scenarios. It was mentioned that the most influential block to the overall consumed energy was block 3, responsible for the lunar propellant production. The latter accounted for around 45% of the total energy used under the system boundary assigned conditions, remaining the highest contributor for all assessed conditions.

Considering the environmental impact before technological advancements, agencies have already been focusing on decreasing the impact made by monitoring and regulating their impact.

Launching space vehicles utilizing propulsion systems with liquid propellant engines that use LOX and LH2 would produce water vapor making it the cleanest burning fuel, not causing impacts on air quality by not having CO2 emissions[56]. Unfortunately, it is not anymore very sustainable when liquid hydrogen manufacturing on earth comes from fossil fuels via processes of steam reforming natural gas which takes energy usually from coal-fired plants. Evaluating the true impact of the liquid fuel requires its investigation within all phases of its entire life cycle (including ground-based segments), that are related to the following acquisition, manufacturing, distribution, and finally its use.

Based on data from a big producer of liquid hydrogen, Praxair uses 15 kWh of energy only to liquify the hydrogen[57]. The environmental impact assessment of liquifying amounts (113 tons) of liquid hydrogen consumed by an average shuttle results in 5.94 tons CO2 emitted per tons LH2. Since the latter emission only considered the liquification process, more emission is probably to be added when evaluating other product stages such as manufacturing, distribution, and so on.

A lunar propellant production outpost using energy directly from solar renewable source would have a negligeable carbon footprint impact compared to Earth-based propellant production. The real take here is to actually account for the footprint generated to produce and manufacture the solar panels employed on the surface of the Moon responsible to power the outpost up there and to compare it to Earth's carbon footprint.

9.2 Limitations and Suggestions

This section provides some limitations of the research and suggests options for better enhancements to the analysis study.

Accounting for energies used in transportation blocks was based on unavailable technologies and only considered assumptions of alike engineering settings available that can perform similarly. If the study tackled in-use or under development spacecrafts design such as the Space Launch System (SLS), results could be varied obtaining a more accurate analysis.

The approach used in the lunar mining phase validated an extraction method that is not employed yet but expected to be in the foreseeable future, being the most efficient scalable sustainable method available. In this regard, additional work on the overall mining design and infrastructure enables better understanding of the lunar environment eventually validating a new set of properties that could correct the ones used currently.

The propellant production facility was analysed in its simplest hypothetical form only accounting for its key subsystem components disregarding other logistical contributions (communications-robotic services-power infrastructures). Hence its efficiency would highly depend on new demonstrated observations and newer energy analysis studies that could tackle improved boundary conditions required to make estimates of subsystems efficiency and power consumption.

In this study the obtained energy input or consumed by the system was only accounted for as wasted, without assessing its conversion into any possible mechanical or thermal added value to the system. It is of interest to go after the energy flows thus inspecting any potential use into other functional elements, improving efficiencies, and reducing cost.

The system tackled establishing an energy station at Low Lunar Orbit level as it was most favourable within the cis-lunar environment while addressing deep space exploration missions. Hence only considering the transportation to and from that location. However, examining other locations such as near Lagrange points on Moon's orbit could perhaps support a more feasible outpost and even more effective for foreseen space trajectories.

A carbon footprint has not been developed as no expanded investigation was considered to check the facility's contribution of green-house gas emissions. Environmental impact assessments are required to better help shape the future of such an outpost, especially to help guide a space outpost development and maintain it politically, socially, and economically effective.

9.3 Recommendations and Future Work

In this final section some suggestions for future research is delivered from closely related to this study to others diverted.

Establishing this lunar outpost is fundamental to the growth and prosperity of humankind be it life beneficiary on Earth from resources it can extract or used for further space exploration. To properly succeed in this undertaking many future obligations agencies and contributing entities should carry. More research should focus on its business viability to secure the funding needed. It is hence necessitated to prospect and secure investment for technology maturity as well as secure the market forecast. The latter can further be reinforced and made attractive for investors by improving space related laws that facilitate the commercialization of lunar resources. It is to be mentioned that as sustainability became more and more socially, economically, and environmentally important for any endeavour, the use of environmental impact assessment analysis give best judgement of any system adopted.

All the science described and based upon for the energy analysis is basically used to conceptually design a possible lunar propellant outpost. For successful implementations, a proved to be effective and maintained plant design should be demonstrated considering the reliability of developed technologies, hardware, and operational concepts. Proof-of-concepts are necessary in all operations including the discussed extraction, production, transportation, and storage. Detailed modular design concepts for different functional element are required to drive additional detail into the overall system.

It is undeniable that an on-orbit lunar-derived refuelling station would be of great economic and scientific value; it is also key for securing on a future scheme the realization of a new revolutionized relation between space and mankind.

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