ENERGY ANALYSIS OF EXTRACTING HELIUM-3 FROM THE MOON

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Department of Environment, Land and Infrastructure Engineering

Supervisor:
Prof. Stefano Lo Russo
Prof. Rouhi Farajzadeh

Co-Supervisor:
Sebastien Vincent-Bonnieu

Author:
Samer Matar

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ABSTRACT

A global energy crisis is emerging and it is therefore necessary to concentrate on alternative sources of energy that offer long-term solutions. As a critical element in the cleanest and most efficient type of fusion, the exploitation of He-3 can potentially generate significant amounts of energy. Nevertheless, the He-3 that occurs naturally on the Earth only comprises 1.37 parts per million of He on the planet. As the Moon does not have an atmosphere, its surface is only partially protected from the solar wind that transports He-3 created by fusion in the Sun. He-3 is embedded in the lunar regolith as the solar wind passes over the Moon's surface. Analysis conducted on samples extracted during Apollo missions indicates that the concentration of He-3 contained in the regolith is at least 10 to 20 ppb, suggesting that it is a relatively abundant source. According to satellite data recorded during NASA's Lunar Prospector missions, two specific regions named "Mare Tranquillitatis" and "South Pole Aitken" have been identified as offering significant potential in terms of increased He-3 concentrations. As a result of the pressing need for space exploration and humanity expansion, the potential to harvest the energy-rich He-3 from the lunar surface is an ideal but problematic objective. It is possible to use He-3 with Deuterium within a nuclear fusion reactor to generate significant energy outputs with minimal waste. This project focuses on calculating the energy required for each process to harvest Helium-3 from the Moon and return it to the Earth to produce electricity. The energy analysis of the processes was based on a system boundary composed of several operations such as: transporting equipment from Earth to the Moon, mining & storing He-3, transporting He-3 from the Moon to the Earth, processing Deuterium on Earth, and finally producing electricity from the fusion of Deuterium with He-3 in a fusion reactor. Results showed a value of 1,895,809 GJ for the total energy consumed and a value of 5,369,656 GJ for the total energy released. The most sensitive block found to require the largest energy input was the energy needed to power the reactor. To sum up, this

project focuses on the scientific innovations necessary in space, the technical operations, and the energy analysis for successfully harvesting He-3 from lunar surface to produce electricity back on Earth.

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List of Abbreviations

He-3	Helium-3
He-4	Helium-4
Al	Aluminum
Mg	Magnesium
Ti	Titanium
Si	Silicon
Ca	Calcium
O	Oxygen
Fe	Iron
BWE	Bucket Wheel Excavator
REE	Rare Earth Elements
PET	Positron Emission Tomography
ITER	International Thermonuclear Experimental Reactor
LEO	Low Earth Orbit
LLO	Low Lunar Orbit

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Introduction

A lack of certainty and fear characterize the current energy situation. It is anticipated that by 2030, the demand for energy is expected to increase by 50% because of population growth and energy needs, particularly in developed countries such as China, the United States, and India[1]. Along with the rise in the energy demand, it is estimated that the production of oil will peak in the next ten years[2], and based on conservative projections, may be entirely depleted by the middle of this century[3]. Against this backdrop, alternative sources of energy do not represent “alternatives” but are, in fact, necessary. Based on this new requirement, efforts are being made to explore Helium-3 fusion's potential as a replacement energy source or as a complement for other sources of energy. To meet and face this challenge, humans are continually working on exploring and creating energy sources to provide the required needs for the masses. Basic and traditional energy sources used in the past years consist of several aspects of hydrocarbons such as petroleum, natural gas, and coal. These sources still provide the most considerable bulk of the world’s energy production. As efficient as hydrocarbons are, the amount of pollution they cause and the release of greenhouse gases from burning coal, natural gas, and oil cannot be disregarded[4]. Over the past decades, the vast amount of petroleum reservoirs present has played a vital role in maintaining low prices of gasoline, diesel, and natural gas; therefore, using them as the primary energy source is economically beneficial. However, due to their extremely polluting nature, alternative energy sources such as helium-3 is marking importance by providing a potential in replacing fossil fuels in the near future[5].

He-3 is a heavy isotope of the noble gas helium and can be found across the universe in different volumes. Although the levels of He-3 on the Earth are minimal, samples of soil extracted from the Moon's surface during NASA’s Apollo 11 mission revealed copious amounts of the mineral[6]. Subsequently, experts in the field of physics, geology, social science, and economics have become increasingly interested in the potential to extract and utilise the He-3 found on the Moon. The primary reasons suggested for exploring He-3 can be listed as: first, its energy density is high when combined with Deuterium in a fusion reaction; thus, compared with energy supplied by oil, the amount of He-3 required to generate the same amount will be significantly less. Second, the reduced emissions of radioactive waste and the He-fusion reaction safety are particularly appealing factors compared to the elevated safety risks associated with fission reactors employed in modern nuclear power facilities[7]. Additionally, He-3 offers the potential to explore and establish a permanent Moon base, which would provide solid foundations for the further exploration of space.

This thesis investigates and assesses the energy feasibility of the involved plans to extract He-3 on the Moon, transport it to the Earth, and then react the mineral with Deuterium within a fusion reactor. The study will also focus on the energy analysis of lunar mining and how much energy each sub-system needs to produce electricity. In the end, we will focus on the sensitivity analysis of each block and the technical viability of this study.

Chapter 1: Literature Review

1.1. Lunar Geology

The success of the project targeted at mining He-3 on the Moon is significantly dependent on the concentration of He-3 in the lunar regolith. To investigate this issue further, the geology of the Moon will first be described.

Soil and rocks on the Moon are substantial and have an abundance of different minerals that are favourable for future exploitation. Technologies with the ability to process and utilise such minerals will be critical in future lunar programs. The elements that have the greatest abundance in terms of weight are aluminium (8%), magnesium (5%), the metal oxides of iron (8%), titanium (1%), silicon (22%), and calcium (7%). Metals can be extracted from lunar materials as part of the reduction process[8]. Studies have also indicated that an estimated 45% of the Moon's surface is oxygen consisting of oxides[9]. On the other hand, hydrogen only accounts for 0.01 percent. Due to the higher frequency of meteor strikes on the Moon compared to the Earth, its geology exhibits specific differences. The Moon's top layer is comprised of topsoil defined as the regolith, which has an abundance of debris resulting from meteor impacts called ejecta.

Since the Moon has a weak electromagnetic field and no atmosphere and the high frequency of meteor strikes, its soil has specific properties, and these characteristics enable the increased prevalence of Helium-3 on the Moon. Various factors have caused the volume of He-3 in lunar soil:

1. The extent to which the lunar latitude and longitude are exposed to solar wind flux.

2. The regolith's temperature profiles based on the location

3. Interaction between the Moon and the magnetosphere of the Earth.

4. Frequency of meteor impacts on the lunar surface.

5. Redeposition of volatiles on the regolith after being disturbed by thermal cycling and meteor strikes.

It is possible to add more factors to this list, which demonstrates the challenges associated with estimating the amount of He-3 remotely. However, an empirical correlation that establishes a connection between Ilmenite's existence and concentration to that of He-3 has been highly beneficial. Analysis of soil samples collected during the Apollo mission revealed that the concentration of He-3 in soil rich in Ilmenite was two to three-fold higher than the bulk sample[8]. Likewise, the content of He-3 in the portion of the sample rich in Ilmenite was four-fold higher than the bulk. It has been suggested since Ilmenite has a closed packed hexagonal framework, it is more effective at confining He-3 in comparison to silicates and it is capable of preventing release when thermal cycling occurs. Nevertheless, this does not necessarily imply that areas of the Moon with reduced Ti content contain no He-3. The benefit of this correlation lies in the fact that remote spectrometric analysis can be used to monitor the titanium content, which does not apply to He-3.

The surface of the Moon is separated into two primary geological regions: the ancient, light-coloured lunar highlands, and the darker-coloured, lunar mare contained within the huge basins caused by meteor impacts, which are largely on the side visible from the Earth. Figure 1 illustrates the face of the Moon, which is divided into the lighter areas “Lunar Highlands” and the darker areas referred to “Maria”.

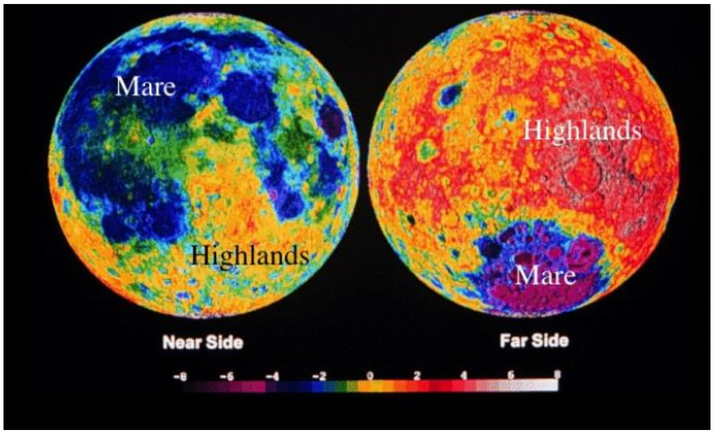


Figure 1. The Lunar Near Side and Far Side[10]

It is believed that the lunar highlands represent the Moon’s original crust and mostly consist of anorthositic rocks, which means rocks that contain more than 90% plagioclase feldspar. Plagioclase on the Moon is predominantly rich in Ca, and it is estimated that anorthite $CaAl_2Si_2O_8$ is the primary mineralogy of the highlands, and minerals that contain iron and magnesium such as pyroxene and olivine generally only account for a few percent by volume. As shown in figure 2, although the highlands have an abundance of O, Ca, Si, and Al, the content of Mg and Fe is significantly lower.

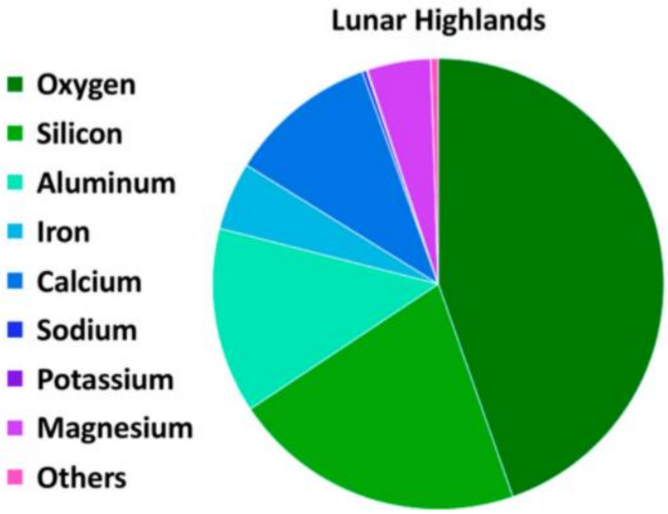


Figure 2. Major Element Relative Abundance in the lunar highlands[11]

Lunar highlands cover approximately 83% of the Moon's surface, and titanium's content is considerably reduced. While it is believed that the content of He-3 in these regions is significantly lower compared to the Basaltic Mare, it has additionally been suggested that as the depth of the regolith layer in these regions reaches 5 metres; there is the potential for deposits of He-3 to be located at increased depths, leading some to estimate that the content of He-3 could be as much as 1 million tonnes[12]. The distribution of titanium on the Moon is shown in Figure 3. Mappings such as this are generally utilised for estimating the content of He-3.

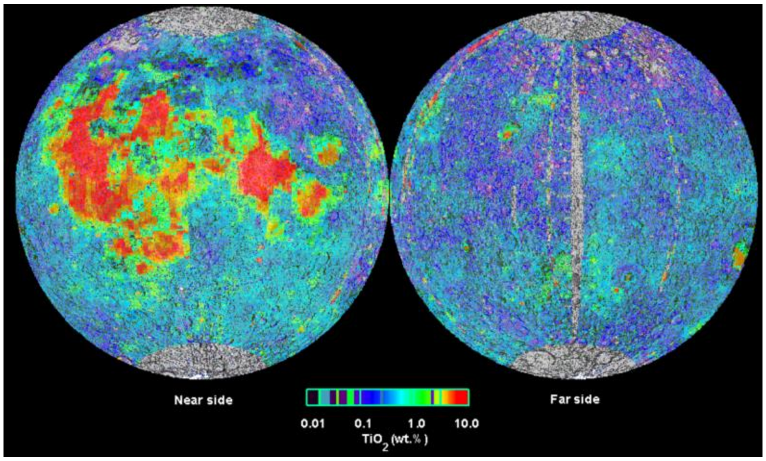
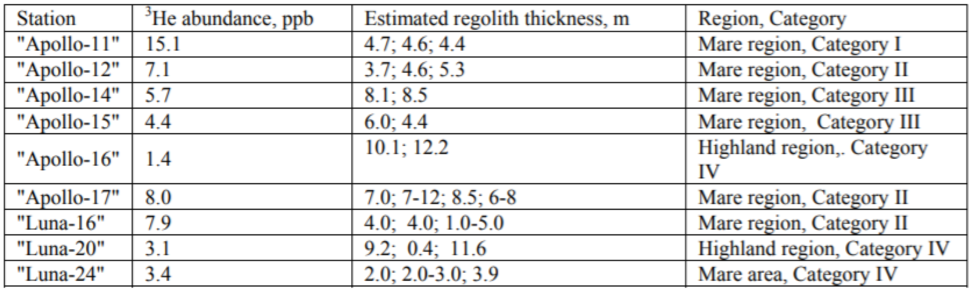


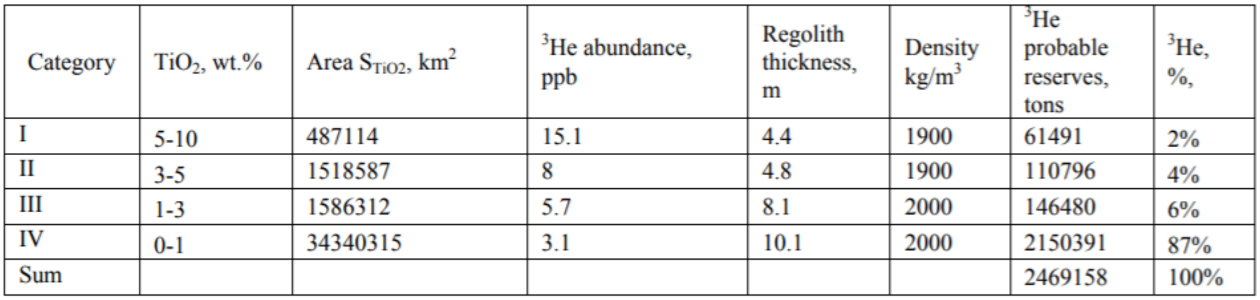
Figure 3. Titanium Oxide Distribution on the Moon[13]

Conversely, the lunar maria consists of basaltic lava flows. The mineralogy of these areas is comprised mainly of the combination of five minerals: orthopyroxene, clinopyroxene, plagioclase, ilmenite, and olivine. It follows that the relative content of Mg, Fe, and Ti in the mare basalts is higher, with lower levels of Ca and A1. Approximately 17% of the moon consists of such regions. It has also been demonstrated that the areas rich in titanium have a uniform deposition of He-3 at depths of around 3 metres. As shown in table 1 and 2, approximately 50% of the Maria or Basaltic mare are rich in Ti, with an estimated He-3 content of 1 million tonnes in these regions[14].



Station	^{3}He abundance, ppb	Estimated regolith thickness, m	Region, Category
"Apollo-11"	15.1	4.7; 4.6; 4.4	Mare region, Category I
"Apollo-12"	7.1	3.7; 4.6; 5.3	Mare region, Category II
"Apollo-14"	5.7	8.1; 8.5	Mare region, Category III
"Apollo-15"	4.4	6.0; 4.4	Mare region, Category III
"Apollo-16"	1.4	10.1; 12.2	Highland region,. Category IV
"Apollo-17"	8.0	7.0; 7-12; 8.5; 6-8	Mare region, Category II
"Luna-16"	7.9	4.0; 4.0; 1.0-5.0	Mare region, Category II
"Luna-20"	3.1	9.2; 0.4; 11.6	Highland region, Category IV
"Luna-24"	3.4	2.0; 2.0-3.0; 3.9	Mare area, Category IV

Table 1. Helium-3 regolith abundance at different landing sites[15]



Category	TiO_2, wt.%	Area S_{TiO2}, km^2	^{3}He abundance, ppb	Regolith thickness, m	Density kg/m^3	^{3}He probable reserves, tons	^{3}He, %,
I	5-10	487114	15.1	4.4	1900	61491	2%
II	3-5	1518587	8	4.8	1900	110796	4%
III	1-3	1586312	5.7	8.1	2000	146480	6%
IV	0-1	34340315	3.1	10.1	2000	2150391	87%
Sum						2469158	100%

Table 2. The estimation of He-3 probable reserves in the lunar regolith[12]

An additional fact that significantly affects the content of He-3 is the distribution of particle size in the regolith. Smaller particle sizes generally indicate higher He-3 content, which is an expected correlation as the finer particles' surface area is greater. They are therefore more exposed to solar winds, which is one of the important criteria that affect the deposition of He-3 in lunar soil.

Apollo 17 astronaut Harrison Schmitt claimed that the reserves of He-3 contained within the Moon's regolith would significantly exceed uranium's energetic potential as a fuel used in fusion reactions. Schmitt estimated that 17 square kilometers of the Moon's surface has the potential to generate enough electricity to satisfy the demand of a city with 10 million residents for an entire year, but also recognises that the technology needed for such a project will require at least 15 years to develop[16].

Geological estimations of the content of He-3 represent a significant factor that determines whether the enterprise should be initiated. Provisional data indicate that the He-3 content is sufficient to meet the increasing energy needs and provide a reliable financial basis for future exploration and development.

1.2. Mining Methods on the Moon

With the aim of starting to excavate helium-3 and other minerals on the Moon, it is essential to focus on the development of infrastructure to ease the activities on the Moon surface. Before starting to mine the lunar surface, humans need to develop and create a self-sustaining power lunar station and technology to transport the materials and equipment from Earth to the Moon and vice versa. Several methods and strategies are present to mine and process the lunar regolith's minerals, such as in-situ mining, open pit mining, and mobile excavation[17]. Each of these techniques will be examined thoroughly in the next section.

1.2.1. IN SITU MINING

In situ mining consists of extracting the minerals present in the lunar regolith without excavation. The system is composed of a mobile vehicle and an equipment to deliver thermal radiation or microwave energy onto the lunar regolith's surface. The gas molecules released are collected in a capture tent and propelled to a storage tank. The schematic of an in-situ gas device can be shown in figure 4.

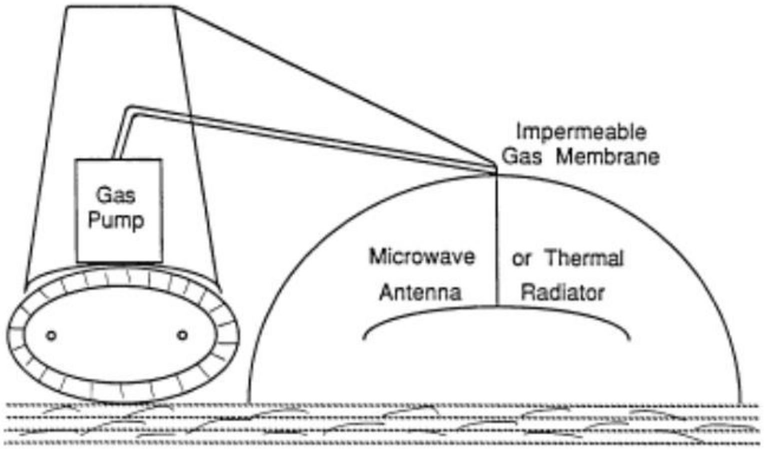


Figure 4. Sketch of an in-situ gas evolution device using either solar thermal energy or microwave radiation[18]

Due to the regolith's weak thermal conductivity (0.0001 to 0.03 $W\,m^{-1}K^{-1}$)[19] in the lunar atmosphere, in situ mining using concentrated sunlight cannot be applied. As a result, maintaining the temperature at 1000 degrees C to prevent sintering, to raise the temperature to 600 degrees C at a depth of 1cm would require five hours[17]. An alternative in-situ mining technique is to use microwave radiation to heat the surface regolith. The European space agency are focusing on creating a spaceship that uses the microwave processing of regolith[20] because it presents several advantages such as its energy efficiency and requires less time to heat the lunar surface[21].

1.2.2. Open-Pit Mining

Open-pit mining is a technique where the lunar soil is deposited on a conveyor belt and transferred to a processing machine; the same procedure is used for Earth mining. It should be mentioned that the residue produced during the operation will be disposed of into the original mine pit. The disadvantages of this technique are the following:

1. It requires a considerable amount of lunar soil to be mined in order to obtain a large amount of product.[22]
2. The amount of needed products is proportional to the conveyor belts' distance, which means that if the amount of product required is higher, the length of the conveyor belts from the mining location to the processing plant needs to be modified.
3. When the volume of processed regolith increases, the number of conveyor belts needed to transport the lunar soil to the open pit increases.

1.2.3. Mobile Mining

The mobile mining machine is formed from several sub-units. The front consists of a bucket-wheel excavator, which is attached to several mobile components. As shown in figure 5, each component performs a specific task such as excavation, beneficiation, preheating, gas extraction, and heat recovery. Each module can work separately. The whole system can move from the base to the mining site separately or as a unit, depending on the task needed. In case of technical issues, each model can be returned separately to the base. The BWE is very efficient since it can excavate up to a depth of 5 meters of the lunar surface. The BWE has multiple functions; it excavates the regolith and discharges the soil onto a belt conveyor. This excavating machine has several advantages compared to the other mining techniques since:

1. It offers a permanent supply of minerals and is used when the excavation rate is elevated.
2. On the Earth, the BWE has an effective output that varies between several hundred to several thousand $m^3/\ hr$. If this production capacity can be sustained on the Moon, it will be sufficient to use one BWE to meet the demand for a 500 MW electrical output power plant.
3. The BWE has a low mass, requiring less propellent to transport it from the Earth to the Moon. In other words, less energy is needed to lift the BWE to the Moon.
4. The BWE can be returned easily to the base in case of a technical problem.

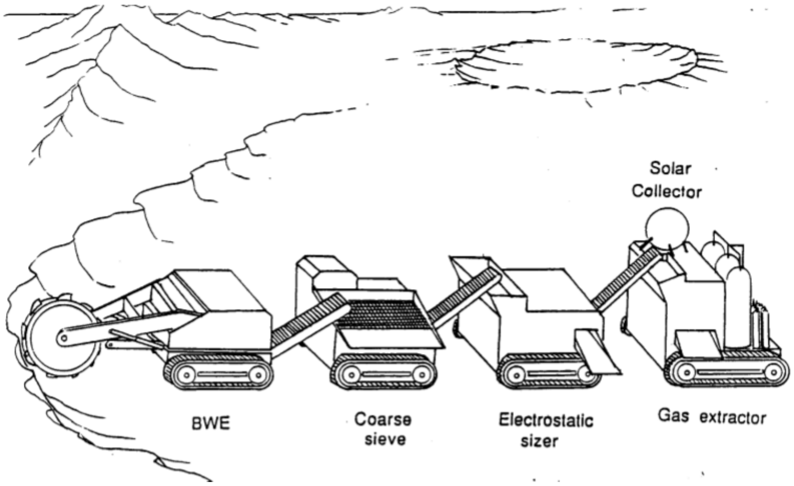
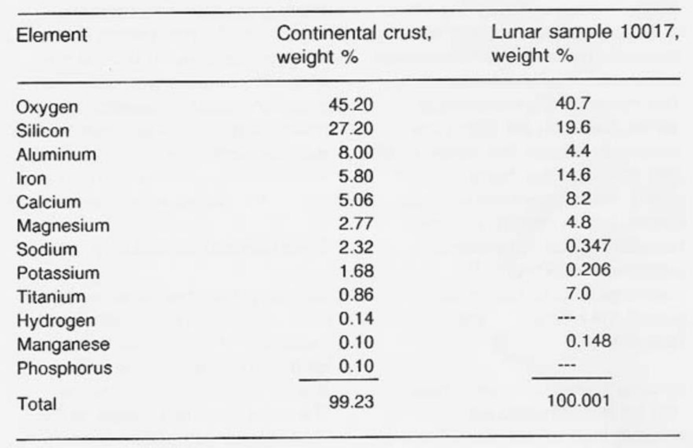


Figure 5. Conceptualized mobile mining arrangement[23]

1.3. Application of each mineral on the Moon

Up to the present, humankind is dependent on the material and energy sources provided by the Earth. According to Michigan State University, the consumption of Earth resources is increasing each year. The increase of the resources demands to meet the population growth has transformed land use and caused a huge level of pollution hence affecting biodiversity, forests, and air quality. The problem is that people are consuming more resources than the ones generated by the Earth. One alternative solution is to use the resources found on the Moon. Lunar resources present several advantages such as helping the growth of the scientific and economic activity on the Moon, they can contribute to developing a permanent base on the Moon, and excavating the lunar regolith could be very useful by using the Moon's resources to decrease the cost of launching material from the Earth to the Moon. Although there are numerous elements present on the Moon, we will tackle only seven: rare earth, aluminium, precious metals, titanium, water, silicon, helium 3, and many others. The abundances of the elements present on the Moon and in the Earth's crust are shown in table 3. In the next section, we will focus on the utility of each mineral on the Moon. The diversity of the elements that could be mined on the Moon and their applications are illustrated in figure 6.



Element	Continental crust, weight %	Lunar sample 10017, weight %
Oxygen	45.20	40.7
Silicon	27.20	19.6
Aluminum	8.00	4.4
Iron	5.80	14.6
Calcium	5.06	8.2
Magnesium	2.77	4.8
Sodium	2.32	0.347
Potassium	1.68	0.206
Titanium	0.86	7.0
Hydrogen	0.14	---
Manganese	0.10	0.148
Phosphorus	0.10	---
Total	99.23	100.001

Table 3. Major Chemical Elements in the Earth's Crust and in a Typical Lunar Mare Basalt[24]

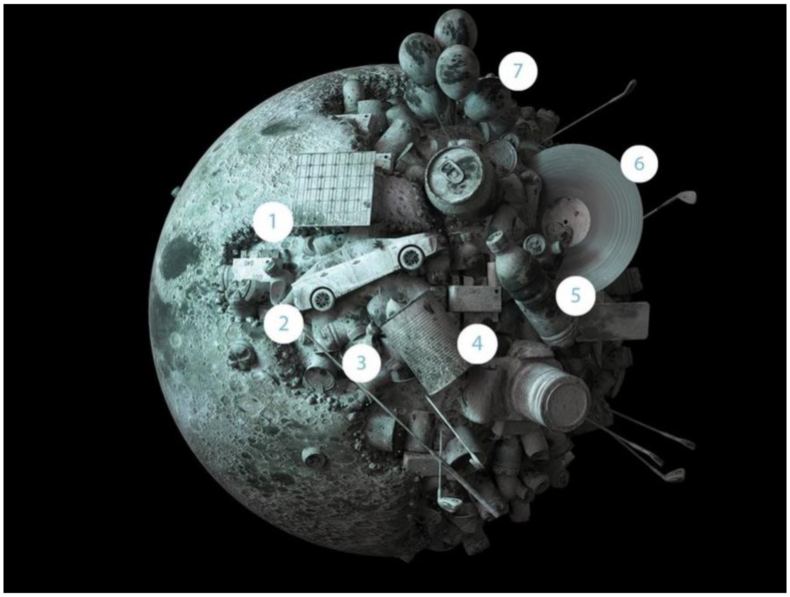


Figure 6. Elements on the moon[25]

1.3.1. Silicon

Silicon is present in abundant quantities on earth; however, this does not mean exploring them in space will not be useful. Silicon is one of the most important components for humans and is used to produce alloys, which is useful to manufacture transformer platers, engine blocks, and machine utensils. Also, silicone rubber is made from silicon which is impermeable and is used to seal bathrooms and pipes. Future excavators could mine silicon and refine it to produce semi-conductors that could be transformed into solar panels to power their outposts[26].

1.3.2. Rare Earths

Due to the lithology of the Moon, rare earth elements are deposited in the lunar crust. REE could be used to produce hybrid car batteries, phones, computers, and medical equipment. The deposition of REE happened on the Moon because the magma's cooling caused minerals to crystallize and become more concentrated. This rock was named "KREEP" which is distributed in large quantities on the Moon and contains many potassium and phosphorus useful for fabricating the batteries. This is one reason for exploring the lunar resources because the limited supply of those resources on earth can have a significant impact on all humans in the near future.

1.3.3. Titanium

Titanium can be found in the dark spots of the moon, which are the mare basalts. They are present in the ilmenite mineral and are combined with oxygen and iron. This means that processing it will result in getting other elements. Titanium can be used in aircraft, missiles, and spacecraft because it is denser than steel, offers more strength per unit weight than aluminum, and can resist extreme temperature. Due to their ability to resist corrosion, they are used in power plant condensers, desalination plants, and as a protection for the ships and submarines body.[27]

1.3.4. Aluminum

Aluminum can be found in the lunar highlands; it is one of the most conductor elements used on earth for buildings, aircraft, and mirrors construction for solar radiation collection. When applied in powder form, it can react with oxygen to make a good fuel[28]. Aluminum is known for its low-density material, highly conductive, and can resist corrosion; thus, it is used in numerous products such as windows frames, electrical transmission lines, and to produce lightweight parts for lunar structures[29]. Since there is no information for the presence of copper on the moon, aluminum can be an excellent replacement to produce electrical wiring. In addition, due to its high thermal conductivity, aluminum could be helpful in producing heat exchangers.

1.3.5. Water

Water ice is found in the regions where sunlight is absent; those regions are called the south pole craters. The discovery of water in the lunar region leads to a promising future; this means that improving the technologies present can ease life on the moon. The water present can be separated into oxygen and hydrogen to refuel the spacecraft and opens a second horizon to refuel the Mars missions' rockets. According to space expert Dr. Chris Welch from Kingston University, water exploration made a living on the moon easier for the future. For instance, water is a must on the lunar surface and transporting it from the earth would be expensive and difficult since water is very heavy, which means that we will consume many propellants to lift it to the moon. In addition, astronauts who will live on the moon for future exploration will have a source for drinkable water and make rocket propellent for their future missions.[30]

1.3.6. Precious Metals

The platinum group can be found in the lunar crust in different forms such as rhodium, osmium, ruthenium, and iridium which have the same functions as the platinum itself[31]. Platinum is one of the best conductors which cannot be oxidized in air. It is a multifunctional element that can be used as a catalyst in different chemical reactions; it can also serve as a catalytic converter in vehicles or spacecraft because it facilitates the combustion of unburned hydrocarbons[32]. Platinum can be a suitable replacement for copper to produce electrical wiring on the moon and can also be used in electronic devices. To sum up, platinum properties are essential to many processes in the industry that enhance our livings. Those industrial processes can be divided into three main parts:

I. Environmental: Platinum reduces vehicle emissions and is used in fiberglass manufacturing.

II. Healthcare: Platinum can be classified as a non-reactive metal and nontoxic hence it can be used in medical devices and in cancer treatment such as the platinum compound “cisplatin” which can treat specific types of cancer.

III. Manufacturing: Platinum is widely used in different industries to produce fiberglass, fertilizer, airbags, and lightbulbs.

1.3.7. Helium-3 Deposition

He-3 is a scarce isotope of the noble gas helium; the formation of Helium-3 has occurred as a result of three primary mechanisms. The first of these originated from the universe's conception around 15 billion years ago when the elements deuterium and hydrogen emerged from the Big-Ban explosion, which subsequently reacted and produced He-4 and He-3. In the early stages of the universe, it is thought that the ratio of He-3 to He-4 was approximately $1x10^{-6}$.[33] Another process through which He-3 is formed is nucleosynthesis, which involves the formation of elements through nuclear reactions[34]. Two reactions have particular relevance[35]:

$$\boldsymbol{d + p \rightarrow He^{3} + \gamma}$$

$$\boldsymbol{He^{3} + d \rightarrow He^{4} + p}$$

Where d stands for deuterium, p for protons and $\boldsymbol{\gamma}$ denoted gamma ray.

Furthermore, solar winds also contain He-3, which are geomagnetic fluxes that emanate from the core of the Sun and strike the heliosphere[36]. As an electromagnetic field does not surround the Moon, the isotope can be deposited on its surface via penetration into the soil, defined as the regolith. On the other hand, solar winds cannot pass through the Earth's electromagnetic field due to their charged nature, meaning that the amount of He-3 available on the Earth is negligible and the only trace amounts originate from the Big Bang. Figure 7 shows a summary of Earth's Helium-3 reserves and disposal scenarios.

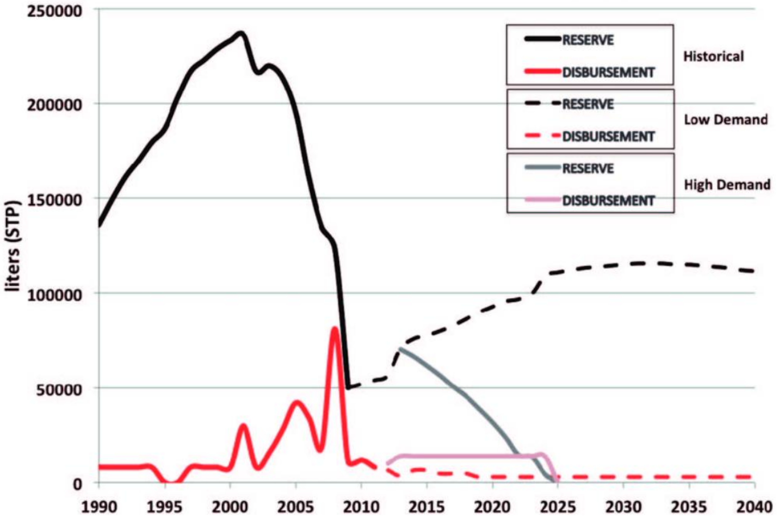


Figure 7. Helium-3 Reserve-Disbursement Scenarios[37]

We can see from figure 7 that the amount of Helium-3 present in the Earth crust from 1990 to 2003 increased from 140,000 to 240,000 litres. This linear ascending line of Helium-3 reserve might be due to the low consumption of Helium-3 in those years and the evolution of technological advancement where people were able to discover more reserves. However, in 2004, the reserve in Helium-3 started declining because the usage and consumption increased in several industries. Hence, in the case of high demand in the long term, the amount of He-3 needed will increase, and the reserves will be depleted.

To sum up, the volume of He-3 found on the Earth is insufficient as a long-term fusion fuel; nevertheless, some of this He-3 can and has been utilised to prove a fusion reaction's feasibility using this isotope.

1.3.7.1. Helium-3: A valuable fuel from the lunar crust

The advantages of He-3 as a source of energy have been acknowledged since it can be utilised in a nuclear fusion reaction for the purpose of generating significant amounts of energy. The large volume of He-3 on the Moon must be mined and extracted before it can be exploited. The lunar regolith contains approximately one million metric tonnes, which has been slowly deposited through solar winds[38]. According to the National Aeronautics and Space Administration, for 1 kg of He-3 to be produced, around 38 metric tonnes of the lunar soil would need to be mined per year[39]. Additionally, elements that offer commercial value could also be extracted, including He-4, carbon dioxide, carbon monoxide, hydrogen, and nitrogen. Hydrogen can be employed for generating electricity in fuel cells, which can be utilised to maintain the functioning of different types of modules and machines on the Moon. Additionally, if combined with oxygen contained in the lunar regolith, it is also possible to use hydrogen to produce water as well as rocket fuel. Nitrogen can be utilised for growing plants within pressurised greenhouses, carbon is useful for manufacturing processes, and He-4 can be employed for pressurisation as well as a working fluid for power plants[40].

As has been acknowledged by scientists at the University of Wisconsin, the concept of extracting and transporting the He-3 to the Earth is highly appealing since it is highly efficient and has significant potential[41]. The value of He-3 has been calculated as approximately $ 1 billion per tonne on Earth, while it has an energy potential that is 10 times higher than that found in all recognised terrestrial fossil fuels and approximately double that contained within the uranium utilised in fast breeder reactors[40]. According to Apollo 17 astronaut and the researcher Harrison Schmitt, reacting 25 metric tonnes of He-3 with deuterium can produce an equivalent amount of electricity to the total US consumption for a year[42].

The following example demonstrates the benefits of using He-3 as a fuel source in comparison to fossil fuels such as oil: one tonne of He-3 reacted with 0.672 tonnes of Deuterium can generate 10,000 MW of energy. It would need 130,000,000 barrels of oil to produce the same volume of energy. If the oil price were $40 per barrel, the total cost would be $5.2 billion. Hence, the value of the energy produced from one tonne of helium is 5.2 billion dollars[43]. In addition, the cargo of a space shuttle would be capable of carrying around 25 metric tonnes of He-3. This information was originally estimated in the 1990s and the viability of extracting and transporting He-3 to Earth was very good[40].

One of the potential areas in which He-3 can be used does not even involve the large-scale production of energy but instead exploits the comparative portability of inertial electrostatic confinement reactors (IECs); an in-depth description will be provided in a subsequent section of this study. Reacting the He-3 with deuterium can generate profits even if the amount of power produced is not sufficient to initiate and maintain the reaction; in other words, if it has not yet achieved a break-even energy potential it can be profitable. An area of particular interest is medical imaging. In such applications, He-3 and deuterium are reacted to generate protons, which are subsequently utilised to convert stable isotopes of different gases into PET images employed in medical imaging.[44]

1.3.7.2. Lunar Mining Base

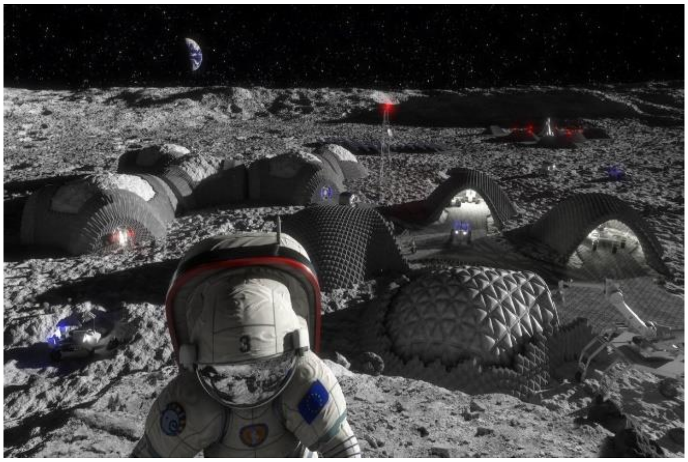


Figure 8. Lunar Mining Base[45]

A permanent lunar base must be built on the Moon's surface to operate all the activities of space mining. Due to the absence of a protective atmosphere or magnetic field on the Moon, astronauts will be directly in contact with cosmic rays and meteorites. This is one of the main reasons for building shelters on the Moon to protect the astronauts during their missions. The shelter characteristics have many criteria such as thick walls to limit radiation from penetrating, strong walls to resist the pressure differences and handle micrometeorites' collision[46]. One of the leading solutions is to use lunar concrete which is a combination of sulphur and aggregate. As shown in figure 9, manmade stone can be grown from lunar regolith by directing sunlight to create bricks that are as robust as concrete. Also, the second solution shown in figure 10 is to transport inflatable living modules from the Earth by adding a coated layer composed of lunar regolith transformed into bricks[47]. According to NASA and Johnson Space Center in Huston, building a lunar base is essential to support three main objectives: to conduct scientific research, to explore resources present in the lunar regolith in order to construct space infrastructure, and to make planetary habitation possible.[48]

Figure 9. Plaster-like bricks[48]

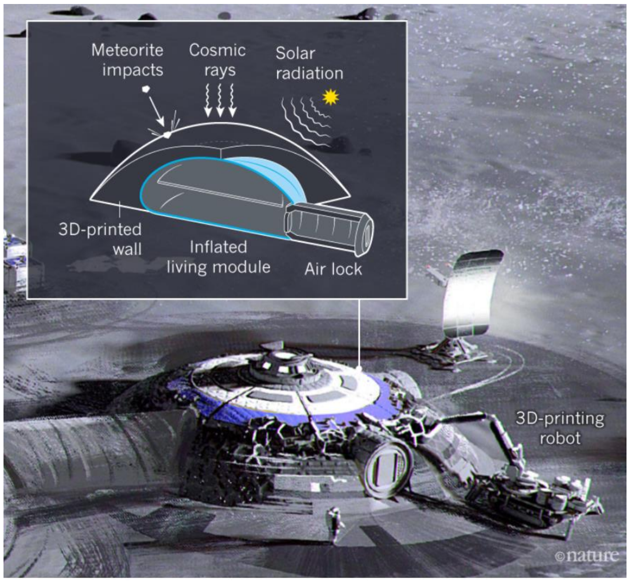


Figure 10. Inflatable living module[46]

Chapter 2: Miners Design

2.1. Mark 2&3 Miners

The Mark-3 design was based on a miner that had previously been developed, namely the Mark-2 demonstrated in Figure 11, which itself was designed based on the Mark-1, illustrated in Figure 12. To understand how the Mark-3 has enhanced the Mark-2 model, the specifications of the Mark-2 must be examined.

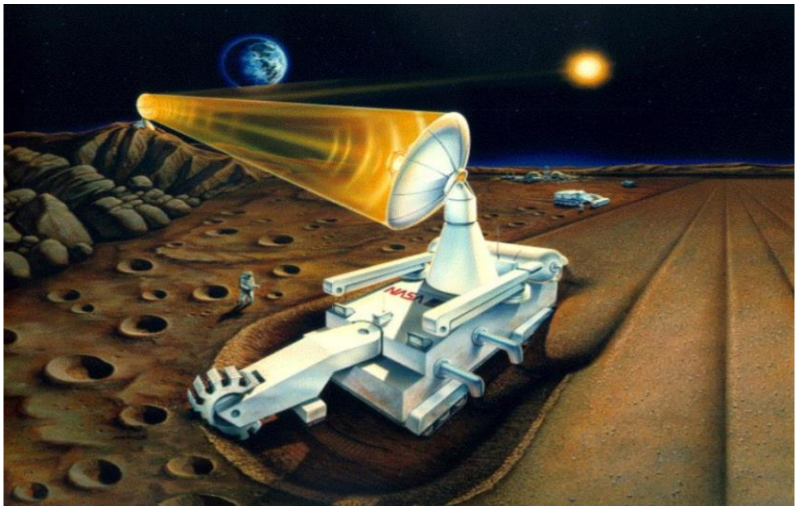


Figure 11. Mark-2 lunar miner[49]

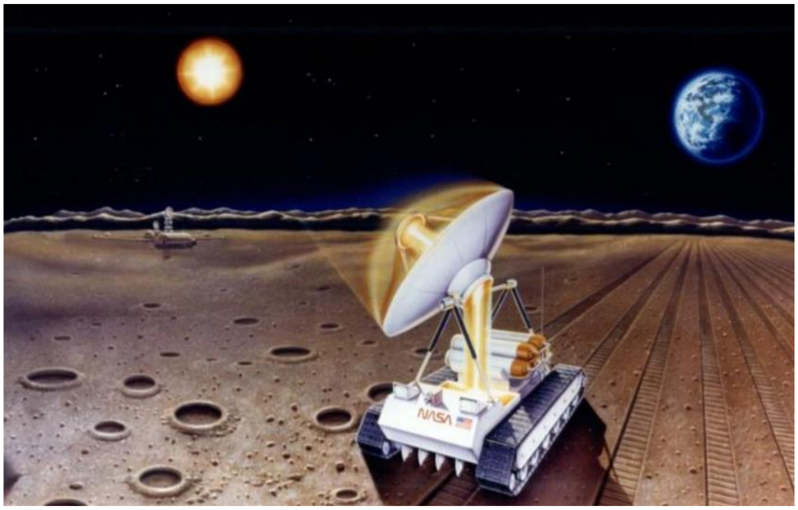
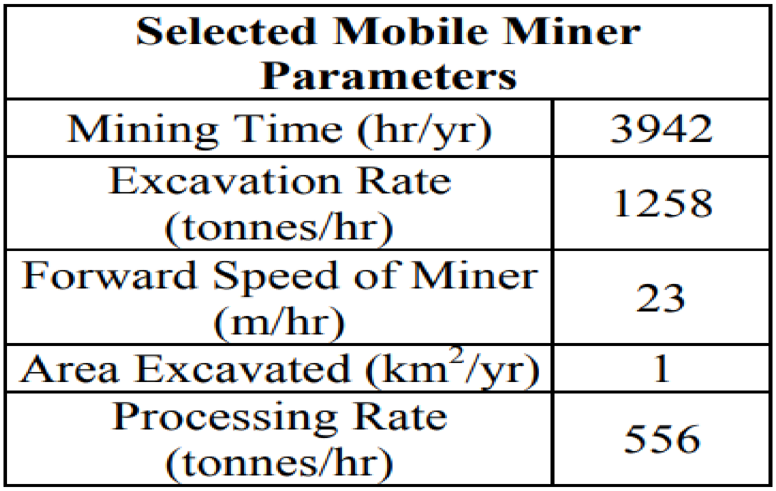


Figure 12. Mark-1 lunar miner[49]

2.2. Design of the Mark-2

The design of the Mark-2 was intended to facilitate the excavation of the regolith, the separation of the small particles, and then the heating of these particles to allow the volatile to be extracted and subsequently stored. Mark-2's design was taken from Sviatoslavsky and it was intended to produce 33 kg of He-3 on an annual basis[50]. The miner parameters shown in Table 4 were fixed based on the assumption that 80% of the He-3 within the regolith concentrated at 10 ppb would be extracted. The above parameters were selected based on the assumption that the Mark-2 would continue to function for 90% of the lunar days.



Selected Mobile Miner Parameters	
Mining Time (hr/yr)	3942
Excavation Rate (tonnes/hr)	1258
Forward Speed of Miner (m/hr)	23
Area Excavated (km^2/yr)	1
Processing Rate (tonnes/hr)	556

Table 4. Mark-2 Parameters[50]

The process of excavating the regolith was performed using a bucket wheel excavator (BWE) that functions with a 150-degree arc sweeping motion, enabling a trench to be cut with a depth of 3m and a width of 11m. The reason for making the trench 3 meters deep was based on the belief that regolith depth in the mare areas can range from 3 to 15 meters. Therefore, the design of the Mark-2 allowed the miner to mine to depths of up to 3 meters as it was not capable of excavating at different depths. This optimised the processing ability while mining the minimum lunar surface area possible.[39]

After excavation, the regolith is deposited from the BWE onto a conveyor belt. The conveyor belt then transports the regolith to a series of sieves that only permit particles under 250 microns to pass through, while particles with larger sizes were permitted to return to the surface of the Moon. The regolith fines that remain passes through a series of three 0.8 meters diameter screw conveyors that work with vacuum pumps to create a seal against the Moon's vacuum.

After passing the screws, the regolith enters the enclosure of the Mark-2, which has a pressure of 0.1 MPA. Subsequently, the regolith is inserted into a fluidised bed with a diameter of 1 m in which all particles whose size exceeds 100 microns are elevated by a stream of hydrogen gas flowing at 0.3 m/s. The particles with larger sizes are deposited at the bottom of the fluidised bed and subsequently released from the miner through the sides. Smaller regolith fines under 100 microns move upwards and enter a cyclonic cylinder that separates the hydrogen gas from the regolith using centripetal forces. To repeat the cycle, the hydrogen gas is returned to the fluidised chamber, whereas the separated regolith fines are dropped into the heater, which comprises three distinct sections: a preheater, a supplemental/central heater, and a recuperator. The working fluid contained within the heat pipes consists of potassium, mercury, water, and sodium, where the hottest part contains sodium and the coolest part has water.[51]

The miner is powered by concentrated solar energy. It has a 110-meter stationary dish that gathers, concentrates, and then redirects the solar rays to the miner’s solar collector. The collection of solar energy is performed by a solar collector with a diameter of 12 meters installed over the heater. This collector facilitates the rays' concentration, guiding them down the shaft so they can enter the heater, where the sodium working fluid within the primary heater is heated by the solar beam, which subsequently causes the regolith to be heated. The extraction process is followed by compression of the volatiles to 15 MPA, which are then stored in gas storage tanks. As one of the storage tanks is filled, it is disconnected by a manipulator’s arm and then placed on the ground next to the miner.

Subsequently, an empty cylinder lying adjacent to the miner will be picked up and attached in the position where the full cylinder was removed. After leaving the heater, the regulator will be released from the enclosure via similar screw conveyors that facilitated the miner's regolith entrance. The used regolith is then ejected behind the miner and returned to the lunar surface. Mark-2's electric power is generated by a ring of photovoltaic cells installed on the solar collector's external surface. This photovoltaic ring generates the 200-kW required for powering the miner.

2.3. Design of the Mark-3

Figure 13. Mark-3 Model[52]

Since the Mark-3 was intended to incorporate identical capabilities offered by the Mark-2, the specifications shown in Table 4 were also utilised as the basis for designing the Mark-3. The regolith will be heated using solar energy to indirectly supply power to the miner via RF beaming, which means that mining will only be possible during lunar days, and any necessary maintenance will need to be conducted during the lunar night. If it is also assumed that the miner will function for around 90% of the lunar days, this means that on an annual basis, mining will be conducted for 3,942 hours. These figures indicate that an excavation rate of approximately 1,258 tonnes of lunar regolith per hour is needed in order to obtain 33 kg of helium per year. A particular objective of the Mark-3 was to be able to fly one miner to the moon on one rocket. NASA claims that the SLS rocket can transport 38 tonnes to the moon[53]. Hence, the miner's weight was restricted to 10 tonnes based on the necessity to transport additional equipment to the moon along with the miner. The 10 tonnes limit caused the miner to be designed in such a manner that it fits into a rocket whose payload diameter is 5.4 meters and is 13. 5 meters long[53]. The dimensions mentioned above do not consider the radio frequency receiving antenna or solar collector, as illustrated in Figure 13. Both the solar collector and RF rectenna assembly can be collapsed, where the solar collector dish is comprised of several curved sections of aluminised mylar. Consequently, both pieces of equipment can be fit into significantly smaller rockets and transported individually to the moon. The SLS payload cannot exceed a diameter of 8.4 meters, which means that the Mark-3 can be transported by this rocket in its fully assembled form. As demonstrated in figures 14 to 18, the Mark-3 is constructed from multiple different constituents that function in harmony to extract solar wind volatiles from the lunar crust.

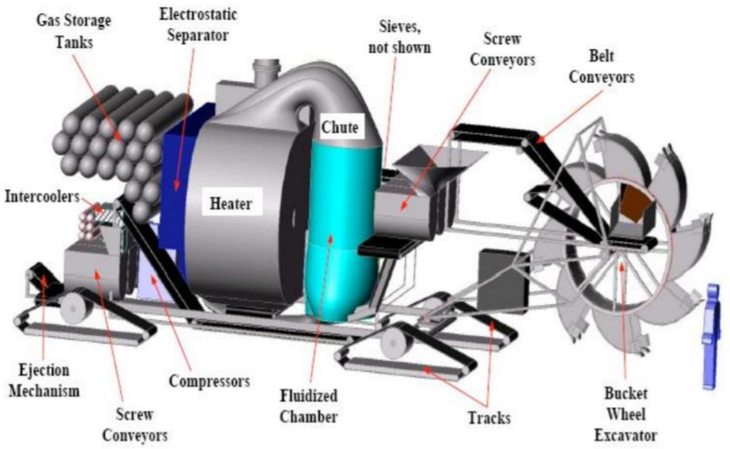


Figure 14. Side View of the Mark-3 lunar miner[52]

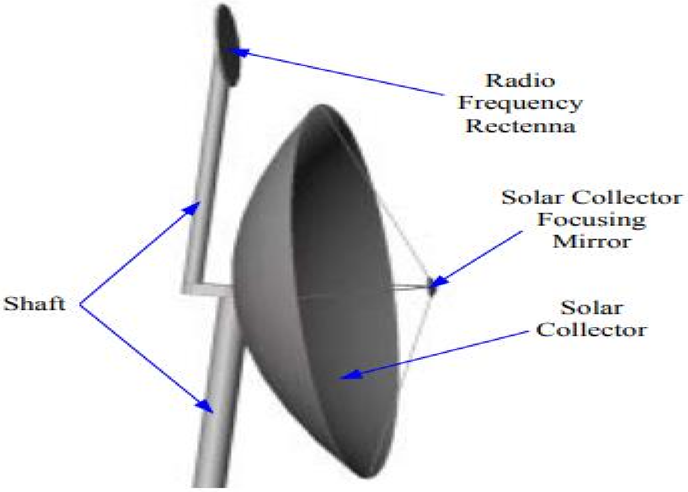


Figure 15. Side view of the solar collector[54]

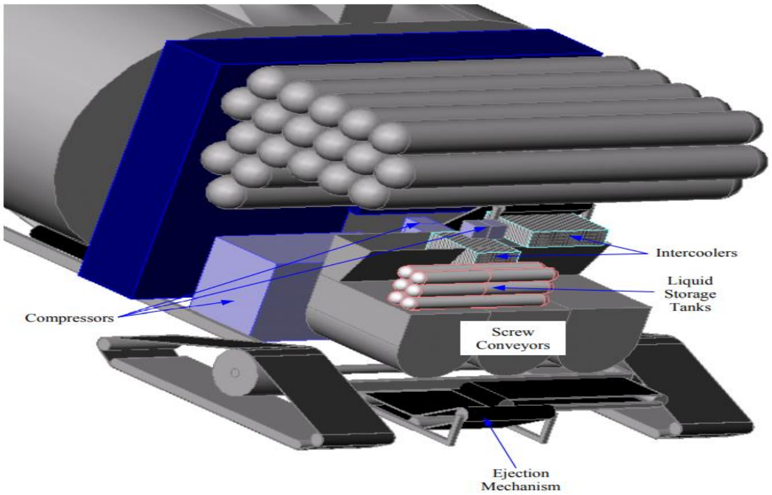


Figure 16. Rear view of the Mark-3 lunar miner[54]

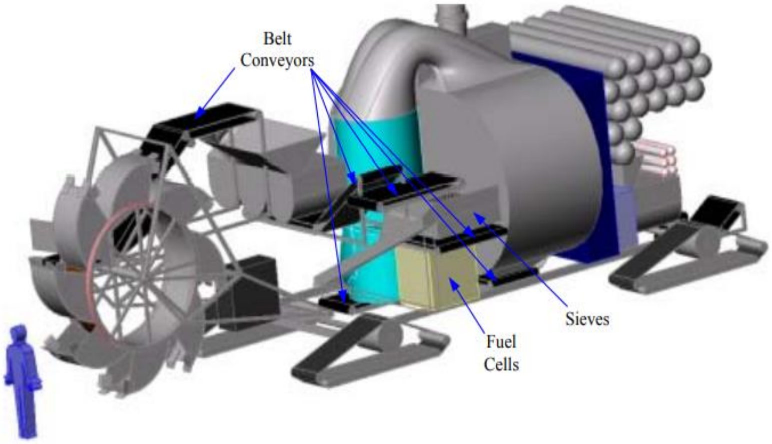


Figure 17. Side view of the Mark-3 lunar miner[54]

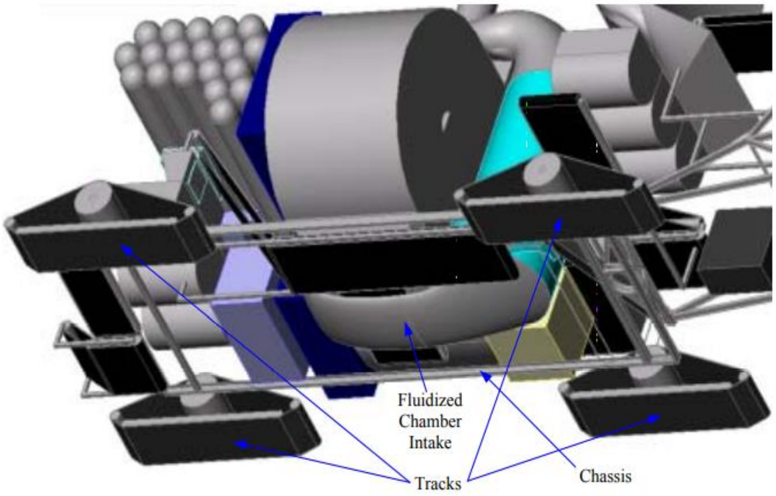


Figure 18. Bottom view of the Mark-3 lunar miner[54]

The process of excavating the regolith is performed with a multiple belt conveyor that has reduced mass and consumes less power. A 3.8-meter bucket is used for the excavation of the regolith. A path with a length of 8.4 meters and a depth of 3 meters will be cut by the BWE, which results in the excavation of 1,258 tonnes of regolith per hour. After the regolith has been excavated, a small sieve is used to remove any regolith pieces whose size exceeds 5 cm. A belt conveyor then transports this regolith to a hopper. The regolith within the hopper creates a seal between the vacuum of the Moon and the miner’s pressurised enclosure. The speed at which the regolith within the hoppers flows into the screw conveyors exceeds that by which the gas is capable of diffusing through the tightly packed regolith fines, which ensures that the volatiles cannot escape and thus secures the system against leakage. Subsequently, the small fines with a size of under 250 microns are separated by the sieves, which are then transported to the fluidised chamber. A gas flows upwards within this chamber at a pre-set velocity to carry all particles under 100 microns up into the heater via a chute, while larger particles join those previously separated by the sieves on a belt conveyor. The heater then heats the regolith fines within it to a temperature of 700 degrees C, which is not sufficiently hot for the extraction of solar wind volatiles. It is necessary to beneficiate the regolith particles down to 100 microns since the energy required for the regolith to be heated is directly proportional to the particle size square, which means that it is more practical to attempt to heat smaller particles where possible. Subsequently, the volatiles flows into an electrostatic separator, where the gas is separated from the fine regolith dust flowing with the gas. A large proportion of the gas exiting the electrostatic separator is re-used as the fluidised chamber's working fluid. The remaining gas will pass through six staged compressors that include intercoolers, which causes the gas volume to be reduced for the purpose of storing it in storage tanks installed on the miner. The intercooling process includes the condensing and storage of H_20 and CO_2 in different liquid storage tanks. Both gas and liquid storage tanks are regularly emptied by a different vehicle to ensure no interruptions to the mining process.[49]

Chapter 3: Methodology

3.1. Goal and Functional Unit

The study's goal is to mine Helium-3 on the Moon, assess and calculate the energy required for each subsystem to function to produce electricity. In this system boundary, six processes were required: transportation of mining equipment to the moon, mining Helium-3, storing He-3, transporting He-3 from the moon to the earth, processing deuterium on the earth, and finally reacting Helium-3 with Deuterium within a fusion reactor to produce electricity on the Earth. We calculated the energy required for each functional unit as well as assessing each subsystem with the others. Several limitations were used, such as the mark 2&3 miners, which NASA had already designed to mine He-3. The payload fraction was assumed to be 5% since reaching the Moon requires higher Δv hence higher payload fraction. Also, in this study, we will assume that Helium-3 is going to be liquified and transported in liquid form. In addition, the mark-2 mass was assumed to be 18 tonnes since the heater was calculated to be half of the mobile miner mass[39]. Finally, the fusion reaction will take place in the International Thermonuclear Experimental Reactor "Tokamak" which is located in France and designed by the French Alternative Energies and the Atomic Energy Commission[56]. Noting that, more details for each subsystem will be provided in the following sections.

3.2. System Boundary Description

As discussed before, this study's system boundary consists of six functional units illustrated in figure 19.

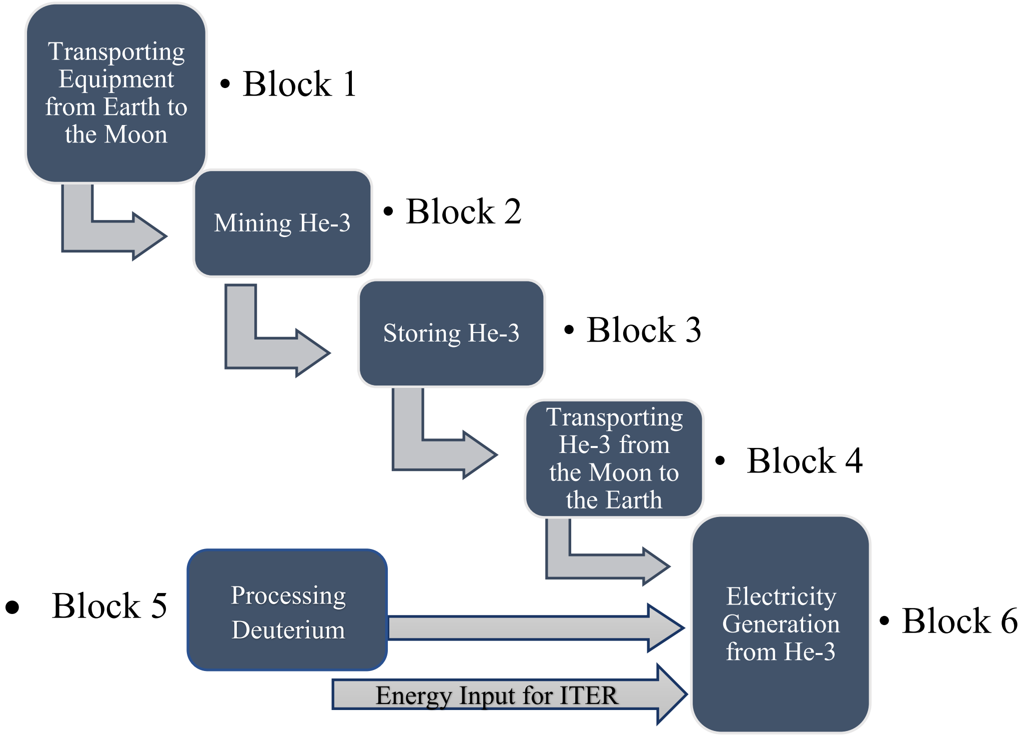


Figure 19. System Boundary

3.2.1. Functional System 1

In the first block entitled "Transporting equipment from Earth to the Moon" several key terms were used. First, the average payload fraction for spacecraft which values the efficiency of different spacecraft designs and is equal to the payload mass over the lift-off mass. Knowing that this term varies from 1% to 7%, it was assumed to be equal to 5% since higher Δv is needed to reach the Moon, noting that Δv and payload fraction are proportional[57]. Also, the payload was assumed to be the mobile miner "Mark 2" which has a dimension that can easily fit into the rocket and a mass of 18 tons. Besides, the Tsiolkovsky rocket equation was used to calculate the total mass of propellent needed to reach the Moon; this ideal rocket equation is based on the conservation of momentum which defines the motion of the spacecraft[58]. In this block, the rocket's trajectory starts from Earth to Low Earth Orbit, then from LEO to Low Lunar Orbit, and finally from LLO to the Moon. Hence, the first goal is to achieve LEO by considering two main parameters: the escape velocity and the orbital velocity. After reaching LEO and making sure that all the systems are working, it is time to turn on the thrusters and go towards the Moon. The next mission is to reach the lunar orbit where the thrusters will slow down the spacecraft's velocity to settle on LLO. Finally, the spacecraft goes from LLO to the Moon where the Mark-2 miner can be diploid to start mining.

3.2.2. Functional System 2

The second block concentrates on the energy needed to extract Helium-3 from the lunar regolith using the Mark-2 miner. Table 5 shows that this block is comprised of various operations that necessitate distinct power sources: locomotion/excavation, conveyors/beneficiation, process heat as well as the compressor. The energy required for each operation will be investigated in the following section. According to Nasa, several assumptions are used to heat the regolith; the most important one is "the Deissler Boegli method" which was used to calculate the effective thermal conductivity of lunar crust in order to estimate the specifications of the solar collector used on the Mark-2 miner[59]. The researchers developed the concept of an automated mobile lunar machine that is capable of excavating the regolith to a maximum depth of 3 meters. The rationale behind making the trench 3 meters depth was founded on the assertion that the mare regions' regolith depth can vary between 3 and 15 meters. Hence, the Mark-2 miner is designed in such a manner that will allow it to mine to a maximum depth of 3 meters as it cannot excavate to varying depths. The regolith excavation process was conducted with a bucket wheel excavator (BWE), which operates with a sweeping action in a 150-degree arc. The excavated regolith is then collected, and particles with a size of micrometers are separated electrostatically as their Helium content is the highest. The rest of the soil is returned to the surface of the moon. The separated particles are then heated to temperatures of 600-700 degrees Celsius for any trapped gases to be boiled off, which are subsequently collected and stored in cylinders via compression. After cooling, these particles are also returned to the lunar surface. The heat necessary for heating the particles is acquired from the sun utilising 'solar disks' with a size of approximately 110 meters, which enables the heat to be concentrated in an oven. The remaining regolith fines are transferred through successive screw conveyors with diameters of 0.8 meters, which function based on vacuum pumps that form a seal against the lunar vacuum. Finally, the amount of Helium-3 extracted and stored will be equal to 33 kg.[60, p. 1]

Operation	**Source**	**Electrical Power (kW)**
Locomotion & Excavation	Battery/Solar	30
Conveyors & beneficiation	Battery	10
Process Heat	Solar	…
Compressor	Fuel Cell	160

Table 5. Mining Operations[39, p. 3]

3.2.3. Functional System 3

In order for the daily functions of space mining and other activities to continue, the Helium must be transported from the Moon to the Earth, which can be achieved via two different alternatives: firstly, the He-3 can be liquified so that it can be carried in liquid form, or secondly, it can be transported as a gas. The former is favourable in terms of volume and therefore the magnitude of the boosters; nevertheless, the costs of liquifying the He-3 are higher, and the spacecraft required to ensure that products remain in liquid form will be highly complex. On the other hand, the latter necessitates larger equipment for the transportation of Helium-3 in gaseous form, which suggests increased costs.

Therefore, in the current study, the assumption is made that the transportation of He-3 will be performed using the first approach. The third block focuses on the calculation of the energy necessary for separating the gaseous elements from He-3 by investigating the amount of energy required for each operation used in table 6. As demonstrated in Table 6, this block comprises various functions, including the hydrogen separator, robotic manipulator, gas circulator, and liquefier.

Operation	**Source**
H_2 Separator	Permeable Membrane
Robotic Manipulator	Battery
Gas Circulator	Battery
Liquefier	Photovoltaic

Table 6. Separation Processes[59]

After collecting and compressing the gases within the previous block, they are sent to a condensing station via automated ground service vehicles. These gases, which consist of hydrogen, nitrogen, oxygen, carbon dioxide, and Helium, are then cooled to approximately 55 degrees Kelvin within radiators, after which they are collected as liquids. A ‘cryogenerator’ is used to further cool the Helium to around 1.5 degrees Kelvin for the purpose of separating the He-3 and He-4 isotopes. The condensation process enables the extraction of He-3 as it drains off separately. Additionally, the ‘waste’ that the condensation produces, including oxygen, nitrogen, water, methane, and hydrogen, is critical for life support operations in the moon base that will be constructed. The process by which the mixed gases are refined is complicated and consists of several successive stages. In the first stage, the hydrogen is separated, which is achieved by passing the hot volatiles through a heated niobium window. In the next stage, sequential cooling of the raffinate is performed to liquefy water, carbon compounds, and nitrogen compounds via their different boiling points. The resulting liquids are then carried to an intermediate storage zone. Oxygen, which is likely the most significant waste product, is acquired by separating water into oxygen and hydrogen via electrolysis[16]. A superleak membrane process is used for separating He-3 from He-4[61]. Figure 20 shows the different operations required to process and liquefy Helium-3.

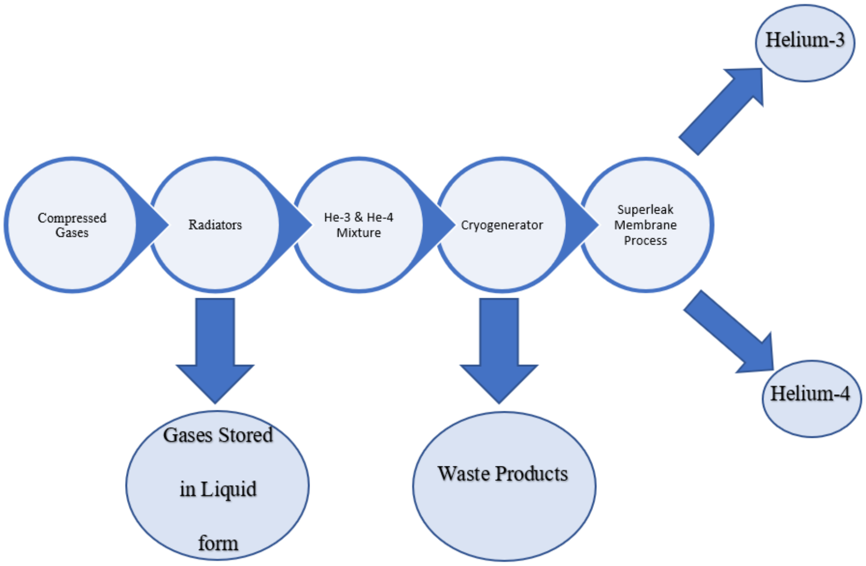


Figure 20. Process of Storing Helium-3

3.2.4. Functional System 4

Firstly, because the Moon's gravitational field has less strength and lacks an atmosphere, the forces needed to launch a rocket from the Moon would be significantly less in comparison to an equivalent launch on Earth. When launching the spacecraft from the Earth, approximately 50% of the payload comprises the fuel needed to achieve escape velocity and reach the LEO. When launching from the Moon, the same spacecraft can transport approximately 50% more cargo rather than fuel. A preferred system of propulsion would be one that is based on hydrogen-oxygen. Oxygen and hydrogen exist in abundance on the Moon, and the process of extracting them from the soil is relatively simple. Several studies focus on processing water on the Moon to produce oxygen and hydrogen as a propellant for refuelling the spacecraft; this would facilitate transporting Helium-3 from the Moon.[62]

This block will focus on the energy required to transport the 33 kg Helium-3 from the Moon to the Earth. As illustrated in figure 21, spacecraft travelling from Earth loaded with cargo would then dock with the LEO station, and then the payload would be transferred from this station to the Moon station using Orbital Transfer Vehicles. Subsequently, a Lunar Lander, which only travels between the lunar station and lunar surface, would carry cargo in both directions. Conventional space shuttles or similar vehicles would then be used to transport the Helium-3 to the Earth.

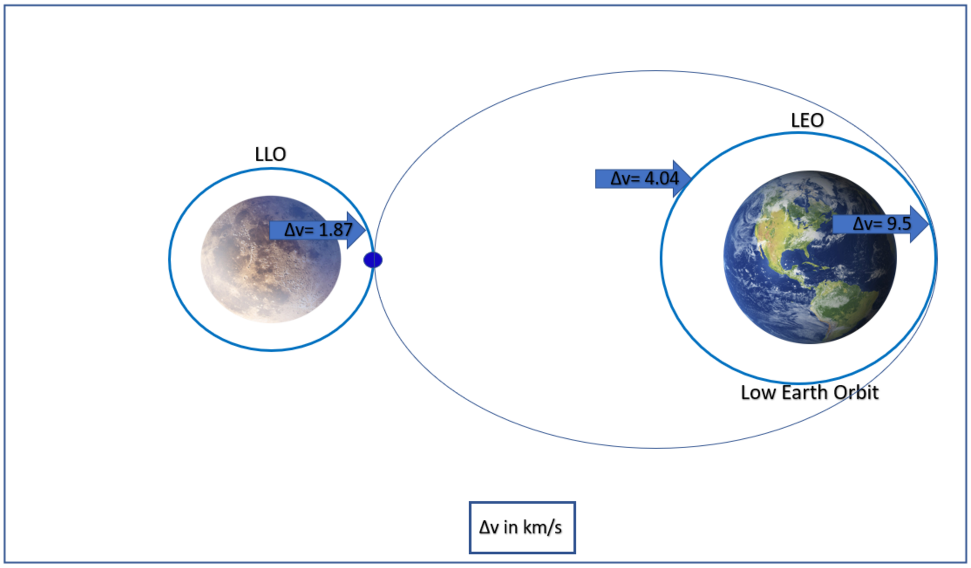


Figure 21. Transport between Moon and Earth

3.2.5. Functional System 5

Knowing that several isotopes can be combined to achieve fusion, researchers have found that the Deuterium/Helium-3 reaction is the most efficient combination and releases a massive energy amount when collided together[63]. Our study will use Deuterium and Helium-3 to fuel the fusion reactor “ITER Tokamak”. Figure 22 shows four different fusion reactions with the amount of energy released when combining two different compounds. It clearly indicates that the reaction producing the most considerable amount of energy is the combination of Deuterium and Helium-3 with a total amount of 18.4 MeV.[64]

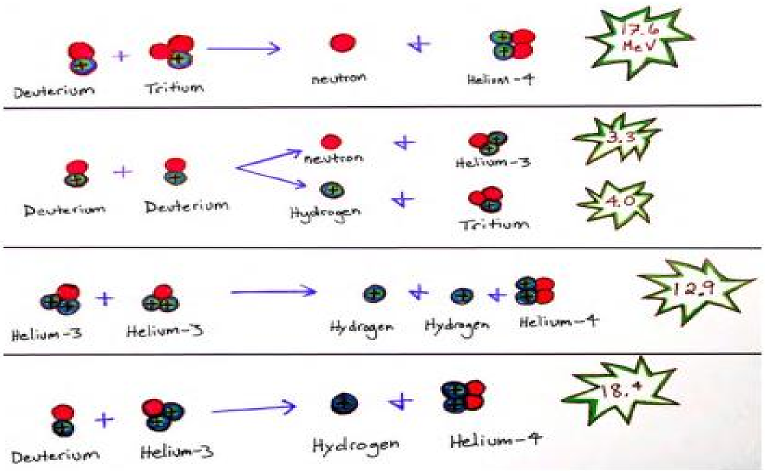


Figure 22. Energy Released from Different Fusion Reactions[64, p. 3]

Deuterium is widely present on Earth, non-toxic, and inexhaustible resource. This resource can be found in seawater and can be produced by distillation of all forms of water. In this block, it was assumed that in every cubic meter of brine, the amount of Deuterium present is 33 grams[65]. The production of Deuterium on Earth is used for scientific and industrial purposes. For example, this resource can be used for industrial purposes as an alternative for hydrogen and in biochemistry for spectroscopy due to the non-radioactivity of these resources and finally in fusion research[66]. The processes required to produce Deuterium are the following:

1) Desalination of seawater by natural osmosis to separate deuterium from water.
2) Electrolysis of the compound to obtain deuterium gas.

Further calculations will be made in the next section to get the amount of Deuterium required to fuel the ITER reactor for 434 days.

3.2.6. Functional System 6

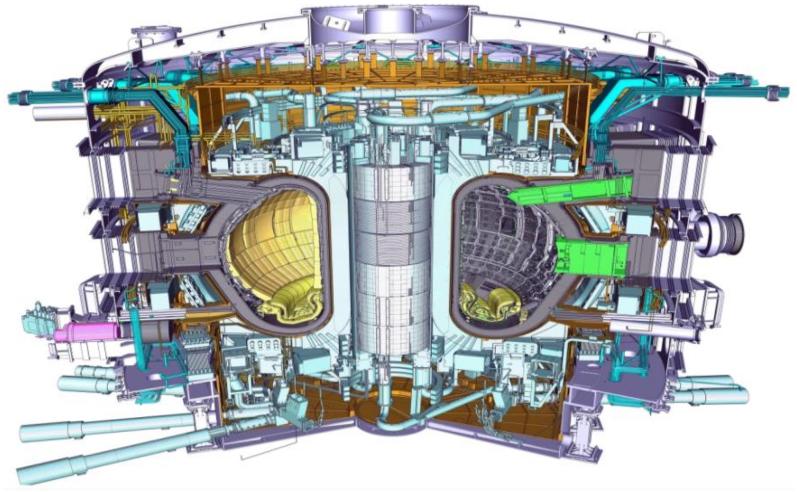


Figure 23. ITER Tokamak[67]

This block will focus on how much energy is released during a fusion reaction between Helium-3 and Deuterium. Researchers from 35 nations are working together in order to construct and operate the ITER Tokamak[68]. The reactor specifications are listed in table 7.[69]

ITER TOKAMAK	
Machine Weight	23,000 tonnes
Plasma Temperature	150 million degrees C
Steel Plasma Chamber	8,000 tonnes
Plasma Volume	840 m^3
Input Power	50 MW
Output Power	500 MW

Table 7. ITER Specifications[69]

This fusion reactor will produce electricity by transforming mechanical power into electrical power with 40% efficiency. Due to the extreme temperature and pressure at the center of the tokamak, plasma formation occurs. Then, due to the collision of D-He3, the plasma will begin to heat up, reaching a temperature of 150 million degrees C. Due to these extreme temperatures, Deuterium and Helium-3 are subjected to fuse rather than collide, which will lead to vast amounts of energy released[70]. Fuelling the reactor can be done by using different elements such as Deuterium/Tritium, Deuterium/Deuterium, Deuterium/Helium-3. However, tritium is found in a small amount on Earth; using it as a fuel for the reactor will limit the amount of electricity provided and won't allow the reactor to work for a long period of time; so it cannot be used as a fuel for the ITER. As for Deuterium/Deuterium, the energy released from this fusion reaction is equivalent to 4 MeV, which is very low compared to the fusion of He-3 with Deuterium. Hence, the best fuel for a fusion reactor is He-3/Deuterium since it releases enormous amounts of energy, and Deuterium is found in unlimited quantities on Earth, which will allow the reactor to deliver huge amounts of electricity for a long duration of time. To simplify the work, we will use the entire amount of Helium-3 extracted from the Moon, which means that the reactor will work continuously for 434 days. All the calculations related to the input & output power of the reactor, in addition to the energy released during the fusion reaction, are going to be performed in chapter 4.

Chapter 4: Energy Analysis for Each Block

In this chapter, the calculation of the energy required for each process to harvest Helium-3 from the Moon will be performed. The operations involved have been described in the previous section. Based on the assumptions made in chapter 3, information obtained from articles and specialists in the field, we will assume that mining 33 kg of Helium-3 will be achieved using the Mark-2 miner which operates during 90% of the lunar days. We will not take into consideration the energy used to produce commodities or the production of machinery.

4.1. Block 1: Transporting Equipment from Earth to the Moon

The Mark-2 miner's transportation from the Earth to the Moon is the first step to harvest Helium-3. In this block, the average payload fraction was assumed to be equal to 5% and the mass of the Mark-2 miner is equal to 18 tons, as discussed in section 2.2.

$$Payload\ fraction = \frac{payload}{lift\ off\ mass\ (m_0)}$$

Equation 1. Payload Fraction[57]

The lift-off mass would be equal to:

$$m_0 = \frac{payload\ (kg)}{payload\ fraction} = \frac{18000}{0.05} = 360{,}000\ kg$$

The propellant mass fraction is given by the following Equation:

$$\zeta = \frac{m_p}{m_0} = \frac{m_0 - m_f}{m_0} = \frac{m_p}{m_p + m_f} = 1 - \frac{m_f}{m_0}$$

Equation 2. Propellent Mass Fraction[71]

Where:

- ζ is the propellant mass fraction
- $m_0 = m_f + m_p$ is the initial mass of the spacecraft
- m_p is the propellant mass
- m_f is the final mass of the vehicle

As discussed in the previous section, we will use the Tsiolkovsky rocket equation to calculate the total mass of the propellant required to reach the Moon.

$$\Delta v = ln(\frac{m_i}{m_{dry}}) \times g_0 \times I_{sp}$$

Equation 3. Tsiolkovsky Rocket Equation 1[72]

Where:

- Δv is the maximum change of the vehicle velocity
- $m_i = m_p + m_{dry}$ is the initial total mass
- m_{dry} is the dry mass which is the final total mass without taking into consideration the mass of the propellant
- g_0 is the standard gravity

Knowing that the mass fraction takes an essential role in equation 3 and making some modifications to the rocket equation we get:

$$\Delta v = -v_e \ln (\frac{m_f}{m_0})$$

Equation 4. Maximum Change of Velocity [73]

$$\Delta v = -v_e \ln\left(\frac{m_f}{m_0}\right) = -I_{sp} x g_0 x \ln\left(\frac{m_f}{m_0}\right) = -I_{sp} x g_0 x \ln\left(\frac{m_0 - m_p}{m_0}\right) = - I_{sp} x g_0 x \ln\left(1 - \frac{m_p}{m_0}\right)$$

Equation 5. Tsiolkovsky Rocket Equation 2

Where:

- I_{sp} is the specific impulse
- $v_e = I_{sp} x g_0$ is the effective exhaust velocity[73]

Using the equations above and table 8 to pick the proper velocity change, we will calculate the mass of propellent required to reach the two different orbit hence calculating the total mass of propellant needed to reach the moon with our Mark-2 miner as payload.

Δv (km/s) from/to	LEO-Ken	LLO	Moon
Earth	9.3-10	…	…
Low Earth Orbit (LEO-Eq)	4.24	4.04	5.93
Low Lunar Orbit (LLO)	0.90	…	1.87
Moon Surface	2.74	1.87	…

Table 8. Delta-V Budgets[74]

First, we will calculate the mass of propellant required to reach LEO:

Earth → LEO:

- $\Delta v = 9.5 x 10^3\ m/s$
- $I_{sp} = 460\ seconds$
- $g_0 = 9.80665\ m/s^2$
- $m_{01} = 360{,}000\ kg$

From Tsiolkovsky rocket equation we get $m_{p1} = 316{,}177\ kg$

Second, we will calculate the mass of propellant required to launch the spacecraft from LEO to LLO:

LEO → LLO:

- $\mathit{\Delta} v = 4.04x10^3\ m/s$
- $I_{sp} = 460\ seconds$
- $g_0 = 9.80665\ m/s^2$
- $m_{02} = m_{01} - m_{P1} = 360{,}000 - 316{,}177 = 43{,}823\ kg$ (m_{02} is equal to the initial mass of the spacecraft minus the mass of propellant burned along the delivery of the payload from Earth to LEO)

Then, from the ideal rocket equation we get $m_{p2} = 25{,}927\ kg$

Third, we will determine the propellant's mass needed to launch the spacecraft for its destination.

LLO → Moon:

- $\mathit{\Delta} v = 1.87x10^3\ m/s$
- $I_{sp} = 460\ seconds$
- $g_0 = 9.80665 \frac{m}{s^2}$
- $m_{02} = m_{02} - m_{P2} = 43{,}823 - 25{,}927 = 17{,}896\ kg$

From the rocket equation we get $m_{p3} = 6{,}073\ kg$

Finally, the total mass of propellant required to transport the Mark-2 miner from Earth to the Moon will be equal to:

- $m_{tot} = m_{p1} + m_{P2} + m_{P3} = 316{,}177 + 25{,}927 + 6{,}073 = 348{,}177\ kg_{propellant}$

To calculate the energy needed for this block, we will use the liquid-hydrogen/liquid-oxygen propellant's energy density listed in table 9.

Energy Source	**Power Density** (MW/kg)	**Energy Density** (MJ/kg)
SSME H_2/O_2	2.8	19.4
Nuclear Fission	0.08	68.9
Lion Battery	$3x10^{-4}$	0.7
Triple-junction Solar Panel	$7x10^{-5}$	unlimited

Table 9. Comparison of the energy and power density of several energy sources[75]

- $Energy\ Required\ for\ Block\ 1 = Energy\ Density\ (LH_2/L0_2)\ x\ m_{tot}$

$$Energy\ Block\ 1 = 19.4 \frac{MJ}{kg_{propellant}}\ x\ 348{,}177\ kg_{propellant} = 6{,}754{,}634\ MJ = 6{,}755\ GJ$$

Therefore, the calculated total propellant mass would require an energy equivalent of 6,755 GJ.

Hence, we can get the energy needed per kilogram transported which will be equal to:

$$\frac{6{,}755\ GJ}{18{,}000\ kg} = 0.37\ GJ/kg_{transported}$$

Total energy required to bring mining equipment to the Moon		
Equipment	Earth Mass (kg)	Energy required (GJ)
Mobile Miner (Mark-2)	18,000	6,755
TOTAL		6,755

Table 10. Summary of Block 1 results

4.2. Block 2: Mining Helium-3

This block focuses on the energy needed to run the operations performed by the Mark-2 miner. As previously discussed in chapter 2, several processes are present which each one requires different electrical power input. The assumptions used in this section are that the lunar miner will work during lunar days, and the electrical power needed for each operation to mine 33 kg of He-3 per year was assumed based on several studies.

Knowing that the mobile miner will operate during 90% of the lunar days.

- $Mining\ hours\ per\ year = 365\ days\ x\ 12\,\frac{hrs}{day}\ x\ 0.9 = 3{,}942\ hrs/yr$
  - ➢ Operation 1: Locomotion & Excavation

We need $3{,}942\ hrs/yr$ to produce 33 kg of He-3. Hence, the power needed to run the first operation will be equal to:

- $Power\ needed\ per\ year = 30\ kW\ x\ 3{,}942\,\frac{hrs}{yr} = 118{,}260\,\frac{kWh}{yr}$

Knowing that $1\ kWh = 3{,}600\ KJ$

- Energy needed to mine 33 kg of He-3 per year $= 118{,}260\ x\ 3{,}600\ x\ 10^{-6} = 426\ GJ$

Hence, we can get the energy needed per 1 kilogram of He-3:

- $Energy\ needed = \frac{425{,}736{,}000\ KJ}{33\ kg_{He-3}} = 12{,}901{,}091\,\frac{KJ}{kg_{He-3}} = 13\ GJ/kg_{He-3}$

We will not show the other processes' calculations since the same methodology applies. To sum up, we will summarize the results of the energy required for each operation in table 11.

Operational energy requirements of the Mark-2 miner			
Operation	Source	Electrical Power (Kw)	Energy required (GJ)
Locomotion & Excavation	Battery/Solar	30	426
Conveyors & Beneficiation	Battery	10	132
Process Heat	Solar	…	…
Compressor	Fuel Cell	160	2,277
TOTAL			2,835

Table 11. Summary of Block 2 results

4.3. Block 3: Storing Helium-3

This block focuses on the energy required to process, liquefy, and store Helium-3 on the Moon. As discussed in chapter 2, the separation of the gaseous elements from He-3 requires several operations, with each one requiring different electrical input power. We will provide a sample methodology of calculation of the liquefication process below.

- $Mining\ hours\ per\ year = 365\ days\ x\ 12\frac{hrs}{day}\ x\ 0.9 = 3{,}942\ hrs/yr$
  - ➢ Operation 4: Liquefier

We need 3,942 hrs/yr to produce 33 kg of He-3. Therefore, the power needed to run the first operation will be equivalent to:

- $Power\ needed\ per\ year = 180\ kW\ x\ 3{,}942\frac{hrs}{yr} = 709{,}560\frac{kWh}{yr}$

Knowing that 1 $kWh = 3{,}600\ KJ$

- Energy needed to mine 33 kg of He-3 per year $= 709{,}560\ x\ 3{,}600\ x\ 10^{-6} = 2{,}554\ GJ$

Hence, we can get the energy needed per 1 kilogram of He-3:

- $Energy\ needed = \frac{2{,}554{,}416{,}000\ KJ}{33\ kg_{He-3}} = 77{,}406{,}545 \frac{KJ}{kg_{He-3}} = 77\ GJ/kg_{He-3}$

We will not show the other processes' calculations since the same methodology applies. To sum up, we will summarize the results of the energy required for each operation in table 12.

Operational energy requirements for the separation of gaseous components from He-3			
Operation	Source	Electrical Power (Kw)	Energy required (GJ)
H_2 Separator	Permeable Membrane	…	Negligible
Robotic Manipulator	Battery	10	132
Gas Circulator	Solar	3	49.5
Liquefier (55 Kelvin to 1.5 Kelvin)	Photovoltaic	180	2,554
TOTAL			2,735.5

Table 12. Summary of Block 3 results

4.4. Block 4: Transporting He-3 from the Moon to the Earth

In order to use the He-3 on the Earth and produce electricity, we are going to transport the liquified He-3 stored in tanks from the Moon to the Earth. The same methodology and formulas used in the first block are applicable here. Hence, we will not repeat all the calculations previously performed in block 1. Also, the average payload fraction was assumed to be equal to 5%, and the mass of Helium-3 to be transported is equal to 33 kg.

The lift-off mass would be equal to:

$$m_0 = \frac{payload\ (kg)}{payload\ fraction} = \frac{33}{0.05} = 660\ kg$$

First, we will calculate the mass of propellant required to reach LLO:

Moon → LLO:

- $\Delta v = 1.87x10^3\ m/s$
- $I_{sp} = 460\ seconds$
- $g_0 = 9.80665\ m/s^2$
- $m_{01} = 660\ kg$

From Tsiolkovsky rocket equation we get $m_{p1} = 224\ kg$

Second, we will calculate the mass of propellant required to transport the He-3 from LLO to LEO:

LLO → LEO:

- $\Delta v = 0.9x10^3\ m/s$
- $I_{sp} = 460\ seconds$
- $g_0 = 9.80665\ m/s^2$
- $m_{02} = m_{01} - m_{P1} = 660 - 224 = 436\ kg$

Then, from the ideal rocket equation we get $m_{p2} = 79\ kg$

Third, we will determine the propellant's mass needed to reach the Earth.

LEO → Earth:

- $\Delta v = 9.5x10^3\ m/s$
- $I_{sp} = 460\ seconds$
- $g_0 = 9.80665 \frac{m}{s^2}$
- $m_{02} = m_{02} - m_{P2} = 436 - 79 = 357\ kg$

From the rocket equation we get $m_{p3} = 313\ kg$

Finally, combining all the propellant mass obtained from the trajectories, we can calculate the energy needed to transport He-3 from the Moon to the Earth:

- $m_{tot} = m_{p1} + m_{P2} + m_{P3} = 224 + 79 + 313 = 616\ kg_{propellant}$
- $Energy\ Block\ 4 = 19.4 \frac{MJ}{kg_{propellant}}\ x\ 616\ kg_{propellant} = 11{,}950\ MJ = 12\ GJ$
- Therefore, the calculated total propellant mass would require an energy equivalent of 12 GJ.
- Hence, we can get the energy needed per kilogram transported which will be equal to:
- $\frac{12\ GJ}{33\ kg} = 0.36\ GJ/kg_{transported}$

Total energy required to transport He-3 from the Moon to the Earth		
Equipment	Mass (kg)	Energy required (GJ)
He-3 Liquid form	33	12
TOTAL		12

Table 13. Summary of Block 4 results

4.5. Block 5: Processing Deuterium

This block focuses on the energy required to process Deuterium on the Earth. As previously discussed, Deuterium will be used as a fuel for the fusion reactor. This means it is necessary to know the amount of Deuterium needed to power the tokamak reactor of 500 MW output. Based on several studies, we assumed that in every cubic meter of seawater, the amount of Deuterium present is 33 grams[65]. It was also assumed that the energy required by natural osmosis to desalinate seawater is 1 kWh/m^3 water produced.[76]

Giving that the amount of Helium-3 mined per year is 33 kg. From block 6, we got that 27.74 kg He-3 require 18.25 kg Deuterium which implies that 33 kg He-3 requires 21.71 kg Deuterium.

From the assumption used, 1 m^3 of seawater contains 33 grams of Deuterium, so the amount needed of seawater to produce 21.71 kg Deuterium will be equal to:

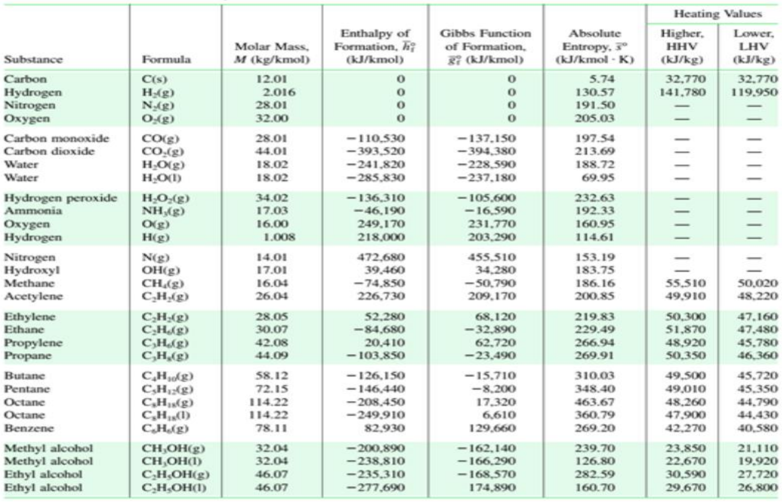
- $\frac{(21.71x10^3)gx1m^3}{33g} = 658\ m^3$ of seawater

The first step to process Deuterium is desalination, hence the energy required by natural osmosis to desalinate seawater is $1\frac{kWh}{m^3}$ of water produced. Therefore, the energy needed to desalinate 658 m^3 of seawater is 658 kWh. In addition, the second step to produce Deuterium is electrolysis. Knowing that $\rho\ (kg/m^3) = \frac{m(kg)}{V(m^3)}$ we can calculate the mass of seawater needed which will be equal to 656,026 kg.

Where:

- $V = 658\ m^3$
- $\rho_{sea\ water} = 997\frac{kg}{m^3}$
- $n = \frac{m}{MW} = \frac{656{,}026\ kg}{18\frac{kg}{kmol}} = 36{,}445.8\ kmol = 36.4x10^6 moles$

From table 14, we can get the Gibbs free energy of liquid water which is equivalent to $237.13\frac{KJ}{mol}$



Substance	Formula	Molar Mass, M (kg/kmol)	Enthalpy of Formation, $\bar{h}_f^\circ$ (kJ/kmol)	Gibbs Function of Formation, $\bar{g}_f^\circ$ (kJ/kmol)	Absolute Entropy, $\bar{s}^\circ$ (kJ/kmol · K)	Heating Values Higher, HHV (kJ/kg)	Heating Values Lower, LHV (kJ/kg)
Carbon	$C(s)$	12.01	0	0	5.74	32,770	32,770
Hydrogen	$H_2(g)$	2.016	0	0	130.57	141,780	119,950
Nitrogen	$N_2(g)$	28.01	0	0	191.50	—	—
Oxygen	$O_2(g)$	32.00	0	0	205.03	—	—
Carbon monoxide	$CO(g)$	28.01	−110,530	−137,150	197.54	—	—
Carbon dioxide	$CO_2(g)$	44.01	−393,520	−394,380	213.69	—	—
Water	$H_2O(g)$	18.02	−241,820	−228,590	188.72	—	—
Water	$H_2O(l)$	18.02	−285,830	−237,180	69.95	—	—
Hydrogen peroxide	$H_2O_2(g)$	34.02	−136,310	−105,600	232.63	—	—
Ammonia	$NH_3(g)$	17.03	−46,190	−16,590	192.33	—	—
Oxygen	$O(g)$	16.00	249,170	231,770	160.95	—	—
Hydrogen	$H(g)$	1.008	218,000	203,290	114.61	—	—
Nitrogen	$N(g)$	14.01	472,680	455,510	153.19	—	—
Hydroxyl	$OH(g)$	17.01	39,460	34,280	183.75	—	—
Methane	$CH_4(g)$	16.04	−74,850	−50,790	186.16	55,510	50,020
Acetylene	$C_2H_2(g)$	26.04	226,730	209,170	200.85	49,910	48,220
Ethylene	$C_2H_4(g)$	28.05	52,280	68,120	219.83	50,300	47,160
Ethane	$C_2H_6(g)$	30.07	−84,680	−32,890	229.49	51,870	47,480
Propylene	$C_3H_6(g)$	42.08	20,410	62,720	266.94	48,920	45,780
Propane	$C_3H_8(g)$	44.09	−103,850	−23,490	269.91	50,350	46,360
Butane	$C_4H_{10}(g)$	58.12	−126,150	−15,710	310.03	49,500	45,720
Pentane	$C_5H_{12}(g)$	72.15	−146,440	−8,200	348.40	49,010	45,350
Octane	$C_8H_{18}(g)$	114.22	−208,450	17,320	463.67	48,260	44,790
Octane	$C_8H_{18}(l)$	114.22	−249,910	6,610	360.79	47,900	44,430
Benzene	$C_6H_6(g)$	78.11	82,930	129,660	269.20	42,270	40,580
Methyl alcohol	$CH_3OH(g)$	32.04	−200,890	−162,140	239.70	23,850	21,110
Methyl alcohol	$CH_3OH(l)$	32.04	−238,810	−166,290	126.80	22,670	19,920
Ethyl alcohol	$C_2H_5OH(g)$	46.07	−235,310	−168,570	282.59	30,590	27,720
Ethyl alcohol	$C_2H_5OH(l)$	46.07	−277,690	174,890	160.70	29,670	26,800

Table 14. Thermochemical Properties of Different Substances at 298K and 1 atm[77]

Hence:

$$1\,mol \rightarrow 237.13\,KJ$$

$$36.4x10^6 moles \rightarrow z = ?$$

$$z = \frac{36.4x10^6 moles\ x\ 237.13\,KJ}{1\,mole} = 8.6\ x\ 10^9\ KJ$$

The total energy required to process 21.71 kg deuterium will be:

- $Energy\ required = 8.6\ x\ 10^9\ KJ + \frac{658\ kwh\ x\ 3{,}600\ KJ}{1\ kwh} = 8.602\ x\ 10^9\ KJ = 8{,}602\ GJ$

The total energy required to process 1 kg deuterium is:

- $Energy\ required = \frac{8{,}602}{21.71} = 396\ GJ/kg_{deuterium}$

4.6. Block 6: Electricity Generation from He-3

In this block, we will focus on the energy released during the fusion reaction of Deuterium and Helium-3. We will also calculate the input energy required to power the Tokamak and the amount of fuel needed to power this reactor. As previously discussed, the input and output power of the Tokamak are respectively 50MW, 500MW. We will also use the Einstein's famous equation to calculate the numbers of fusion reactions per second.

$$E = mc^2$$

Equation 6. Mass-Energy Equivalence [79]

Where:

- E is the energy of a particle measured in Joules
- m is the mass of a particle measured in kilograms
- c is the speed of light measured in meters per second

The nuclear fusion reaction that will take place is:

$$D + He^3 \rightarrow H^1 + He^4 + energy$$

- Atomic mass of Deuterium ($amu_{Deuterium}$) $= 2.014102$
- $amu_{He^3} = 3.016029$
- $amu_{H^1} = 1.0084$
- $amu_{He^4} = 4.002603$

Knowing that the atomic mass of each nuclei involved in this fusion reaction will allow to determine the loss of mass we get:

- $amu_{Reactants} = 5.030131$

- $amu_{Products} = 5.011003$
- $\Delta m = 5.030131 - 5.011003 = 0.019128\ amu$

This means that 0.019128 amu are converted to energy for each nucleus of He-3 that goes through fusion. Consequently, the energy release from 1 nucleus of He-3 going through a fusion reaction will be:

- $\Delta E = \Delta m x c^2 = (0.019128\ amu) x \left(\frac{1.66056x10^{-27}kg}{1\ amu}\right) x \left(3x10^8\,\frac{m}{s}\right)^2 = 2.86x10^{-12}J =$ $17.85\ MeV$

Hence, the total energy output for the fusion of 1 kg He-3 can be calculated. Knowing that the mass of 1 mol reactants is 5.030131 grams. Therefore, we can calculate the number of moles in 1 kg reactants:

- $\frac{1{,}000g}{5.030131\ g/mol} = 198.801\ moles\ of\ reactants$

Consequently, we can use the Avogadro number to calculate the number of fusion reactions that will occur:

- $198.801\ moles\ x\ 6.02\ x\ 10^{23} mole^{-1} = 1.197x10^{26}\ reactions$
- $E = (1.197x10^{26}\ rxc) x \left(17.85\,\frac{MeV}{rxc}\right) x \left(\frac{1.602x10^{-13}J}{1\ Mev}\right) = \frac{3.42x10^{14}J}{kg\ He^3} = 342{,}290\,\frac{GJ}{kg\ He^3}$

The energy released by 33 kg He-3 will be equal to $11{,}295{,}587\ GJ$

Taking a basis of 1 kg He-3 and knowing that the power is the energy per unit time we can calculate the power released by 1 kg of He-3:

- $P = \frac{E}{t} = \frac{3.42\ x\ 10^{14}J}{3.15\ x10^{7}s} = 1.08x10^{7}W = 10.8\ MW$
- $P = \frac{3.42X10^{11}KJ}{3{,}600} = 95x10^{6}kWh = 95\ GWh$

Now we will calculate the input energy required to power the Tokamak:

First, we will calculate the number of fusion reactions required to power the 500 MW ITER reactor.

- $\frac{500x10^{6}(J/s)}{E\,(J)} = \frac{500X10^{6}}{2.86X10^{-12}} = 1.74x10^{20}\ fusion\ reaction\ per\ second$

Knowing that the mass of deuterium and He-3 is known, we can proceed with the calculations of the amount needed to fuel the reactor:

- $m_{Deuterium} = 2.014102\ amu$ (atomic mass unit)
- $m_{He-3} = 3.016029\ amu$
- 1 kg of deuterium would contain

  $\frac{1\,kg}{m_{Deuterium}} = \frac{1\,kg}{2.014102\ amu} x \frac{1\ amu}{1.6726x10^{-27}kg} = 2.968x10^{26} deuterium\ atoms$

- 1 kg of He-3 would contain

  $\frac{1\,kg}{m_{He-3}} = \frac{1\,kg}{3.016029\ amu} x \frac{1\ amu}{1.6726x10^{-27}kg} = 1.98x10^{26}$ He-3 atoms

This means that to power the tokamak for 1 day long we will require:

- $1.74x10^{20}\left(\frac{fusion\ reaction}{s}\right)x3{,}600x24\ (s) = 1.5x10^{25} fusion\ reaction$

Since an equal amount of He-3 and Deuterium atoms is required for the fusion reaction, the fuel mixture must have a 50:50 ration. Therefore, an amount of $\frac{1.5x10^{25}}{2.968x10^{26}} = 0.05\ kg$ of deuterium fuel and $\frac{1.5x10^{25}}{1.98x10^{26}} = 0.076\ kg$ of helium-3 fuel will be used per day. This corresponds to 18.25 kg Deuterium and 27.74 kg helium-3 are required per year to run the ITER tokamak reactor. Finally, knowing that 33 kg of He-3 are mined per year, we can calculate the period for which the tokamak will run which will be equal to 434 days of work without interruption.

The input and output energy of the reactor will be respectively:

- $Input\ Energy = 50MW\ x\ 434\ days\ x\ 24\frac{hr}{day}\ x\frac{3.6\ GJ}{1MWh} = 1{,}874{,}880\ GJ$

Assuming an efficiency of 40% in converting the fusion energy to electrical energy we get:

- Output power of the 33 kg He-3= $\frac{3.42\ x\ 10^{14}x33\ J}{3.15\ x10^{7}s} = 35.8x10^{7}W = 358\ MW$
- $Output\ Energy = 358MW\ x\ 0.4\ x\ 434\ days\ x\ 24\frac{hr}{day}\ x\frac{3.6\ GJ}{1\ MWh} = 5{,}369{,}656\ GJ$

4.7. Results and Discussion of the Energy Analysis

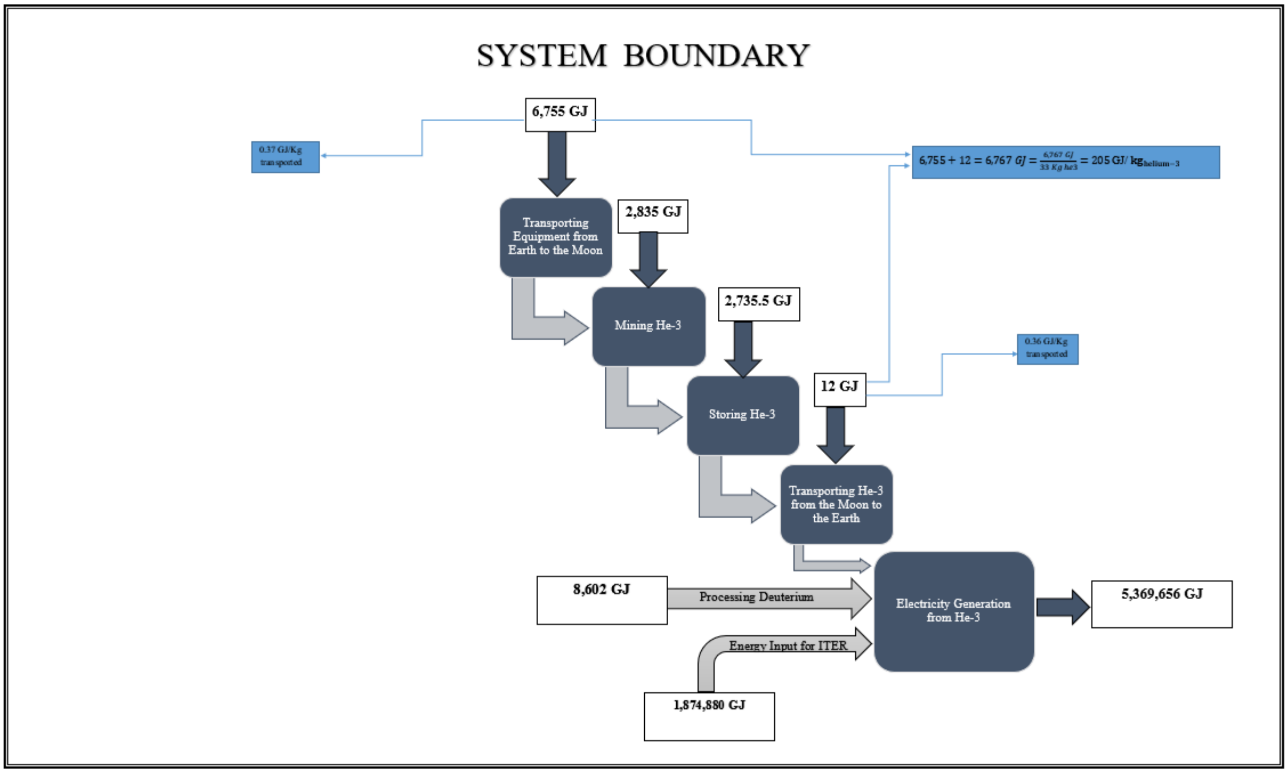


Figure 24. System Boundary of the Energy Analysis

This figure shows the energy needed for the whole operation as well as the output energy in order to extract 33 kg of He-3 from the Moon and use them with Deuterium to produce electricity. As shown in figure 24, the most critical operation that requires an immense amount of energy is the Tokamak's energy input with a value corresponding to 1,874,880 GJ. As per the data calculated in the previous section, it is clearly shown that processing Deuterium on Earth will require 8,602 GJ which is 5% of the entire input energy system. From the previous calculation made, we believe that the ITER Tokamak and the fusion reaction of Deuterium/Helium-3 yield a huge amount of energy. The output energy of $3.42x10^{14}J$ from the fusion of 1 kg of Helium-3 and Deuterium is equivalent to 2.6 million gallons of gasoline which is about 4 times the magnitude of the bomb's energy output that demolished Nagasaki.

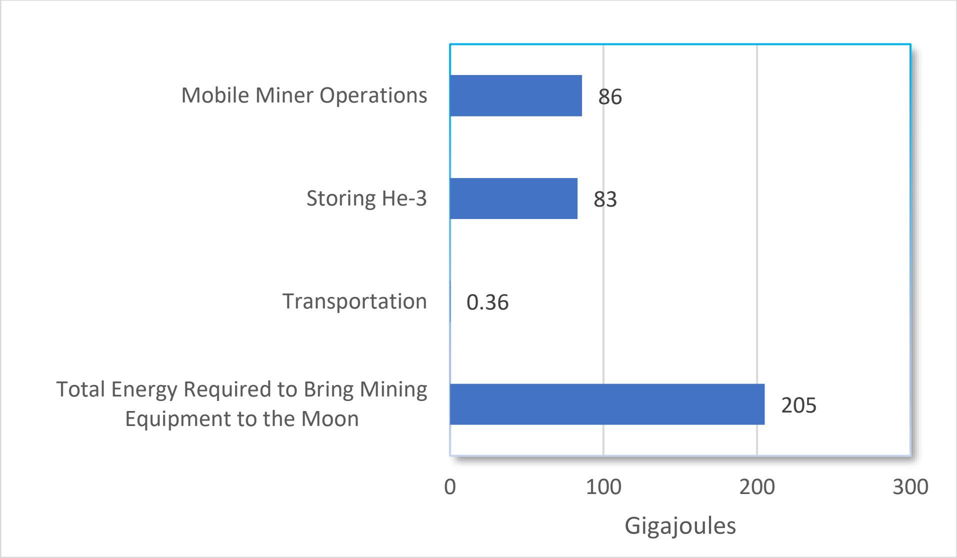


Figure 25. Energy Invested to Obtain and Transport 1 kg of He-3 from the Moon to the Earth

As discussed in section 4.2, the amount of Helium-3 extracted from the Moon per year is equivalent to 33 kg by where there is an additional amount of $33\ kg - 27.74\ kg = 5.26\ kg$ than the actual amount needed to power the Tokamak for one year. Thus, the reactor will be able to run for more than an entire year giving that the amount mined is greater than the amount needed. Therefore, if the total heat output is 500 MW and the reactor electrical input is 50 MW, the reactor will show an amplification of 3 times. Consequently, knowing that the 500 MW heat output should be converted to electricity with a conversion efficiency of 40 percent, the reactor will generate more electricity than it consumes, resulting in an efficiency of 30% and a net gain of 150 MW. The energy payback ratio for mining He-3 will be calculated below:

$$\text{Payback Ratio}=\frac{Energy\ Released\ by\ burning\ 33\ kg\ He{-}3}{Sum\ of\ the\ total\ Energy\ Required}=\frac{5{,}369{,}656\ GJ}{1{,}895{,}819.5\ GJ}=3$$

Systems having a payback ratio of 1 to 1.5 should be neglected. However, in our case, we got a payback ratio of 3 which is similar to the one provided by natural gas; indeed, this payback ratio could increases in the near term since the technologies are becoming more advanced; hence the energy invested will be less. Thus, He-3 could replace natural gases and become a major energy source due to the following advantages:

1) Good Payback Ratio: The fusion of Helium-3/Deuterium showed that the energy returned will be three times the energy invested.
2) Absence of radioactive waste: the fusion reaction of He-3 with deuterium is aneutronic which means that no radioactive decay is released.
3) Energy yield is high: the energy released from the fusion reaction is $3.42\ x\ 10^{14} J$. This energy is more than two million times that of burning gas, coal, or oil.
4) Reduce Greenhouse Gas Emissions: the fusion reaction of He-3 does not release toxic products.[78]

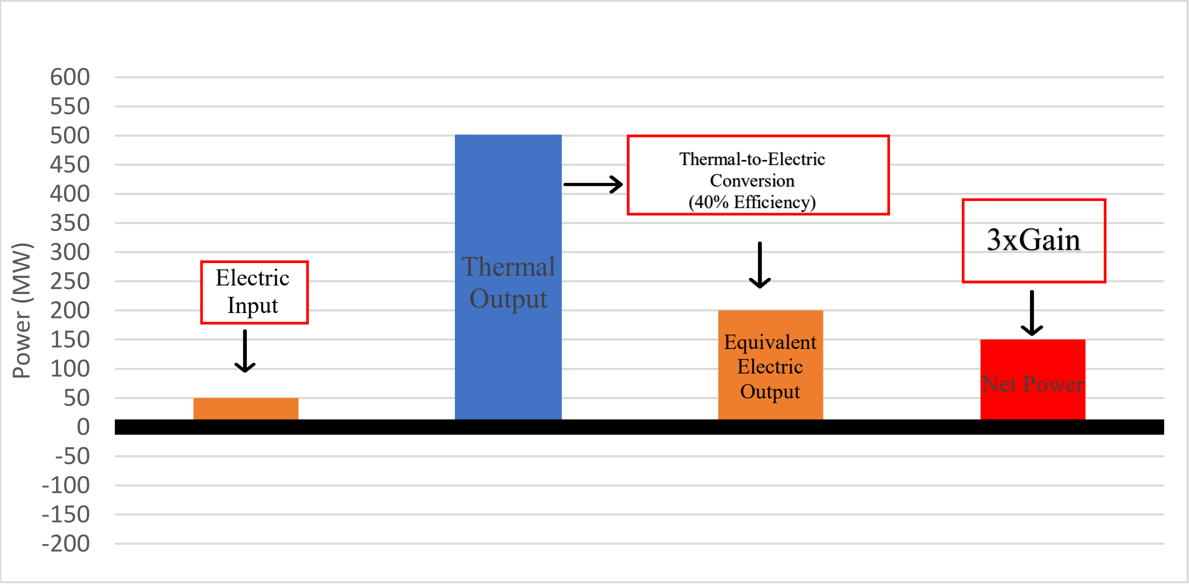


Figure 26. Electric Input and Normalized Electric Output of the ITER Reactor[79]

Chapter 5: Sensitivity Analysis

This chapter outlines the observation of the difference in energy required for each block. This is done by modifying some parameters such as the average payload fraction, the mobile miner's mass, the power needed to operate the miner, and the amount of Helium-3 present on the Moon. The operations involved and the calculation of each block's energy has been discussed in the previous sections. Finally, this section targets all the blocks except Deuterium processing since it is found on Earth in unlimited quantities and some sensitive parameters cannot be modified.

5.1. Sensitivity Analysis of Unit 1

In the first block, which is the energy required to bring mining equipment to the Moon, the uncertainties could be either from the average payload fraction and/or the mobile miner's mass. In section 4, we assumed a payload fraction of 5%. For the sensitivity analysis, we will use two different values for the payload fraction.

Assuming a 1% payload fraction and knowing that the methodology of calculation is the same as in chapter 4, we get:

Earth → LEO:

- $lift\ off\ mass = 1{,}800{,}000\ kg$
- $m_{p1} = 1{,}580{,}883\ kg_{propellant}$

LEO → LLO:

- $m_{02} = 219{,}117\ kg$
- $m_{p2} = 129{,}636\ kg_{propellant}$

LLO → Moon:

- $m_{03} = 89{,}481\ kg$
- $m_{p3} = 30{,}365\ kg_{propellant}$
- $m_{tot} = m_{p1} + m_{p2} + m_{p3} = 1{,}740{,}884\ kg_{propellant}$
- $Energy\ Required = 33{,}773{,}149\ MJ = 33{,}773\ GJ$

Therefore, the calculated total propellant mass would require an energy equivalent of 33,773 GJ.

Thus, we can get the energy needed per kilogram transported which will be equal to:

$$\frac{33{,}773\ GJ}{18{,}000\ kg} = 1.87\ GJ/kg_{transported} = 1{,}876\ MJ/kg_{transported}$$

Let us assume a 7% payload fraction we will obtain:

Earth → LEO:

- $lift\ off\ mass = 257{,}142\ kg$
- $m_{p1} = 225{,}840\ kg_{propellant}$

LEO → LLO:

- $m_{02} = 31{,}302\ kg$
- $m_{p2} = 18{,}519\ kg_{propellant}$

LLO → Moon:

- $m_{03} = 12{,}783\ kg$
- $m_{p3} = 4{,}338\ kg_{propellant}$
- $m_{tot} = m_{p1} + m_{p2} + m_{p3} = 248{,}697\ kg_{propellant}$
- $Energy\ Required = 4{,}824{,}722\ MJ = 4{,}824\ GJ$

Therefore, the calculated total propellant mass would require an energy equivalent of 4,824 GJ.

Thus, we can get the energy needed per kilogram transported which will be equal to:

$$\frac{4{,}824\ GJ}{18{,}000\ kg} = 0.268\ GJ/kg_{transported} = 268\ MJ/kg_{transported}$$

Mark-2 Miner (Payload)	Payload Fraction		
	1 %	5 %	7 %
Total mass of propellant needed ($kg_{propellent}$)	1,740,884	348,177	248,697
Energy needed for 1kg transported ($GJ/kg_{transported}$)	1.87	0.37	0.268
Total Energy needed (GJ)	33,773	6,755	4,824

Table 15. Summary Block 1 Results for Different Payload Fraction with Mark-2 Miner as Payload

As we can see from table 15, the energy required to transport 1 kg of a payload is the highest when using a payload fraction of 1% with a value of 1.87 GJ for each kilogram transported. Hence, it is preferable to use a 7% payload fraction since transporting 1 kg of payload would require less energy compared to the others. However, we cannot decide which payload fraction to use because it depends on each type of rocket, the rocket's performance, and the technologies provided.

Also, we will vary the payload; instead of using the Mark-2 miner, we will be using the Mark-3 miner. The Mark-3 miner mass is 9.9 tons, which is approximately half the weight of the Mark-2. We will be using three different payload fraction values with a fixed payload of 9.9 tons for the sensitivity analysis. Note that the method of calculation is the same as the previous section.

Let us assume a 1% payload fraction we will obtain:

Earth → LEO:

- $lift\ off\ mass = 990{,}000\ kg$
- $m_{p1} = 869{,}485\ kg_{propellant}$

LEO → LLO:

- $m_{02} = 120{,}515\ kg$
- $m_{p2} = 71{,}300\ kg_{propellant}$

LLO → Moon:

- $m_{03} = 49{,}215\ kg$
- $m_{p3} = 16{,}701\ kg_{propellant}$
- $m_{tot} = m_{p1} + m_{p2} + m_{p3} = 957{,}486\ kg_{propellant}$
- $Energy\ Required = 18{,}575{,}228\ MJ = 18{,}575\ GJ$

Therefore, the calculated total propellant mass would require an energy equivalent of 18,575 GJ.

Thus, we can get the energy needed per kilogram transported which will be equal to:

$$\frac{18{,}575\ GJ}{9{,}900\ kg} = 1.87\ GJ/kg_{transported} = 1{,}876\ MJ/kg_{transported}$$

The same methodology applies to the other calculation. Hence, the results are shown in table 15.

Mark-3 Miner (Payload)	Payload Fraction		
	1 %	5 %	7 %
Total mass of propellant needed ($kg_{propellent}$)	957,486	191,497	136,782
Energy needed for 1kg transported ($GJ/kg_{transported}$)	1.87	0.375	0.268
Total Energy needed (GJ)	18,575	3,715	2,653

Table 16. Summary Block 1 Results for Different Payload Fraction with Mark-3 Miner as Payload

Comparing the results shown in table 16&17, we can say that the energy needed to transport the Mark-3 miner is less than the one needed for the Mark-2 miner since the Mark-3 is lighter than the Mark-2, which implies that smaller amounts of propellant are needed, hence less energy needed to transport the miner to the Moon. In addition, the energy needed for 1 kg to be transported will be the same for both miners since the propellent used to fuel the rocket is the same (liquid oxygen/liquid hydrogen) and the payloads fraction chosen are the same in both cases.

5.2. Sensitivity Analysis of Unit 2

In the second block entitled "Mining He-3 on the Moon", the uncertainties could be from the amount of He-3 present in the lunar regolith and/or the possible variation of the miners' power. In general, the materials on the Moon's surface contain Helium-3 at concentrations between 1.4 and 15 parts per billion in sunlight areas[52]. In the previous section, we assumed a 10 ppb He-3 grade; thus, we got 33 kg of He-3 mined per year. However, in this part, we will choose a 1.4 ppb He-3 grade and analyse the changes in energy needed. Knowing that based on a 10 ppb Helium-3 grade we got 33 kg He-3 mined per year; hence using a 1.4 ppb grade we will be able to mine 5 kg of He-3 per year. To estimate sunlight incidence in the north or south polar regions, the NASA team collected the data by using the Japanese lunar orbited KAGUYA (SELENE). The area with the maximum incidence of sunlight was 90% at the North Pole and 86% at the South Pole.[80]

In this case, we will use the North Pole with a He-3 grade of 1.3 ppb and the Mark-2 miner will need an input power of 200 kWe to operate.

- $hours\ of\ sunlight\ a\ year = 3{,}942\ hr/yr$
- $Power\ needed = 788{,}400\ kWh/yr$
- $Energy\ needed\ for\ the\ miner = 2{,}838{,}240{,}000\ KJ$
- $Energy\ needed\ for\ the\ miner = \frac{2{,}838{,}240{,}000\ KJ}{5\ kg} = 567{,}648{,}000\ \frac{KJ}{kg} = 567\ GJ/kg_{He-3}$

On the other hand, using the Mark-3 which requires 350 kWe input power we get:

- $Power\ needed = 1{,}379{,}700\ kWh/yr$
- $Energy\ needed\ for\ the\ miner = 4{,}966{,}920{,}000\ KJ$

- $Energy\ needed\ for\ the\ miner = 993{,}384{,}000 \frac{KJ}{kg} = 993\ GJ/kg_{He-3}$

All the calculations for this block follow the same methodology previously done; hence, we will summarize the results in table 17.

Mark-2 Miner	Helium-3 concentration in sunlight areas (ppb)		
	1.4	10	15
Energy Needed ($\frac{GJ}{Kg\ He-3}$)	567	86	56
Total Energy Needed (GJ)	2,835	2,838	2,800
Mark-3 Miner	Helium-3 concentration in sunlight areas (ppb)		
	1.4	10	15
Energy Needed ($\frac{GJ}{Kg\ He-3}$)	993	150.5	99
Total Energy Needed (GJ)	4,965	4,966	4,950

Table 17. Summary Block 2 Results after Sensitivity Analysis

Table 17 shows that when the concentration of He-3 in sunlight areas is higher, the energy to mine 1 kg of Helium-3 will be lower. Also, given that the power needed to operate the Mark-3 is higher than the one of the Mark-2 miner, the energy required to mine the same amount will be greater. However, it is essential to mention that even if the Mark-3 miner requires more power to operate. It is more efficient to use it because of its lightweight compared to the Mark-2, which results in less amount of propellant needed to transport it to the Moon. It is also more beneficial to use the Mark-2 because it provides the separation of smaller particles. As previously discussed in the first block of the sensitivity analysis, the total energy required to transport the Mark-2 from the Earth to the Moon is 4,824 GJ compared to 2,653 GJ for the Mark-3 miner, which implies that the Mark-2 requires additional energy of 2,171 GJ to transport it to the Moon. Also, comparing the energy needed to mine He-3 on the Moon, we can see that the Mark-2 requires 56 GJ compared to 99 GJ per kg He-3 for the Mark-3. The results show that the Mark-3 miner requires additional energy of 43 GJ to mine 1 kg of He-3 on the Moon. It is evident that the Mark-3 requires more energy to mine the same amount; however, if we compare the energy needed to transport it to the Moon, we will see that using the Mark-3 miner will be more feasible and efficient. Finally, the miner's transportation to the Moon is the most critical block in terms of energy. Hence our primary goal is to lower the amount of energy needed; therefore, even if the Mark-3 requires more input power, it is more beneficial to use it due to its lighter weight.

5.3. Sensitivity Analysis of Unit 3

In the third block which is the energy required for separating the gaseous components from He-3, the uncertainties could be from the variation of power needed for each operation. Taking an estimation of +/- 15% of the electrical power needed for each component we get:

<table>
<tr><th colspan="8">Operational Energy Requirements for Separating Gaseous Components from He-3</th></tr>
<tr><td>Operation</td><td>Source</td><td>Electrical Power -15% (Kw)</td><td>Electrical Power +15% (Kw)</td><td>GJ/Kg He-3 -15% (Kw)</td><td>GJ/Kg He-3 +15% (Kw)</td><td>GJ -15% (Kw)</td><td>GJ +15% (Kw)</td></tr>
<tr><td>H2 Separator</td><td>Permeable Membrane</td><td>----</td><td>----</td><td>Negligible (small value)</td><td>Negligible (small value)</td><td>Negligible (small value)</td><td>Negligible (small value)</td></tr>
<tr><td>Robotic Manipulator</td><td>Battery</td><td>9.5</td><td>11.5</td><td>4.08</td><td>4.94</td><td>134</td><td>163</td></tr>
<tr><td>Gas Circulator</td><td>Battery</td><td>2.55</td><td>3.45</td><td>1.09</td><td>1.48</td><td>36</td><td>49</td></tr>
<tr><td>Liquefier (55K TO 1.5K)</td><td>Photovoltaic</td><td>153</td><td>207</td><td>65.8</td><td>89</td><td>2,171</td><td>2,937</td></tr>
<tr><td colspan="4">TOTAL</td><td>70.97</td><td>95.5</td><td>2,341</td><td>3,149</td></tr>
</table>

Table 18. Summary Block 3 Results after Sensitivity Analysis

We can see from table 18 that the most critical operation is to liquefy Helium-3 with a value of 2,937 GJ. It is evident that when the electrical input power is reduced by 15 percent, we will require less energy for the activity needed. Hence, we must focus on the electrical input and lower it as much as possible to obtain the most efficient process. Finally, Reducing the operational energy requirement for the separation of gases will result in a higher payback ratio, consequently, better energy contribution.

5.4. Sensitivity Analysis of Unit 4

In the fourth block, which is the energy required to transport He-3 from the Moon to the Earth, the uncertainties could be from the average payload fraction. The methodology and the reasoning are the same as block 1; thus, we will show the results in table 19, assuming a 1 and 7 percent average payload fraction.

	Payload Fraction		
	1 %	5 %	7 %
Total mass of propellant needed ($kg_{propellant}$)	3,191	638	455
Energy needed for 1kg transported ($GJ/kg_{transported}$)	1.87	0.36	0.267
Total Energy needed (GJ)	62	12	8.8

Table 19. Summary Block 4 Results for Different Payload Fraction

5.5. Sensitivity Analysis of Unit 6

As previously discussed, the materials on the Moon's surface contain Helium-3 at concentrations between 1.4 and 15 ppb in sunlight areas. In my previous work, we assumed a 10 ppb Helium-3 grade; in this part, we will use two different He-3 grades. The results will be shown in table 20.

	Helium-3 concentration in sunlight areas (ppb)		
	1.4	10	15
Energy Released (GJ)	$1.7X10^{6}$	$1.1X10^{7}$	$1.7X10^{7}$

Table 20. Summary Block 6 Results after Sensitivity Analysis

From the table above, we can see that when the concentration of Helium-3 in sunlight areas is higher, the amount of energy released during a fusion reaction of Deuterium/Helium-3 will be higher. For a value of 1.4 ppb, the concentration of He-3 is minimal, which results in a small amount of energy released compared with 15 ppb.

In addition, the uncertainties could be from the input power of the ITER tokamak. Future reactors will use superconducting magnetic coils, those reactors have a higher efficiency compared with the previously used ones. It is expected that the power needed will be between 200 to 300 MW of electrical power. The magnet system is going to need 80 MW of electrical power. As for the heating system the power needed will be 150 MW. Also, the subsystems required to run the plant will require 100 MW. Adding those numbers, we would require 330 MW of electrical power to run the ITER tokamak which is equivalent to 12,374,208 GJ taking into consideration an active period of 434 days. The output of the system will be equal to 500 MW. Therefore, if the total heat output is 500 MW and the reactor electrical input is 330 MW, the reactor will show a power gain of 1.5 times. Consequently, knowing that the 500 MW heat output should be converted to electricity with a conversion efficiency of 40 percent, the reactor will create less electricity than it consumes, leading to an efficiency of 0.7 and a net loss of 130 MW.

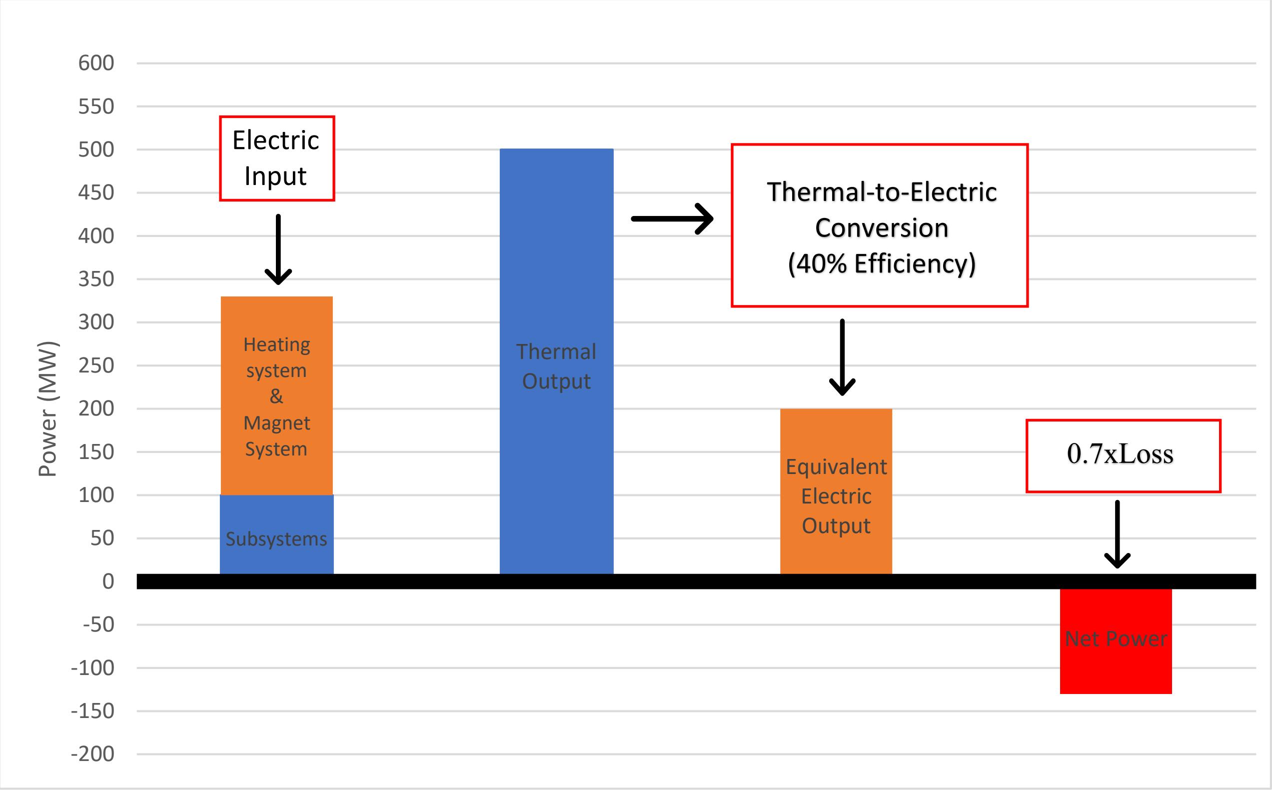


Figure 27. Electric Input and Normalized Electric Output of the ITER Tokamak[79]

5.6. Discussion of the Sensitivity Analysis

	Block 1 Mark-2 Mark-3			Block 2 Mark-2 Mark-3			Block 3			Block 4		
Key Variable	Payload Fraction			He-3 Concentration in sunlight area (ppb)			Electrical Power (kw)			Payload Fraction		
	1%	5%	7%	1.4	10	15	-15%	+0%	+15%	1%	5%	7%
Total Energy needed (GJ)	33,773 18,575	6,755 3,715	4,824 2,653	2,835 4,965	2,838 4,966	2,800 4,950	2,341	2,722	3,149	62	12	8.8
Possible Energy Range (GJ)	[4,824 – 33,773] [2,653 – 18,575]			[2,800 – 2,835] [4,950 – 4,966]			[2,341 – 3,149]			[8.8 - 62]		
Energy variation range after sensitivity analysis (GJ)	28,949 15,922			35 16			808			53.2		
Energy Contribution by Block After SA	97% 73.5%			0.09% 22%			2% 4%			0.91% 0.5%		
Total Energy Needed (GJ) (Block 1 → Block 4)	12,327 (Mark 2) 11,415 (Mark 3)											
Minimum Total Energy Needed (GJ) After Sensitivity (Block 1 → Block 4)	9,973.8 (Mark 2) 9,952.8 (Mark 3)											
Maximum Total Energy Needed (GJ) After Sensitivity (Block 1 → Block 4)	39,822 (Mark 2) 26,752 (Mark 3)											

Table 21. Summary Results after Sensitivity Analysis

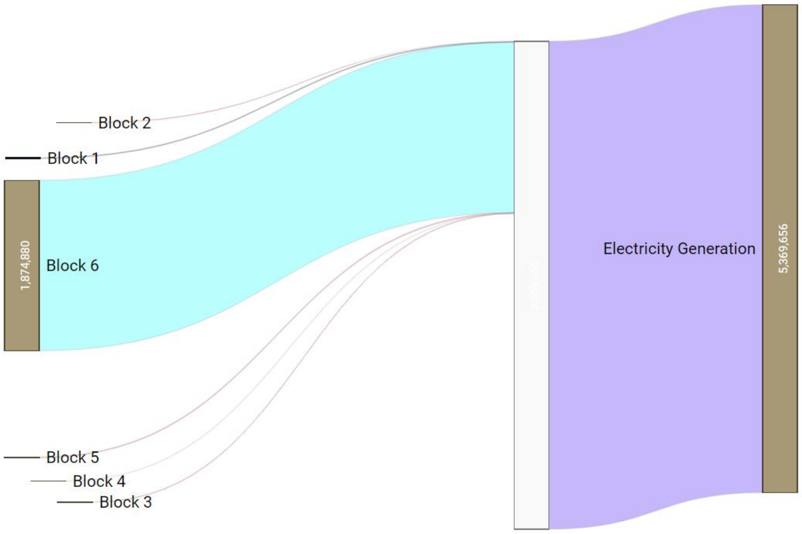


Figure 28. Representation of the System in Terms of Energy

After evaluating the energy impact of different parameters on the total energy, we observed that the most sensitive block and contributing to the whole energy consumption of our study is the one responsible for the energy input of the reactor. Even after the sensitivity of all the functional units except Deuterium's processing, the Tokamak's input energy remains the most energy-requiring block, contributing to 98% of the energy required for the entire system. Also, figure 29 highlights a comparison between the lowest/highest energy needed using the Mark-2 or the Mark-3. As illustrated in figure 29, the change in energy required of blocks 1 to 6 cannot be depicted since it is negligible compared to the most significant share of energy needed to run the reactor. Also, Deuterium's processing (Block 5) is the second most sensitive block, contributing around 0.45% of the total energy needed to run the system. The transportation of equipment accounts for 0.35%; hence, it is evident that the energy required for all the block is negligible compared to the input energy of the reactor, which stresses the idea that other techniques and technological advancement should be made to decrease the input energy of the Tokamak for the system to be more efficient. As we can see from table 21, after doing the sensitivity analysis on block 1, for a payload fraction of 1%, we have the maximum total energy needed, which is equivalent to 1,917,255 GJ for Mark-2 and 1,902,057 for

Mark-3; this considerable difference in energy required to transport the miner is due to the lighter weight of the Mark-3. As a result, even if the Mark-3 requires more power to operate, it is preferable to use it since the entire system's energy using the Mark-3 is lower. Figure 30 indicates a detailed view of each block contribution regarding the conditions the study was evaluating. The results were summarized in 3 different conditions: the normal system boundary conditions, the lowest energy condition, and the highest energy condition. All these conditions where outlined in figure 30 by considering two different miners. Finally, figure 28 represents the system energy where the arrows' width is proportional to the magnitude of the energy. Hence, comparing the lines' width, we can see that all the input blocks are negligible in terms of energy except block 6. Besides, figure 28 shows the different block energy repartition, allowing us to identify each block's influence on the total energy outcome of the design. Hence, it is clearly illustrated that the input energy is smaller than the output energy, highlighting the idea previously discussed that our system presents a gain or amplification since the width of the output is wider than the input.

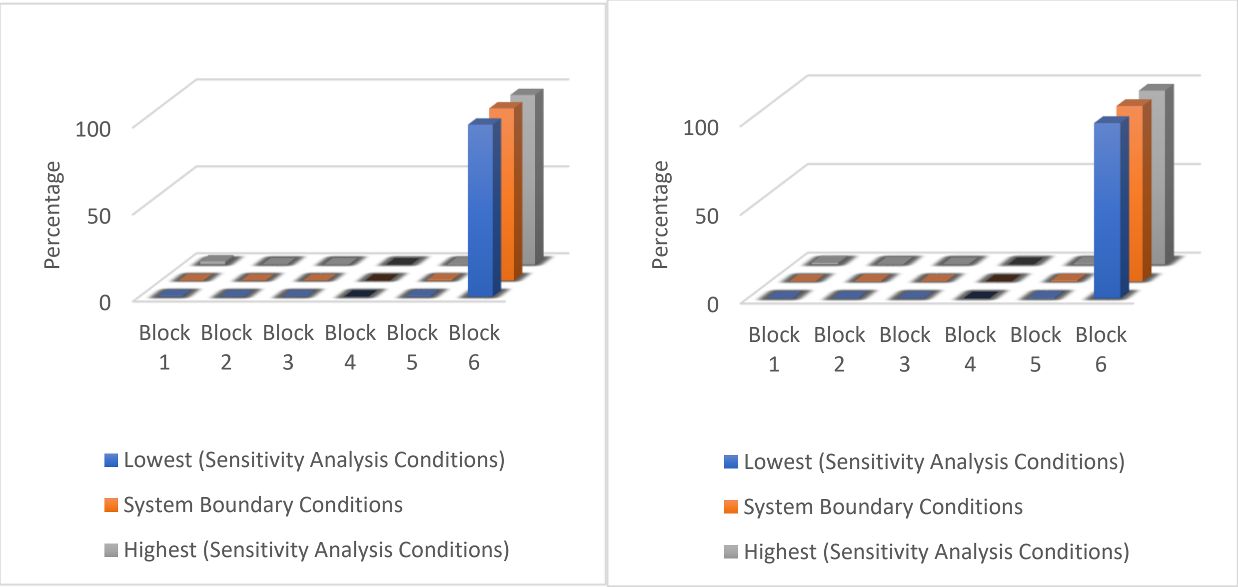


Figure 29. Energy Contribution to the System using the Mark-2 and the Mark-3 Respectively

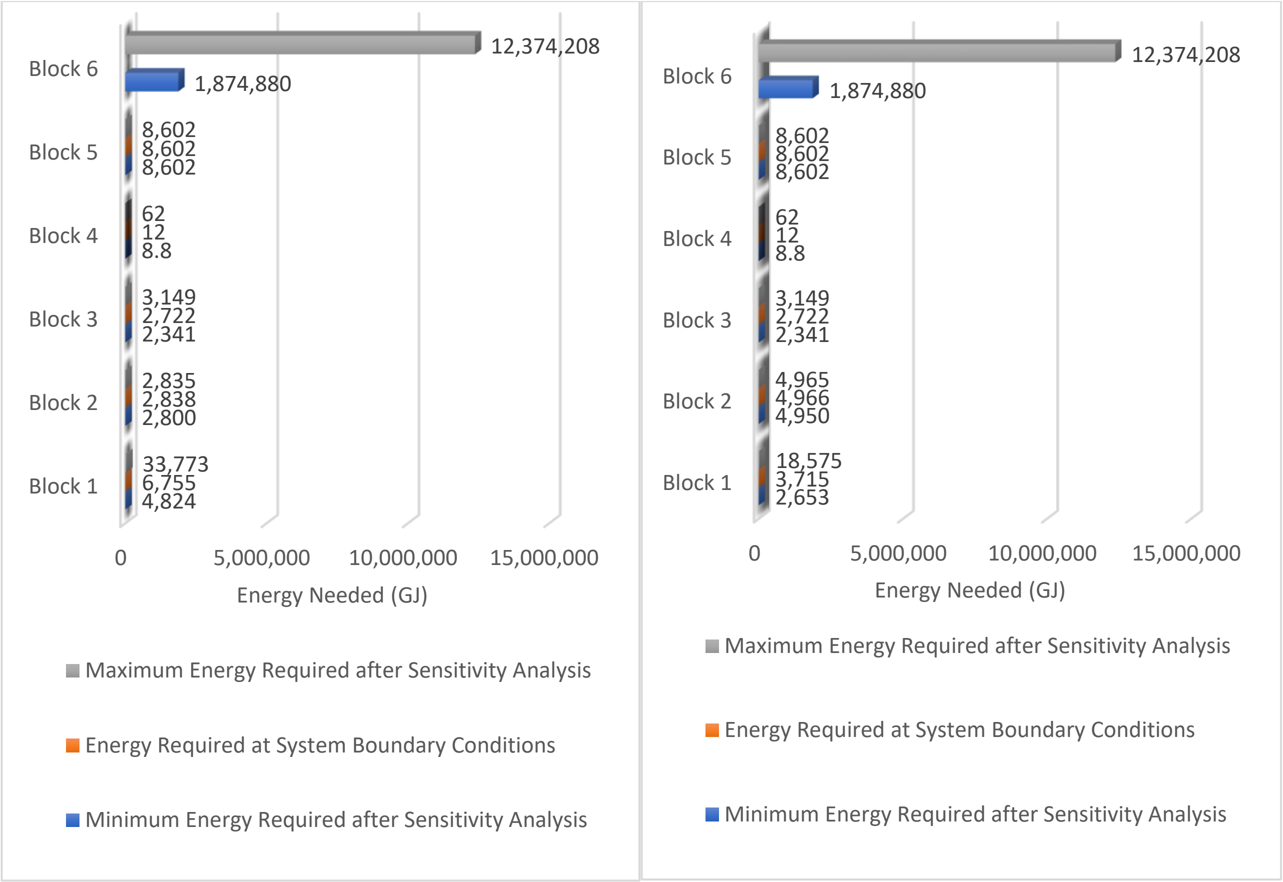


Figure 30. Energy Required for the Sub-systems using Mark-2 and Mark-3 Respectively

This graph visually explains and identifies the blocks one should focus on. It is therefore clear using both miners doesn't show a difference in energy needed for block three to six since the input of the reactor, the processing of deuterium, the transportation of He-3 from the Moon, and storing He-3 does not depend on the type of the miner. However, the miners' transportation to the Moon shows a considerable difference in energy required since the Mark-2 is heavier than the Mark-3 hence requiring more propellant to lift it off. Even if the energy needed for the Mark-3 is higher, it is desired to use it since the transportation block shows a more considerable difference in energy required compared to Block 2.

Chapter 6: Conclusion

This chapter addresses the most important results of our study. A brief recapitulation of the study outline and the most critical parts will be handled. This chapter is divided into three sections where section 6.1 highlights the technical feasibility of our study by focusing on the technological aspect, section 6.2 features the possible future scenarios that can occur, and the last section is a brief summary of the main goals achieved in our research.

6.1. Technical Viability

This project's technical viability can be tackled by focusing on three aspects: technical, political/legal perspective, and financial. In our study, we only focused on the technical part. For He-3 to be used as an alternative for fossil fuels, an additional examination should be made because the operations are very demanding and complicated. Nevertheless, all the needed technologies to mine He-3 are present and doable. However, to make our system more efficient, researchers should concentrate on:

1) Lowering the input energy required to run the reactor.
2) Reducing a fusion reactor's costs by designing new technologies that are not so expensive since a fusion reactor costs more than five billion euros to be created.[81]
3) Lowering the energy needed to process Deuterium on Earth.

Those are the most essential criteria to focus on since their influence is far more critical and energy demanding than all other operations. As for our study using the Mark-2 miner, the resulting regolith mining rate would be 1,258 tons/year to obtain 33 kg of He-3; this means that producing 1 kg He-3 would require the mining and processing of about 38 tons of lunar rock. The International Energy Agency estimates that the total primary energy supply in 2019 was $1.48x10^{10} GJ$[82]. In our case, we can produce $5.4x10^{6} GJ$. Hence, we need $\frac{33x1.48x10^{10}}{5.4x10^{6}} = 90$ tons of He-3 per year to supply the world energy demand. From the calculations previously done, we can supply 0.03 percent of the global energy demand. Hence, to provide 10% of the world energy requirement, we need 272 mining vehicles to work simultaneously. This could be achieved by transporting more vehicles to the Moon or by improving the technologies of the Mark2&3 miners in order to increase the excavation rate. If we compare the energy sources on Earth with those found on the Moon, we can conclude that only the richest currently known lunar sources are in the future to compete economically with terrestrial energy sources. This implies that further lunar exploration is required to locate richer deposits of He-3. Finally, according to several researchers, the Tokamak reactor will achieve full fusion by 2023, which means that fusing Deuterium with He-3 will become possible.[81]

6.2. Future Scenarios

In this section, it is essential to mention the probable situations for the mining of He-3 and its application as a fuel resource in the near future. Several scenarios can take place; we will list some of them in the following section:

1. We can create a station on the Moon to mine He-3 and use it with Deuterium to produce energy. This energy could be transformed into power to be utilized in the electrolysis of water to generate hydrogen. The hydrogen can be transported to the Earth in fuel cells to produce electricity. Besides, all the required metals to produce hydrogen fuel cells can be found on the Moon. However, this scenario is not technically viable because the energy required will be very high since we will be obliged to transport hydrogen to the Earth and to process Deuterium on Earth, which will be transported afterward to the Moon for the fusion reaction to be made.
2. We can transport the Tokamak reactor to the Moon and use it to produce electricity by fusing He-3. The output power of the reactor could be sent to Earth in platinum form. This means

that the reactor's output energy will be used to harvest platinum metals from the lunar regolith. Finally, the platinum metals could be sent to Earth to manufacture fuel cells.[83]

3. The most feasible and viable scenario is the one used in our study, where He-3 is harvested from the lunar regolith and transported to the Earth to be used with Deuterium in the ITER reactor. However, using this scenario requires the reactor to be developed as soon as possible. Several countries are working on producing a fusion reactor, such as the United States, China, Europe, and India. The battle depends on how the nations will obey the global agreements, how much they are willing to spend on this project to make it possible, and how much they are ready to help each other.

6.3. Final words and prospects

He-3 offers significant potential as a key energy source and if it can be effectively developed and adopted, it can bring considerable changes to support our current society, which is primarily petroleum and Earth-based. This project has facilitated a thorough comprehension of the technical challenges inherent to projects aimed at acquiring and processing He-3 for producing electricity. Additionally, the designs of the Mark 2&3 miners have been described since they were both used in this study. Moreover, our system boundary has been presented and analysed for the purpose of calculating the energy necessary for the individual operations to work. The yearly projected estimations of He-3 excavation were found to be equal to 33 kg corresponding to 1,258 tons of lunar rocks processed. The energy analysis conducted targeted the energy required within each block to achieve the desired He-3 production. The total energy consumed by the system using the Mark-2 miner was equal to 1,895,809 GJ, and the energy output from using He-3 in the fusion reactor was estimated to be equal to 5,369,656 GJ; hence an energy gain of 3,473,847 GJ. The sub-system's sensitivity was also analysed to determine what changes occur in terms of energy when modifications were applied to certain parameters. It was mentioned that the most influential block to the overall consumed energy was the block responsible for the energy input of the reactor, which accounted for 98% of the total energy used under the system boundary conditions and all the assessed conditions. Potential scenarios involving the harvesting and application of He-3 were reviewed. Lastly, the project's technical viability was evaluated on the basis of a general review of the benefits and challenges of the project.

According to the analysis of the energetics of the extraction of He-3 from the lunar regolith, transporting it back to the Earth and then creating an Earth-based fusion reactor for producing electricity based on the fusion reaction between He-3 and Deuterium, we can highlight the fact that He-3 is a potentially reliable alternative. Although such a project has inherent difficulties, according to the current research focused on He-3 fusion technology, He-3 offers promise as a future source of energy. It is possible to implement the scenarios reviewed in this study if both governments and private enterprises prioritise such a venture in terms of addressing the continuing energy challenges. Public awareness should also be raised regarding the alternative sources of energy that are available to solve the current energy crisis, and He-3 should be emphasised as one of these alternatives. It is clear that He-3 has significant potential in overcoming the existing crises and offers numerous advantages if exploited in a judicial and humanitarian manner. Global interest in developing an He-3 fusion reactor should be a primary concern for different nations around the world to collaborate on this project. The future expectations that clean fusion energy will be developed are also reliant on this valuable resource being accessed. As stockpiles within the US continue to be depleted and demand rises, the economic advantages of acquiring lunar deposits of He-3 make it an increasingly appealing alternative.

The demand for energy that offers affordability, safety, and reduced pollutants to meet the increasing global population's needs is becoming increasingly clear and pressing. Although the potential for developing fusion energy based on He-3 sourced from the Moon remains uncertain, it offers the global community a plausible option to satisfy the demand for many centuries. Hence, it is unsurprising that the United States, along with other countries that have proposed the ultimate establishment of bases on the Moon, have shown an interest in potentially mining and exploiting lunar He-3. Nonetheless, international space law currently does not stipulate any specific rules pertaining to the mining, ownership and exploitation of He-3 and different resources found on the Moon and does not offer such assurance. Resultantly, if the US Government seriously considers the potential development of fusion energy based on He-3, it would be in the country's interest to take steps to determine what it would regard as an admissible and mutually agreed international lunar resource regime – and to achieve this relatively quickly. The United States could aim to establish this type of admissible lunar resource regime in various ways. The most straightforward approach with the most significant potential would involve collective accession by the United States and different key "space powers" to the Moon Agreement according to conditions or arrangements that ensure that the agreement incorporates an acceptable lunar resource regime. A further initiative that should certainly be explored is the potential for the United States, private entreprises, and other countries interested in forming a user-based international organisation that will engage in the collaborative development and implementation of activities involving the mining of He-3 and other lunar-based resources. This type of collective enterprise could be established in isolation or could also be integrated within the structure of the Moon Agreement. Despite the inherent challenges and limited potential to succeed, it is undoubtedly essential that the United States and international lawyers' government should increase their focus on whether He-3 and other lunar resources can be exploited. If efforts are now started to contemplate and devise collective solutions to the problems that are likely to emerge when implementing such programmes, this may assist with such national activities and prevent future challenges and disputes. Furthermore, to facilitate the emergence of a new and optimistic era for the world, countries worldwide should cooperate in developing a potentially ideal and plentiful source of inexpensive, safe, and non-polluting sources of energy accessible to all nations and people.

While the project is constrained by significant physical and technical limitations, which could prevent it from being achieved within the next two decades, the necessity to investigate alternative sources of energy, such as He-3, has particularly relevance now and will only gain more relevance in the future. We contend that transformation of the energy regime will lead to massive societal and ideological changes. Hence, it is essential that this change is anticipated in order to prepare for the future.

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