LUNAR NIGHT SURVIVAL

Final Report
Space Studies Program 2018

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SPACE UNIVERSITY

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International Space University

SSP 2018

Acknowledgments

We would like to express our sincere gratitude to our sponsors at ESA and NASA for presenting us the opportunity to work on this compelling project. We would also like to thank our hosts at TU Delft, Leiden University, and ESTEC.

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All artwork in this summary is original and credited to the Lunar Night Survival team.

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Abstract

Future lunar exploration will involve a combination of human and robotic elements engaging in a variety of activities: science and exploration, resource prospecting, space tourism, and preparing for future exploration of other planetary bodies. In an era of renewed interest in lunar exploration, spacefaring nations are evaluating missions that enable a sustained human presence on the Moon, commencing within the next decade. Reliable, scalable power generation and distribution systems will be the keystone in supporting such missions, especially those that require operation during lunar nights, in which the absence of direct sunlight and the extreme temperature variations create an exceptionally inhospitable environment. In these periods of darkness, temperatures may drop several hundred degrees Celsius within minutes of sunset, and subsequent electrostatic changes of the lunar regolith present additional complications.

Our solution, the Power Cell, is able to withstand these challenges and enables survival of lunar nights. It is based on space-proven power systems, such as photovoltaics, fuel cells, batteries, and the newly demonstrated Kilopower fission technology. Kilopower is a compact fission reactor that can produce up to 10 kW of power for over ten years. Together these systems can provide reliable power for several astronauts.

To support our power solution, we have also formulated a legal and economic framework that will enable future power-related activities in outer space under a regulatory and financial body called the International Space Power Organization (ISPO). Within ISPO, The Outer Space Energy Regulatory Authority will assume regulatory responsibility to ensure compliance with the relevant treaties and international law, while the Outer Space Energy Development Bank will facilitate economic development. We envision that these agencies will cooperate to facilitate activity on the lunar surface by both private and public actors.

Faculty Preface

Although it has been more than 40 years since humans last walked on the Moon, the international space community has once again set its eyes on our closest neighbor in the solar system, now with the intention of establishing a permanent presence. Such permanent habitation will require enabling facilities and services, such as life support, communications, and the generation and distribution of power.

The challenge posed to the Lunar Night Survival team was to specify a solution for the generation and provision of power, in support of the range of activities which are planned to be deployed on the Moon in the near future. The importance of this topic is highlighted by the fact that this work has been sponsored by the Directorate of Human and Robotic Exploration Programs of the European Space Agency (ESA) and the Space Technology Mission Directorate of the National Aeronautics and Space Administration (NASA).

The participants have succeeded in developing an innovative solution for the generation and distribution of electrical power that will support human and robotic exploration activities during the lunar day and night. This problem is particularly challenging given that the lunar night can last for up to 14 days in the equatorial regions of the Moon, making the exclusive use of solar panels impossible. In response to this challenge, the Lunar Night Survival team designed a modular, multi-faceted power solution and devised a viable mission framework to deliver it to the surface of the Moon. Within the process of developing this power solution, the team has also proposed a novel approach to the governance of lunar power distribution, taking into account existing legal frameworks and potential business models. This work shows creative forward thinking which can be instrumental to the discussion of future Moon activities.

It is with great pride that we that we offer this preface, and we applaud the tireless efforts of all those who contributed to this report. In particular, we acknowledge the incredible team of 35 ISU students from 16 countries who comprised the Lunar Night Survival team. It has been our privilege and pleasure to work with such a talented, motivated, and diverse group comprised of architects, engineers, lawyers, doctors, and business professionals, amongst others. These participants will represent an international network of young space professionals that are well-versed in the challenges of power generation and distribution in support of lunar activities. As a result, they will be ready to participate in, and contribute to, future lunar activities in an international setting. We encourage policy makers, industry leaders, and the public to consider what might be accomplished by humanity through the establishment of a permanent presence on the surface of the Moon.

It is our pleasure to offer you this report, anticipating it will represent a valuable addition in the discussion of future Moon exploration, and a way forward for generating and distributing electrical power on the Moon. We trust you will enjoy reading this report.

Project Chair	*Associate Project Chair*	*Teaching Assistant*
Rob Postema	Matt Sorgenfrei	Antonio Martelo Gómez
European Space Agency (ESA)	NASA Ames Research Center	German Aerospace Institute (DLR)

Participant Preface

As Eugene Cernan, the last astronaut to step foot on the Moon, climbed the ladder to return to Earth with Apollo 17 before Christmas 1972, he paused and said:

"As I take man's last step from the surface, back home for some time to come, I'd like to say what I believe history will record: that America's challenge of today has forged man's destiny of tomorrow. We leave as we came and, God willing, shall return, with peace and hope for all mankind."

Forty-six years later, our ISU SSP 2018 Team Project "Lunar Night Survival" presents a power solution to support this destiny: our return to the Moon.

The recent Global Exploration Roadmap (GER) establishes the vision of the Moon as a hub to support scientific research, technology, business, mining, tourism, and future missions to Mars.

In this context we have, with the support of our Chairs from ESA and NASA, developed a multi-source power solution – our "Power Cell" – to provide continuity of energy supply throughout the lunar night. This capability is critical to enable a sustainable human presence on the Moon.

Each Power Cell is designed to be delivered to the lunar surface by integrated autonomous landers, as an interconnected series of Power Cells is scaled-up to create a lunar power grid. This will allow the establishment of an energy distribution model to stimulate the burgeoning New Space sector, while benefiting the world's space agencies.

A pioneering infrastructure project such as this will require broad support from the international community. We have therefore considered how lunar resources can be utilized in a manner that benefits all humankind, reflecting key values from the Outer Space Treaties.

We propose a new international organization: the International Space Power Organization (ISPO) with the dual function of regulating energy on the Moon and providing access to finance. Finally, we see the experience of our team of 35 participants from 16 countries as an example of the international cooperation that the next phase of space exploration will require.

Our way of working, in which every person was first-among-equals, did not inhibit innovation, creativity, or concrete decision-making. On the contrary, we present this report conscious of the extent to which we have not only drawn on the traditional disciplines, but the power of story.

As the last Apollo mission prepared to return to Earth in 1972, the maverick geologist-astronaut Eugene Cernan held a Moon rock up to the camera, explaining that he wished to share it with the countries of the world as a symbol of the peace and harmony to which we might aspire. But the world did not yet know how he intended to leave a more personal mark.

In the hours before returning to Earth, Cernan drove the rover some distance away. There he knelt in the sand and etched his nine-year old daughter Tracy's initials "TDC" in the lunar dust.

Even among the monumental challenge of space exploration, it remains a profoundly human endeavor.

Legacy. Remembrance. Love. Curiosity. A rallying call to the people.

To return to the Moon will undoubtedly unite and inspire the world again.

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List of Acronyms

AC	Alternating current
AI	Artificial Intelligence
ARED	Advanced Resistive Exercise Device
CCO	Current Concepts of Operations
CFR	Compact Fusion Reactor
CHeCS	Crew Health Care System
CLPS	Commercial Lunar Payload Services
CM	Crew-Member
CNSA	Chinese National Space Agency
CO_2	Carbon Dioxide
COPUOS	The Committee on The Peaceful Uses of Outer Space
COSPAR	The Committee on Space Research
CSP	Concentrated Solar Power
DC	Direct current
DLR	German Aerospace Institute
DNA	Deoxyribonucleic Acid
DPR	Disaster Recovery Plan
DRP	Disaster Response Plan
EAC	European Astronaut Center
ECLSS	Environmental Control and Life Support Systems
ESA	European Space Agency
ESM	European Service Module
EVA	Extra-Vehicular Activity
GER	Global Exploration Roadmap
GUI	Graphical User Interface
HPRs	Human Power Requirements
ISECG	International Space Exploration Coordination Group
ISPO	International Space Power Organization
ISRU	In-Situ Resource Utilization
ISS	International Space Station

ISU	International Space University
IT	Information Technology
IWRS	Integrated Water Recovery System
JAXA	Japanese National Aerospace and Space Agency
LEO	Low Earth Orbit
LiOH	Lithium Hydroxide
LOP-G	Lunar Orbital Platform-Gateway
MSK	Musculoskeletal
NASA	National Aeronautics and Space Administration
NPSOS	Principles Relevant to the Use of Nuclear Power Sources in Outer Space
O_2	Oxygen
OECD	The Organization for Economic Co-operation and Development
OSEDBA	Outer Space Energy Development Bank
OSERA	Outer Space Energy Regulatory Authority
OST	Outer Space Treaty
PC	Power Cell
PMS	Power Management System
PV	Photovoltaic
ROSCOMOS	The Roscosmos State Corporation for Space Activities
SLS	Space Launch System
SPDM	Special Purpose Dexterous Manipulator
SPLSS	Spacesuit Portable Life Support System
SPS	Solar Power Satellite
SSP	Space Studies Program
TLI	Trans-Lunar Injection
TP	Team Project
TRL	Technology Readiness Level
UN	United Nations
VO_2	Maximal Oxygen Consumption
Wk	Week
WPT	Wireless Power Transmission

1 Introduction

Spacefaring nations have recently taken up the pursuit of establishing a sustained human presence on the Moon. This interest has been spurred by a desired to use both the surface of the Moon and the general lunar vicinity as a proving ground for exploration to Mars and beyond. To do this, the International Space Exploration Coordination Group (ISECG), an international collaboration of 14 space agencies, has set forth the Global Exploration Roadmap (GER) 2018 to outline the plans for exploration. One of the major goals of the GER is the completion of the Lunar Orbital Platform-Gateway (LOP-G) sometime in the 2020s as a critical stepping stone to support activities on the Moon and beyond (International Space Exploration Coordination Group, 2018).

The European Space Agency (ESA) and the National Aeronautics and Space Association (NASA) have demonstrated a commitment to achieving this goal and that of the GER as evidenced by the programs they are leading or funding. An example of this is the collaboration between NASA and commercial industry regarding the development of the Space Launch System (SLS), a super heavy lift launch vehicle. The SLS will enable the transportation of both crew and cargo to the Moon and beyond (International Space Exploration Coordination Group, 2018). Related to this, ESA and NASA are collaborating on the development of the European Service Module (ESM), which will be an integral part of Orion in transporting astronauts to the Moon. Other ISECG agencies, such as Roscosmos and the Chinese National Space Agency (CNSA), are pursuing complementary technological developments that will contribute to the portfolio of international abilities of all to explore space. Roscosmos has plans to develop and launch a super heavy launch vehicle that will be used to first support lunar robotic missions as a technology verification before transporting crew to the Moon (International Space Exploration Coordination Group, 2018). CNSA has also been developing its Long March 9 rocket to launch a sample return mission from the Moon in the near term and establish a research station in the long term (Foust, 2018).

Many governments are again beginning to place increasing priority on space exploration and charging their space agencies to pursue large scale space projects. This has created an emerging business case within the commercial sector to develop technologies to support these missions. One such commercial entity is Space Exploration Technologies Corporation (SpaceX), that has demonstrated the ability to reuse its first stage rocket boosters multiple times. Their successes have decreased launch costs markedly and taken a step towards making space more affordable and accessible. Blue Origin has also been in development of their new rocket, New Glenn, with the purposeful intent of servicing a Moon base via regular launches of a reusable vehicle. The combined actions of the governmental and commercial space players have created an environment in which both are key stakeholders in the space industry.

The synergy between the private and commercial space industry has led to space agencies prioritizing the need to fund research and development to solve the technical challenges associated with returning to the Moon. These technical challenges arise due to the fundamental differences of the Moon missions from the Apollo program and those being planned for the future. The latter are focused on establishing a long term lunar presence, whereas the Apollo missions were considered as relatively short term expeditions. This shift in focus motivates the need for new technological demonstrations to support a sustained presence, similar to that of the International Space Station (ISS), on the Moon. When we go to the Moon this time we are going to stay, and to do so these technical challenges will need to be addressed.

One such technical issue with establishing a sustained presence on the Moon is the ability to provide continuous power for an extended duration and especially throughout the lunar nights. Our project was framed to provide a power solution that is capable of sustaining a long-term human presence on the Moon. To that end, we have provided a solution to this power generation and distribution problem that will allow for humans to survive anywhere on the Moon for an extended period of time and throughout the lunar nights. In the course of evaluating this problem, we have identified other interdisciplinary areas relating to the legal constraints, business outlook, and implementation of our solution that will impact the feasibility of the power system we are proposing. It is within this vein that our International Space University team project has shown that to truly solve a space problem there is definite value in taking an interdisciplinary approach.

We have addressed the problem we were given by developing a technical power solution that can provide power to support various Moon activities during the lunar nights. To enhance the viability of this solution we have proposed a legal framework and business structure to encourage collaboration between both countries and public and private organizations. We also comment on the deployment of the power solution and the human considerations that will need to be taken into account in order to make this a reality.

Our project is structured as follows:

1. We present a technical solution to meet the power demands of a lunar base, under the following conditions: support up to six astronauts continuously, supply power throughout lunar nights, and scale up as power demands increase.

2. We discuss how international collaborations in space can be regulated in such a way that maintains a collective oversight of all actors and presents a model where all space faring nations and independent organizations can access funding to advance international space priorities.

3. We discuss how the technical solution can be implemented considering the feasibility of the deployment and impact of human factors.

1.1 Project Definition

Vision: Our inspiration is to establish a human presence at multiple locations around the Moon, facilitating the exploration of the rest of our solar system and deeper space beyond.

Mission statement: Create a scalable power generation and distribution system for utilization during lunar days and nights to enable a sustained presence on the Moon.

Project scope and assumptions:

We shall propose a scalable solution for supplying and distributing power during the lunar night.

The solution shall address the early, intermediate, and long-term needs of the power supply system throughout the deployment process and will do so by taking a phased approach to the deployment.

The power supply solution shall enable both near and long-term science research, support and encourage commercial involvement, and support future missions beyond the Moon.

The solution shall support six humans who will be on the lunar surface throughout a full lunar night.

1.2 Lunar Environment

When building towards a sustained human presence on the Moon, we have to consider the lunar environment because it is different from what we are familiar with on Earth. Features such as the lack of atmosphere, different lunar regolith, and variation from how long a typical Earth night and day last present different challenges to implementing long term habitation solutions on the Moon.

On the Moon, there is no atmosphere or magnetic field to shield the lunar surface from radiation. Two types of radiation in particular are hazardous to both humans and electronic equipment: high energy galactic cosmic rays and solar particle events. Galactic cosmic rays are highly energetic particles in background radiation originating from outside the solar system, which constantly bombard the lunar surface. They can damage cellular DNA, increasing the risk of cancer later in life. Solar particle events originate from the sun and are sudden events producing large doses of radiation, posing a more immediate risk of contracting acute radiation sickness. Impact of radiation on equipment can range from reduced efficiency of solar panels due to degradation, to damage to electronics from energetic particles and short circuits from electrostatic charging (Girish and Aranya, 2012; Zacny, 2012).

On Earth, the atmosphere provides a pressurized environment with oxygen and nitrogen that we depend upon for cellular life. The Earth's atmosphere also provides habitable temperatures and protects us from micrometeorites. The temperature of the Moon's surface can vary from approximately -173 °C to +127 °C (Benaroya, 2018) between the lunar night and day, with permanently shadowed craters near the South Pole reaching close to -245°C. This is a challenge for both humans and technology. Due to the lack of atmosphere, there is no convection, and thermal conductivity is low. Heat is therefore primarily transferred by radiation. The large temperature variations can cause significant thermal and mechanical stresses on structures as well as impact electronic components.

Lunar regolith is another element of the lunar environment that provides a novel challenge. As there is no atmosphere or weather to smooth the surface, the Moon is covered by fine dust particles that are extremely irregular and abrasive. In addition, lunar dust is electrostatically charged and adheres to surfaces. It not only affects the functionality of seals and damages equipment, but is also toxic to humans (Heiken, Vaniman and French, 1991).

Lastly, the Moon is tidally locked, which means the same side always faces the Earth, resulting in lunar nights that can last up to two Earth weeks depending on the location. During these periods of darkness, power cannot be generated using photovoltaic solar arrays, and energy supply will have to rely on other means.

2 Surviving the Lunar Night

As we return to the moon to stay, we need to understand the challenges that will be faced and activities to be undertaken to achieve this goal. In this Section, we lay out a scenario for the development of a sustained human presence on the Moon and discuss criteria for potential lunar base locations. Many scientific and technological advances will have to be made to enable a continuous presence, which determines the nature of the activities involved in this endeavor. Eventually, all of the preceding aspects ties into the specification, requirements, and development of our power solution.

2.1 Lunar Science

The Lunar Exploration Roadmap is a document, composed by planetary scientists, engineers and other experts, that outlines a coherent and orchestrated plan for lunar exploration. Several scientific goals were identified as a basis for pursuing a future lunar research station (Lunar Exploration Analysis Group, 2016). These general goals are very similar to the prioritized science concepts and findings listed by the National Research Council (2007) and the opportunities defined by ESA (2015).

Inspired by the Lunar Exploration Roadmap, we list a set of scientific objectives that will be investigated as we return the Moon:

1. Study the dynamic evolution and space weathering of the regolith.
2. Study the stratigraphy, structure, and geological history of the Moon.
3. Study the bedrock geology of the South Pole region.
4. Study the mechanisms by which volatile chemicals form in outer space and their various mechanisms of transport and deposition.
5. Study the effects of the lunar radiation environment and the effect of variable gravity on plants.
6. Investigate the use of regolith as a growth medium for plants.
7. Conduct fundamental research to understand the physiological, biological, and mental effects of the lunar environment on humans.

This research will help all of humankind to better understand our universe, and it will also provide valuable input into our lunar settlement activities.

2.2 Technology Demonstration

To enable a long term human presence on the Moon, humans will continually need life sustaining resources, such as oxygen and water. Technology to gather these resources from local environments is currently being developed and the collection of resources in this method is commonly termed In-Situ Resource Utilization (ISRU). Our power solution needs to provide sufficient power to support the development, verification, and eventual utilization of ISRU technology on the Moon.

A potential candidate for ISRU technology is the production of propellant on the Moon's surface for a reusable lander. As the number of crewed landings on the Moon increase, a reusable lander will be required to make this endeavor economically and logistically feasible. Propellant for a reusable lander will not be produced by ISRU initially, so it will have to be brought from Earth. This is a costly operation to transport fuel, providing an incentive for the rapid development of fuel production capabilities.

Within the scope of our problem, we have defined a scenario, outlined in Section 2.4, in which the ISRU facilities are not yet in place when we first land on the lunar surface. ISRU will have to be demonstrated and developed once humans are already present on the Moon. Completely implementing ISRU from the start of our return to the Moon is not feasible as it is unproven technology. This may lead to high overall costs in the long term as it could require architectural adjustments of the infrastructure that is already in place (Sanders, et al., 2010).

This approach of ISRU development can stimulate the creation of a commercial lunar market. When governments and space agencies take responsibility to confirm the presence of resources and demonstrate they can be mined and processed, the private sector does not have to take the financial risk of investing large amounts of money in technology that has not been adequately demonstrated, and for which the market is not yet known. Construction of a permanent lunar base will create a need for in-situ resource development. The need for infrastructure and a sustained supply of resources could attract industry. This reasoning is also inspired by the sustainability principles of affordability and partnership that are described in the Global Exploration Roadmap (International Space Exploration Coordination Group, 2018).

The technology demonstrations in our scenario will include excavation, transportation, and processing of lunar regolith. Robotic rovers can mine volatiles and water ice from permanently shadowed craters. These technology demonstrations will have a staged approach (Sanders, et al., 2010). First, the critical design factors must be verified, unknowns assessed, and the environmental impacts evaluated and considered. Second, the production rate, reliability, and long-term operations must be demonstrated and validated. Third, the facilities must integrate with other surface assets. Processing can be done in-situ, or material can be excavated and transported to processing facilities, possibly at distant locations in the long term.

To support the mining of lunar regolith, humans will need to be involved in the selection of mining locations on the Moon as rovers are not able to factor in all variables for site selection. Eventually, activities would involve the development of mining infrastructure, large scale mining itself, and the operation and maintenance of the mine and associated processing facilities.

2.3 Preliminary Site Selection

To identify potential base sites on the Moon for both robotic and human explorers, we follow Eckart (2006) and consider the following criteria:

1. Terrain
   Large mountains, tall cliffs, and deep impact craters should be avoided to facilitate safe landings. The Apollo missions targeted sites with slopes that are less than 2° (Li, Guo and Peng, 2015). ESA defines a terrain as hazardous when it is shadowed, has slopes steeper than 15°, and has surface features taller than 50 centimeters (De Rosa, et al., 2012).

2. Lighting conditions
   The orbital period of the Moon around the Earth is approximately 27 days. Some regions at the poles receive almost continuous sunlight during an orbit around the Earth and have lunar nights of approximately 48 hours, compared to 14.75 days at the equator. To enhance the use of solar energy, a base should be located close to areas with long periods of illumination.

3. Thermal constraints
   Caused by varying lighting conditions, temperature variations depend on location. In polar regions, average temperatures are 220 K +/- 10 K, whereas equatorial regions experience temperatures of 254 K +/- 140 K on the near side of the Moon (Heiken, Vaniman and French, 1991). A location with smaller temperature variations would help reduce stresses on any structures, electrical equipment, and thermal control systems.

4. Communications
   The chosen base location must have a reliable and uninterrupted line of communication with the Earth. In polar regions, this may only be possible by establishing a relay satellite constellation in lunar orbit, depending on the specific location.

5. Resource utilization
   The utilization of lunar resources will reduce dependency on receiving supplies and cargo from Earth, and is considered necessary for future visions of a sustained human presence on the Moon. For example, water that is present on the Moon can be used to create oxygen, metals in lunar regolith can be extracted for construction, and helium-3 can potentially be used to generate energy via nuclear fusion.
   The observed abundance of elements differs per region on the Moon: the concentration of hydrogen is higher in the lunar mares on the Earth-facing side of the Moon (Li, Guo and Peng, 2015), permanently shadowed regions at the Moon's South Pole are believed to harbor water ice, and equatorial regions show

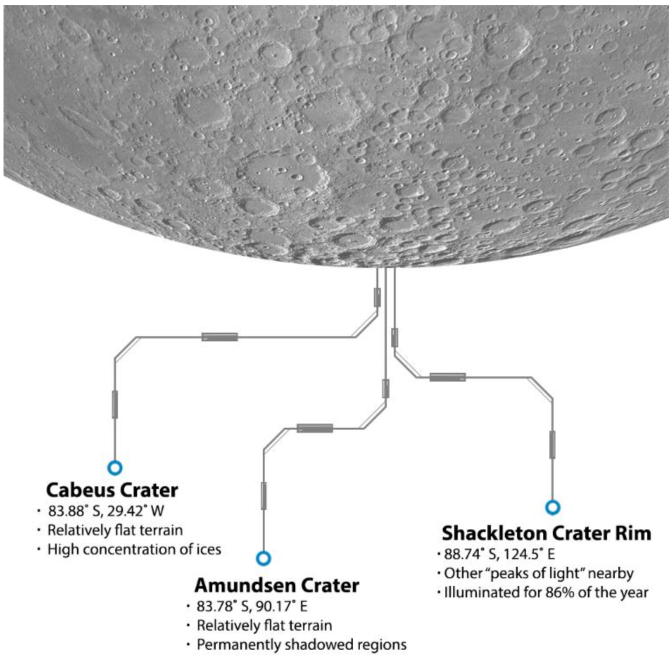


Figure 1 Three potential locations for a lunar base on the South Pole. Data taken from Kring, and Durda, (2012); Byrne, (2005); and Bussey, et al., (2005) respectively

higher concentrations of helium-3 in lunar regolith (Fa and Jin, 2007).

Taking the above considerations into account, and acknowledging that exploration of the South Pole Aitken Basin is a priority of the National Research Council (2007), we have concluded that the South Pole of the Moon will be our target for establishing a base. Using the most up to date data available, and based on our selection criteria, we have identified three potential locations near the South Pole that appear to be the most promising locations. These locations are shown in Figure 1.

We note that despite the shorter lunar night at the South Pole, our power solution must be able to provide power for the duration of the complete lunar nights experienced at the equator.

2.4 Phased Approach

We have divided the establishment of a sustained human presence on the Moon into three consecutive phases (Figure 2). Each phase is defined by the respective activities proposed within them, of which the power requirements must be supported by the power solution. The power required by these activities will continue to increase until it is possible to support tens of people at any given time, working towards the goal of sustaining a long-term human presence. These activities will range from scientific research of the Moon itself, deep space science monitoring, in-situ resource utilization, mining, and successful launching and landing of rockets to an orbiting platform.

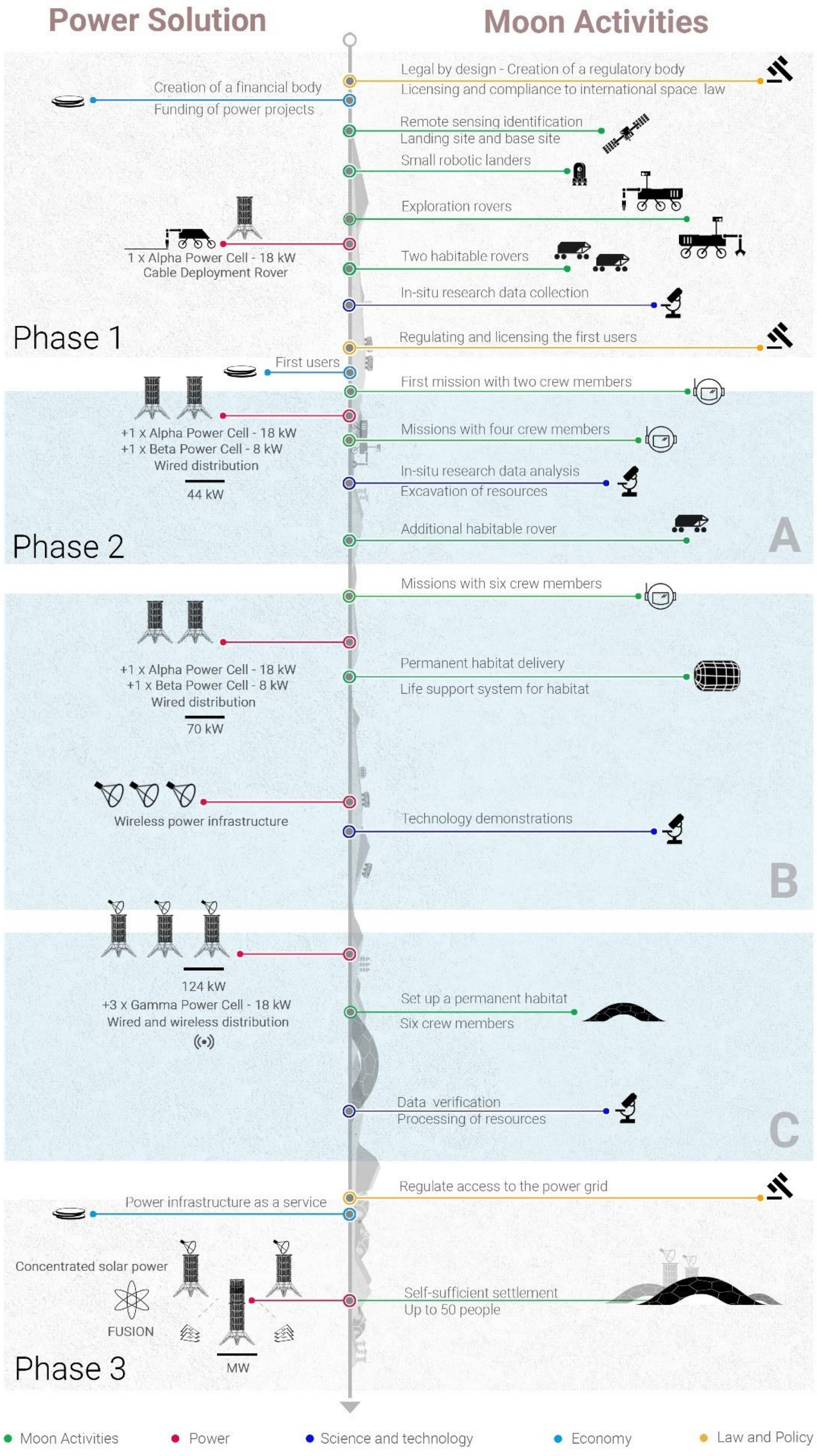


Figure 2: Timeline of deployment activities and power evolution.

2.4.1 Phase 1

In Phase 1, satellites will map the surface of the Moon to identify possible landing sites based on the site selection criteria outlined in Section 2.3. This data will inform where to deploy small robotic landers to take subsurface measurements and determine soil composition. These measurements will enable us to make a recommendation for three landing sites for small robotic rovers, in greater detail than that presented in Figure 1. The rovers will assess the available resources over a larger area, which leads to the selection of the base location. Robotic lander and rover missions can be performed through public-private partnerships, such as the recent NASA call for Commercial Lunar Payload Services and the ESA invitation to tender for commercial in-situ resource utilization mission preparation.

We assume that, during this time, the Lunar Orbital Platform-Gateway (LOP-G) is operational and astronauts will be in lunar orbit for up to six months, conducting science similar to the International Space Station (ISS) science missions.

By the end of Phase 1, two multi-purpose habitable rovers will be delivered directly to the selected site by a separate cargo mission to prepare for the arrival of humans. Each habitable rover can carry two astronauts. We have chosen to deliver two habitable rovers for redundancy. In the event that one rover fails, all four astronauts need to be able to take shelter in the other rover. The rovers are designed in such a way that they can host a total of four astronauts for a short period of time in a contingency incident. This mission design is similar to that outlined in Whitley et al., (2017).

2.4.2 Phase 2

In Phase 2, humans will return to the lunar surface. Eventually, six astronauts will be able to undertake missions from the LOP-G to the Moon, with two support astronauts in orbit. The LOP-G should thus support at least eight astronauts. We acknowledge that this is beyond the currently proposed capacity of the LOP-G, but we view this as a necessary condition to bring humans and materials to the Moon to establish a sustained human presence. This capacity is in line with the current commercial efforts to develop landers by private companies such as Moon Express, Astrobotic and ispace, and previous efforts by NASA to develop a lander that could carry four astronauts (NASA, 2008). We have chronologically divided Phase 2 into three sub phases based on the activities that will be performed on the Moon.

2.4.3 Phase 2A

Phase 2A starts with the first crewed landing at the same location as the two multi-purpose habitable rovers that were already delivered in Phase 1. This will be performed by two astronauts as a risk mitigation measure. The astronauts will check out and set up both rovers. If necessary, they will be able to live in the ascent lander for three to four days (Whitley, et al., 2017). When both habitable rovers are operational, crews of four astronauts will be able to perform short duration missions to the lunar surface during the lunar day. A third habitable rover will arrive at the end of Phase 2A, which will enable two additional astronauts to travel to the lunar surface once it is made operational. Future missions will now have a total crew size of six astronauts which defines the start of Phase 2B.

2.4.4 Phase 2B

In Phase 2B, a permanent habitat for up to six astronauts will be delivered to the landing site by a separate cargo mission. During Phase 2B, the astronauts will prepare for the set-up of the permanent habitat. The capacity of the power system must allow the astronauts to survive a lunar night in their habitable rovers. Their missions will be to perform scientific research and test technologies, such as the excavation and processing of resources from lunar soil.

2.4.5 Phase 2C

During Phase 2C the astronauts set up a permanent habitat. As this phase progresses, the power capacity must increase to enable construction and use of facilities for in-situ resource utilization. At the end of Phase 2C astronauts will move into the permanent habitat, and the power supply must support continuous habitation on the surface of the Moon over the course of consecutive lunar nights. Table 1 summarizes the number of habitable assets and astronaut capacity on the Moon in Phase 1 and 2.

Table 1 Summary of the available habitable assets and astronaut capacity in Phase 1 and 2. The permanent habitat is deployed in Phase 2B and set up in Phase 2C

Assets on the Moon	At end of Phase 1	Phase 2A (end)	Phase 2B	Phase 2C
Habitable rovers	2	3	3	3
Astronauts	0	4	6	6
Permanent habitat	-	-	1 (deployment)	1 (initialized)

2.4.6 Phase 3

In Phase 3, we envision that a single habitat will be developed into multiple habitats similar to the ESA Moon village concept. This requires an increase in the power supply from kilowatt to megawatt scale. Landing pads and roads will be constructed to minimize the wear and damage of equipment, and ISRU facilities will be built to limit the need for resupply missions. According to Juhasz (2006), a lunar colony with up to 50 people "engaged in mining and manufacturing activities" requires a power system of 10 MW. The power solution presented in our report could be scaled to meet this requirement.

Eventually we envision a diverse community of public and private organizations working together on the Moon, with the available resources used in different ways to provide business opportunities. Taylor (2009) identified ten lunar markets, most notably water and oxygen, power generation, mining other valuable resources, building habitable infrastructure and facilities, and tourism. The Moon village will grow gradually as an open, international effort. In theory, it could also serve as a staging post for future missions to other planets such as Mars, or international scientific endeavors such as the construction of a radio telescope on the far side of the Moon.

Once the first Moon village has been successfully built, and is fully operational, humanity can expand its presence on the Moon by building multiple villages. Given the loss of power during transmission with current technologies, new Moon villages should be built independently from previous ones as stand-alone, self-sufficient entities. If technological developments allow for power transmission over long distances without large losses, the power systems of different Moon villages can be coupled to create a large-scale lunar power network. Such a network would be a robust way to adapt to local energy supply and demand as different villages would not be experiencing a lunar night simultaneously.

2.5 Strategic Approach to Mission Planning

2.5.1 Key Assumptions

In designing our mission plan, we have made several important assumptions. First, there should be an operational Lunar Orbital Platform-Gateway (LOP-G) at the start of Phase 2. This will be installed and tested extensively, with several astronaut missions that have been used to gather further landing site information. Second, we assume that our base will be in the region of the South Pole of the Moon. This has important implications in designing for Earth launch criteria. Third, we assume that all infrastructure such as rovers that were deployed to study the landing site at the chosen final location are still accessible before the first astronaut landing mission. Finally, we will operate with the intention of taking a cost-conscious approach to ensure feasibility.

2.5.2 Strategic Approach

We have designed our mission considering key strategic aspects including:

1) Acknowledgement of the 2018 Global Exploration Roadmap (GER) (ISECG, 2018), a joint development of space agencies including NASA, ESA, ROSCOMOS, JAXA, and the national agencies of France, Italy, China, India, Korea, Australia and Ukraine, as a foundation stone of our mission.
2) Harnessing the innovative developments in the commercial sector in the US and European industries to support the space supply chain being developed by our stakeholders.
3) Use of launch technology based upon both current availability and pipeline of rockets being developed by innovative commercial space actors such as Blue Origin and SpaceX (Dreyer, 2009).
4) Interoperability of rockets, landers, and components considering future mission support, maintenance, and replacement of parts.
5) Launch site recommendations considering the operational interests of our two key stakeholders, ESA and NASA.
6) Adoption of a rapid deployment approach to the delivery of lunar payloads, minimizing delivery time and cost.
7) Our vision to build-up the power generation capacity from kW to MW levels by the end of Phase 2 through a series of cargo launches to support Phase 3 Moon activities.
8) The need to ensure strategic alignment between a range of stakeholders so that our mission finds broad international support.

9) The legal framework applicable to Launching States.

2.5.3 Stakeholders

We have undertaken a high-level analysis that defines the relationship between our mission objectives and values, and those of key space stakeholders. By undertaking this analysis, we want to understand our stakeholders' values and needs to ensure that their interests are considered (Hauser, 1988).

We have employed the "House of Quality" methodology, which is a tool that helps understanding the importance of a list of values for the stakeholders of a specific project. These values are then prioritized by calculating their scores, the highest of which guide the mission design choices.

In our analysis, the main values were quality, risk, safety, and reliability, which is a typical outcome for a space mission. It is important to note that scalability and outreach are the focus of the mission, as it will build a strong foundation for the future phases.

Table 2: House of Quality analysis.

	Cost	Safety	Feasibility	Quality	Risk	Law	ROI	Reliability	Scientific Value	Technological Innovation	Outreach	State promotion	Scalability	Sustainability	Humanistic value
Public															
Space agency	3	4	3	5	4	5	1	4	4	4	4	4	5	5	4
Governments	4	5	4	4	5	5	3	4	4	4	4	5	4	3	5
Technical Community	4	4	3	4	3	4	1	3	2	5	2	3	4	3	3
Scientific Community	2	5	4	5	4	2	1	4	5	2	4	3	3	2	3
U.N.	1	5	3	3	5	5	1	4	3	2	3	3	4	5	4
Sum	14	23	17	21	21	21	7	19	18	17	17	18	20	18	19
Private															
Mining and develpment companies	5	3	5	3	3	4	5	4	3	4	4	3	5	2	3
Launch and logistic companies	5	3	4	5	4	3	5	5	3	4	4	3	5	2	2
Robotics companies	3	4	4	5	3	4	4	4	4	5	4	3	4	2	2
Banks	4	3	4	3	4	5	5	4	2	3	5	4	4	3	4
Financing entities	5	4	4	3	4	2	4	3	3	3	2	2	2	2	2
Sum	22	17	21	19	18	18	23	20	15	19	19	15	20	11	13
Popular															
Public interest	4	2	3	3	2	2	3	3	4	4	5	5	4	4	5
Universities / Academics	3	3	3	5	4	3	3	4	5	5	4	4	3	3	4
Enrivornmental organisations	4	5	1	5	4	4	1	3	4	3	4	3	2	5	5
Sum	11	10	7	13	10	9	7	10	13	12	13	12	9	12	14
Total	47	**50**	45	**53**	**49**	48	37	**49**	46	48	**49**	45	**49**	41	46

1 = N/A **3 = Neutral** **5 = Important**
2 = Not care **4 = Care**

2.5.4 Mission Risk Management

We have conducted a risk analysis to identify events that might negatively impact the successful delivery of our power solution for the Moon. Risks identified by each sub-group are presented in the Appendix B section of our report. It sets out a mitigation plan, probability of that event happening (0-1), impact of the risk (1-10) on stakeholders achieving the mission objectives and corresponding risk level, which is the multiplication of probability and impact values. There are five different risk levels and their categorization is as following;

Very Low: 0 < Risk Level < 2

Low: 2 < Risk Level < 4

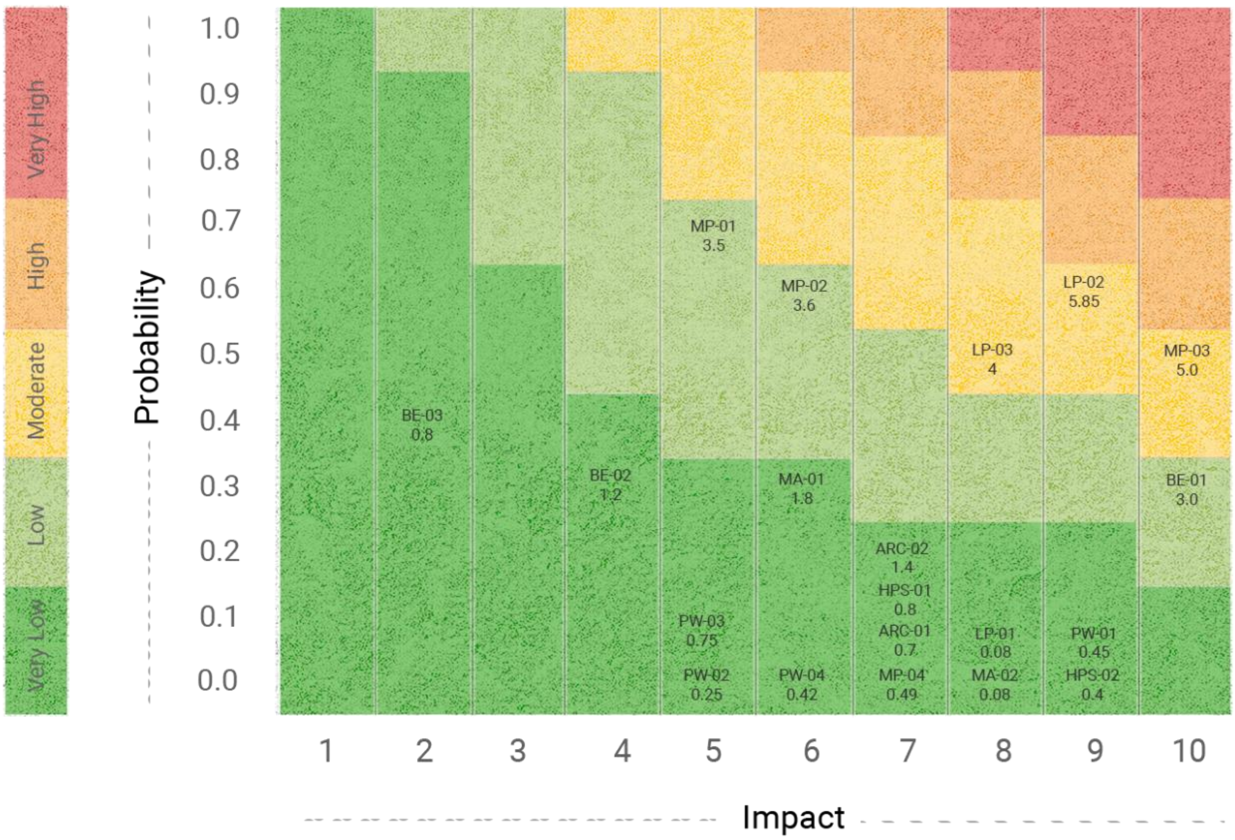
Moderate: 4 < Risk Level < 6

High: 6 < Risk Level < 8

Very High: 8 < Risk Level < 10

Where each risk falls on the risk level matrix is given in Table 3. This gives us an overview of the risk landscape of our whole mission.

Table 3: Risk-level landscape.



2.5.5 Disaster Response Plan

To address some of the key risks identified above that may also result in a catastrophic failure of the power solution, our mission design recommends the development of a disaster recovery plan (DRP).

While the development of a detailed DRP is beyond the scope of this report, we consider it important that this plan documents the processes and procedures that will be followed in the event of a disaster.

First, as our power solution represents critical infrastructure on the Moon, we consider it appropriate to plan for the recovery from any power failure as quickly as possible.

Second, a catastrophic event, such as an explosion during launch or within terrestrial airspace, could have serious consequences. We believe it is important to ensure that a DRP is considered given the use of nuclear energy sources to support our power solution. Key stakeholders including spacefaring nations, international nuclear energy organizations, and the general public will need to be assured that the risks associated with nuclear energy have been mitigated to the greatest extent possible and that a DRP can be activated in the event of any disaster.

Third, the use of nuclear energy on the Moon will require general social acceptance from the public, known as a “social license”. A DRP will assist in ensuring that our mission is not put at risk by public opposition.

2.6 Crew Power Requirements

With the conceptualization of our path to sustained human presence on the Moon, we can quantify how the power supply must scale across the three phases. The requirement to provide reliable and uninterrupted power is the primary motivation for our proposed solution. To facilitate this, we require a well-informed understanding of how much power is needed for activities that may be performed. The requirements are mainly driven by life support systems for the astronauts and leave little room for error. A mistake in calculating the power required by six astronauts could not only compromise the mission but could even lead to loss of life. Here, we discuss human physiological and psychological limitations, what specific challenges must be addressed, exactly what is required to keep astronauts alive, and how much power life support systems need.

2.6.1 Human Physiological Requirements and Power Demands

The fundamental physiological needs of a human, regardless of environment, will remain the same, and are illustrated in Figure 3.

For Phase 2, we assume that resources will be similar to the ISS, where water is limited for hygiene purposes, clothes are not washed, and wet wipes are used for body hygiene. There will be a compact toilet within the pressurized rover. We base the human power requirements on those of the ISS (Anderson, et al., 2015), adapted for a smaller pressurized rover, and summarize them in Table 4. It includes elements that add to those needed for basic survival, such as exercise, a comfortable thermal environment, a health care system, lighting, communications, and adequate amounts of food and water. It differentiates between life within a habitat and a habitable rover, and during a surface exploration extra-vehicular activity (EVA)[1]. The estimated total power need for a two person habitable rover, including EVA is approximately 5.92 kW. This is within the range of 1 to approximately 7 kW for a two person habitat on the Moon found in previous work (Toups and Kennedy, 2008). Each CM could be expected to perform up to 80 hours of EVA per week (Anderson, et al., 2015).

[1] For safety reasons, only one crew-member (CM) per rover would go on EVA at a time.

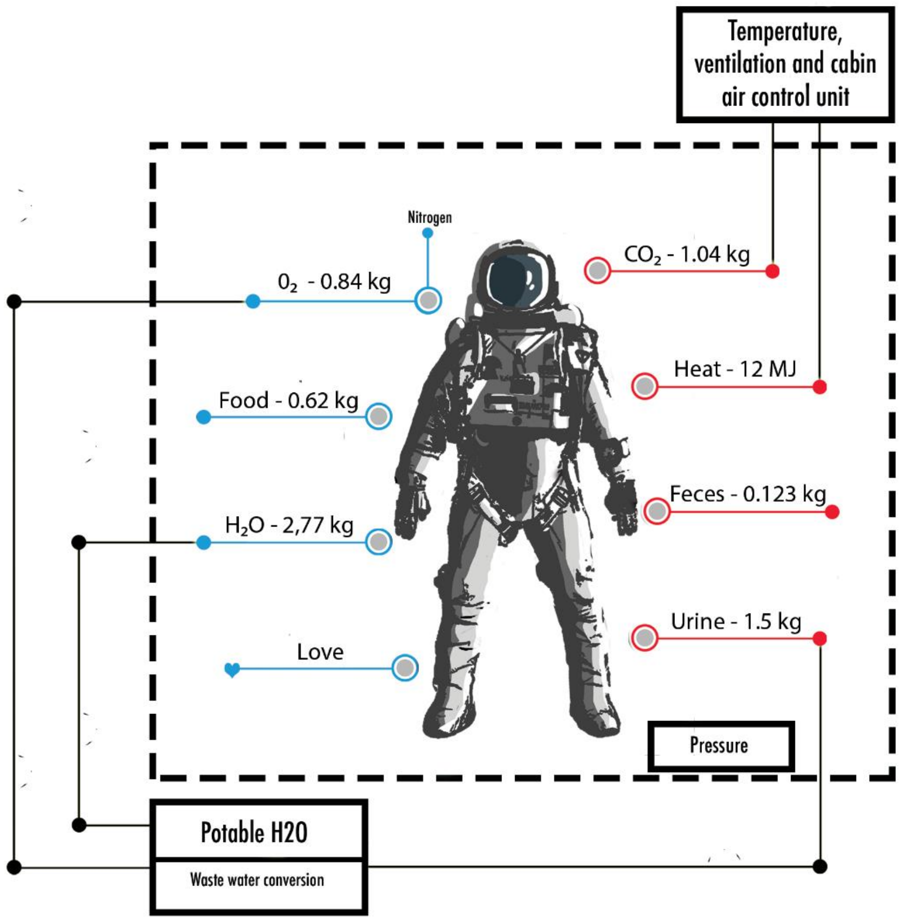


Figure 3: The physiological inputs and outputs for an average 40 year-old male astronaut, 1.92 cm height with a mass of 82 kg, exercising for 30 minutes at 75% of maximal oxygen consumption per day (Anderson, et al., 2015; Jones, 2012).

Table 4: Human power requirements for a habitable rover and for EVA. The reference case is taken from Anderson, et al. (2015), showing the normalized power requirement per CM. EVA values

		Habitat/Rover	EVA	Total	Units
Reference	Normalized	2.88	0.16	3.04	kW/CM
Crew	2	5.76	0.16	5.92	kW
	4	11.52	0.32	11.84	kW
	6	17.28	0.48	17.76	kW

2.6.2 Life Support Systems

The environmental control and life support system (ECLSS) provides the majority of the physiological requirements illustrated in Figure 4. It is fundamental in sustaining human life and is comprised of seven main subsystems for: providing oxygen and water, removing carbon dioxide, maintaining atmospheric pressure, controlling the temperature, managing waste, and monitoring these quantities. Each subsystem has different power requirements (Williams, Dake and Gentry, 2015; Anderson, et al., 2015).

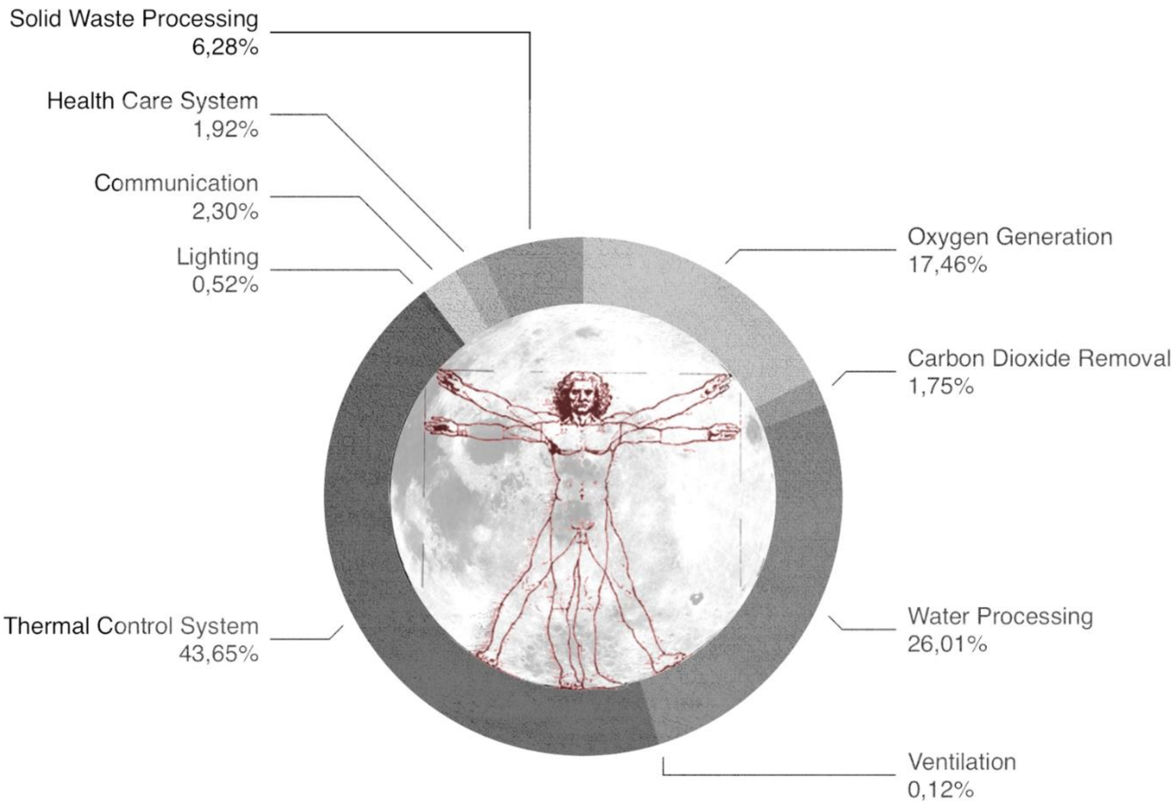


Figure 4: A breakdown of the ECLSS subsystem power requirements, including communication and lighting, to process or recycle natural resources in a habitable rover, occupied by two astronauts. It assumes the ECLSS requires 36 % of the total power (Anderson, et al., 2015).

Table 5: Power requirements to life support systems of a 15m^3 rover for two astronauts.

Resource	Value	Unit	Percentage	Reference
Oxygen	0.28-1.72*	kW	17.46	(Wieland, 1994)
Carbon dioxide removal	100*	W	1.75	(Øi and Kvam, 2014)
Water processing	1.49*	kW	26.01	(Tomes et al., 2007)
Ventilation	6.72*	W	0.12	(Broyan, Welsh and Cady, 2010)
Thermal control system	2.5*	kW	43.65	(Wieland, 1994)
Lighting	30	W	0.52	(NASA Kennedy Space Center, 2008)
Communication	131.6	W	2.30	(NASA, 2007)
Health care system	0.11	kW	1.92	(Anderson et al., 2015)
Solid waste processing	0.274-0.445	kW	6.28	(Fisher and Lee, 2016)

*Calculated from the reference

Oxygen is provided by hydrolyzing water, which could be brought from Earth, or in due time from water extracted from lunar ice at the poles with ISRU technology. Nitrogen is also an important component of inhaled air, but cannot be found on the Moon and must be brought and re-supplied from Earth. The amount of oxygen required per day per crew member is 0.84 kg. This can vary significantly between individuals and also within individuals depending on physical activity, thus a range up to 5 kg per day is given. If it takes 485 J to electrolyze 1 kg of water to oxygen, we can calculate that 0.28 to 1.72 kW is needed to create sufficient amounts of oxygen.

Carbon dioxide (CO_2) is a waste gas exhaled by humans and can have serious detrimental health effects if it accumulates within a living area. There are a number of different way that it can be scrubbed from the atmosphere, such as using passive lithium hydroxide (LiOH) canisters or active amine resin absorption beds. A mixture of both systems are used onboard the ISS (Sadowski, 2006), as well as on submarines; a similar approach should be considered for a return to the Moon. LiOH canisters are simple and reliable, but require frequent replacement and resupply. An amine scrubber is a proven reusable technology to process carbon dioxide requiring 50 W/kg of carbon dioxide scrubbed. Thus, to remove 2.08 kg of CO_2/day, for a 2 person rover, the energy required is calculated to be 100 W. While an amine scrubber is likely to be the primary system, for redundancy, a supply of LiOH canisters should be stored in the event of failure.

Air convection helps prevent a local buildup of carbon dioxide, and will be altered by the effects of partial lunar gravity and the reduced air density of a hypobaric habitat. To ensure adequate mixing of atmospheric contents and to prevent any buildup of carbon dioxide, ventilation must be imposed in the rover by activating fans. On the ISS, two fans are used for a 2.1 m^3 crew quarter (Broyan, Welsh and Cady, 2010) with cabin air at a pressure of 14.7 psia (Anderson et al., 2015). A reduced pressure of 8.2 psia is proposed for the lunar habitat and rover (Norcross, 2013). To introduce a degree of redundancy, it is prudent to plan to double the fans required, 4 fans per 2.1 m^3 Each fan uses 0.84 W (Broyan, Welsh and Cady, 2010), thus eight fans for a two-person rover will require 6.72 W of power.

The Integrated Water Recovery System (IWRS) used onboard the ISS successfully manages its potable and hygiene water supply, waste water, urine water collection, recovery, and disposal. It requires approximately 269.2 W to produce 1 liter of water (Tomes, et al., 2007), and has a 98% efficiency of water recovery (Anderson, et al., 2015). The daily water required per crew member is 2.77 kg, thus the energy needed to produce this can be calculated at 1.49 kW for a two person rover.

The waste management system of the habitat and rover will collect urine and feces, recycle what water it can, and then safely dispose the solid material into a storage facility (Williams, Dake and Gentry, 2015). The heat melt compactor which does this on the ISS requires 0.274-0.445 kW (Fisher and Lee, 2016). During EVA, it is not possible to incorporate such a complicated system into a spacesuit, and biological waste is collected in an absorbency garment, which is then processed on returning to the habitat/rover.

Due to the atmospheric vacuum on the lunar surface, it is essential to provide pressure within the rover, habitat or spacesuit. The pressure must be sufficient enough to drive the inspired oxygen into the lungs, maintaining an adequate partial pressure. It does not need to be equivalent to sea level pressure (14.7 psia with 21% O_2) (Anderson, et al., 2015). In order to facilitate an increase in the number of EVAs that are able to be performed, it is recommended that the habitat pressure be maintained at 8.2 psia and an increased percentage of oxygen (34%) be available (Norcross, et al., 2014).This reduces the hypoxic stress to the equivalent of that at approximately 6,000 ft altitude. By reducing the pressure, the gradient in partial pressure of nitrogen between inside the habitat and the pressure in the spacesuit is reduced. This has the benefit of subsequently reducing the required pre-breath time and risk of decompression sickness. Further research is still needed on the effect of this reduced pressure environment on food preparation and sleep quality, as well as if any risks are exacerbated when considered with the other lunar environmental factors of partial gravity and increased radiation.

A benefit of a reduced pressure environment is that the use of spacesuit ports is more feasible. However, there is some concern that the suits would degrade quickly if continuously exposed to the corrosive lunar dust. The more traditional and proven method of transitioning between the inside habitat pressure and that of the external vacuum in a spacesuit is to use an airlock. If the airlock is used, this will require energy to capture the air and repressurize it into storage canisters as compressed gas to prevent venting it into the vacuum and wasting a precious resource. It is assumed that an airlock capable of accommodating two astronauts contains 3.7 m^3 of air. To repressurize 90% of the airlock volume of air to storage will take 0.087 kW accounting for a 10% leak (Anderson, et al., 2015). Based on this, if two EVAs are performed every day, the power demand increases to 0.174 kW.

During the lunar night, EVA activity is likely to be curtailed to a minimum for safety reasons as it would be dangerous to explore the rocky terrain in complete darkness. The risks include reduced visibility, falling, damage to the spacesuit, and injury to the astronaut. By the latter stages of Phase 2 external lighting systems may be used to facilitate night time EVAs.

A habitable thermal range is considered to be 18 to 27 °C (Anderson, 2015). To calculate how much energy is required to maintain this thermal range it is first necessary to consider how much heat is radiated from the habitat; in the case of Phase 2, a pressurized rover for two astronauts. Using the Boltzmann equation to describe the transfer of energy across a thermal gradient, we deduce that for a rover with a volume of 15 m^3 and approximate surface area of 36 m^2 with a heat gradient from the highest temperature inside the habitat to the lowest temperature outside (~200 K), the total radiated heat is 2.8 kW. We know that humans themselves produce 12,000 kJ/per CM of heat per day, or 0.14 kW (Anderson, 2015), so if there are no other electrical systems producing heat, then the deficit of 2.5 kW must be made up with electric resistance heaters. This figure can be reduced with the addition of insulating protective shielding material on the habitat. However, it shall be used in these calculations as the worst-case scenario to determine power need calculations.

As human presence becomes established on the lunar surface in larger habitats, as envisioned in Phase 3, energy requirements will subsequently increase. For example, if lunar ice can be hydrolyzed, this could become the main source of oxygen. The amount of water used per person will likely increase to an extra 25 L per day per person, considering hygienic needs and laundry for example (Wieland, 1994). Increasing sustainability by maintaining a greenhouse will also require more water. Thus, the power requirements of permanent habitats strongly depend on the technology that will be used and the number of humans involved.

2.6.3 Life Support System Redundancy

The reliability of any ECLSS is determined by the reliability of each subsystem and the life span of its component parts. In the event of a failure or malfunction of a subsystem, a back-up system should be activated to enable continued operations. Redundancy will increase the time available to astronauts to perform maintenance, and the degree of which should increase with mission duration. However, extra redundant systems and the addition of spare replacement parts must be balanced with space and mass of the overall system (Jones, 2012).

In the event of complete power failure, and if there are no stored resources, for a crew of three astronauts, oxygen levels would drop and carbon dioxide levels would rise to dangerous levels after two days (Jones, 2012). If there is only one water source and it becomes contaminated, a person can survive from 3 to 10 days, although this is highly variable depending on the psychological stressors and environmental conditions (Jones, 2012).

One of the greatest challenges to any ECLSS is lunar dust. The small size of dust particles, its abrasive surface and electrostatic charge may render the ECLSS with all its mechanical components vulnerable to damage. If it is compromised, the air revitalization system may even become contaminated with lunar dust, becoming an active dust spreader rather than a dust eliminator, and posing a serious health risk to inhabitants if inhaled. Effective lunar dust filtration systems require further research. Assuming that lunar ECLSS will have similar functionalities to current ISS systems, the redundancy should be greater than three, so that if a subsystem fails, it can be replaced by other two embedded subsystems of the same type.

The space portable life support system (SPLSS) of the EVA suit is smaller than the ECLSS and is more vulnerable to dust contamination (Khan-Mayberry, 2008; Christoffersen et al., 2008). In addition there is less room for redundancy, therefore, in the event of a failure of the SPLSS, there will be more immediate and severe consequences, such as loss of consumables posing a serious risk to life. Potential mitigation strategies to address the challenge of lunar dust are being developed and include potentially using charged materials to repel the lunar dust (Khan-Mayberry, 2008).

2.6.4 Additional Power Demands: Psychological Countermeasures

Isolation as experienced on the Moon may pose significant psychological stress to astronauts. This can negatively impact motivation and may cause fatigue, somatic complaints, such as insomnia, headaches, digestive problems, as well as attributing to social tensions, affecting team dynamics (Palinkas et al., 1998). On Earth in analogous isolated environments, such as polar scientific stations, similar effects have been observed (Ikegawa et al., 1998). At polar stations, particularly over the winter, with prolonged periods of darkness, mood, sleep, and circadian rhythm are negatively affected (Sandal, Leon and Palinkas, 2006; Pattyn et al., 2018). Lighting can be used to counter the negative psychological effects of long periods of darkness experienced during the lunar night. Simulating the Earth day and night cycle is possible with the Solid-State Lighting Module developed by NASA, which has variable colorimetry (NASA Kennedy Space Center, 2008), requiring 30 W of power per module. Blue-enriched white light could be incorporated to aid in improving sleep quality (Viola et al., 2008).

Maintaining communication with the Earth will also act as a countermeasure to the effects of isolation. It provides astronauts close contact with their friends and family (Morphew, 2001). Further psychological monitoring through audio and video communications can assist supporting medical ground personnel in monitoring their wellbeing (Manzey, 2004).

To prevent musculoskeletal deconditioning as a result of reduced mechanical loading in a partial gravity environment, an exercise program will need to be incorporated into the daily schedule of the astronauts. The duration and exact type of exercise suitable in partial gravity is not currently known. The assumption used here is that 30 minutes (Anderson et al., 2015) of exercise will be performed daily. This is accounted for in the oxygen demand and carbon dioxide produced as a result. The Advanced Resistive Exercise Device (ARED) aboard the ISS requires 100 W in continuous operation, and 200 W at peak power (Burkhart, 2018). It is important to note that these are the requirements for the ISS, and a lighter and smaller version of such a device is expected to be present inside the rover, where free space is limited, but we have used it as a reference value for our calculations as a worst case scenario for power demands. Bulkier ARED devices are likely to be incorporated into an established habitat, when space and energy is far more of a commodity.

Exercise has many additional benefits: improving mental well-being of astronauts (Suedfeld, et al., 2016), increasing motivation, and aiding team cohesion (Feltz et al., 2016), which can optimize crew performance on a lunar mission. The benefits of exercise must be weighed against the increased stress placed on the ECLSS, by increasing oxygen consumption, and increasing production of carbon dioxide and heat.

2.7 Total Power Budget

Based on the scenario presented in Section 2.4 and the human requirements presented above, we provide a conservative estimate for the total amount of required power per (sub-) phase in Table 6. The numbers for the habitable rovers, extra-vehicular activity, and habitat are based on Table 4 in Section 2.6.1., assuming 6 kW per two crew members for life support systems and 1 kW for locomotion per rover (Landgraf, 2018). The numbers for science and technology are based on values for an excavation rover (maximum power of 500 W) and Oxygen production demonstrator (1.6 kW) (Sanders, 2018). We assume the amount of activities, and therefore the power operations, will double as we progress into each consecutive phase. We conservatively reserve 50% of the power budget for contingencies.

Table 6: Conservative estimate for the amount of power required per sub-phase. Power operations is the consumption by the power system itself. Science and technology refers to robotic rovers and demonstrators.

Phase	1	2A	2B	2C
Permanent habitat	0	0	0	18
Habitable rovers (kW)	0	14	21	21
Extra-vehicular activity (kW)	0	0.7	1	1
Science and technology (kW)	1	2	4	8
Power operations (kW)	0.5	1	2	4
50% safety contingency (kW)	0.8	8.9	14	26
Total required power (kW)	2.3	26.6	42	78

3 The Power Cell

Surviving lunar nights depends heavily upon a reliable power generation, storage, and distribution system. We have chosen an approach that is rapidly deployable, meets all legal obligations, and is safe for human interaction. Our power system is scalable, with the intention that it can be easily augmented to meet the varying power demands imposed by a lunar base. The total power required for our scenario was identified in Section 2. Our Power Cell will be designed to meet these power demands.

3.1 Power System

Human performance factors and lunar activities are the primary inputs into lunar base power demands. Since our goal is to supply power for six astronauts to survive lunar nights of between 2 to 14 Earth days, the power system cannot rely exclusively upon the Sun. Different means of power generation and energy storage must also be included in case of an emergency. A power management system that can seamlessly provide power to different users with minimal labor is required for scaling the base to meet future energy consumption demands.

3.1.1 Power system deployment

Each phase of the lunar base has its own power requirements that depend upon the defined activities for that phase, see Table 6 in Section 2.7. The ability to sustain a continuous human presence on the Moon will occur by the end of Phase 2, with a gradual increase in power generation throughout the phase toward a 100 kW capacity. This will lay the groundwork for deploying future megawatt-capable systems in Phase 3. As such, we have developed our foundational Power Cell architecture by the end of Phase 2. By Phase 3, we anticipate other emerging power technologies to become feasible, and have identified potential solutions in the corresponding section with a summary in Section 3.3.3.

3.1.1.1 Power Generation and storage system design

Our proposed solution for the power architecture is comprised of the *Power Cell*, which contains a collection of *subunits*. Subunits are individual components of a cell that have a different function ranging from power generation or storage to overall cell monitoring and control. A Power Cell is a combination of four subunits with complementary functions Figure 5. Their architecture is designed to be a complete unit that can land and be commissioned in place.

Physically, subunits are 2.5 m diameter cylinders with a height of 1 m, and cells are composed of up to four subunits. Each subunit is externally identical, but their contents differ depending on the subunit function. Subunits all share a standardized design and can be individually replaced or upgraded, simplifying the supply chain. There are three different types of cells – Alpha, Beta, and Gamma – each comprised of a different combination of subunits. All three types have four 20 m^2 deployable solar cells located on the top subunit. Table 7 summarizes the makeup of the different types. Figure 6 shows a physical diagram of the cell, and Figure 7 shows a functional diagram of the complete system.

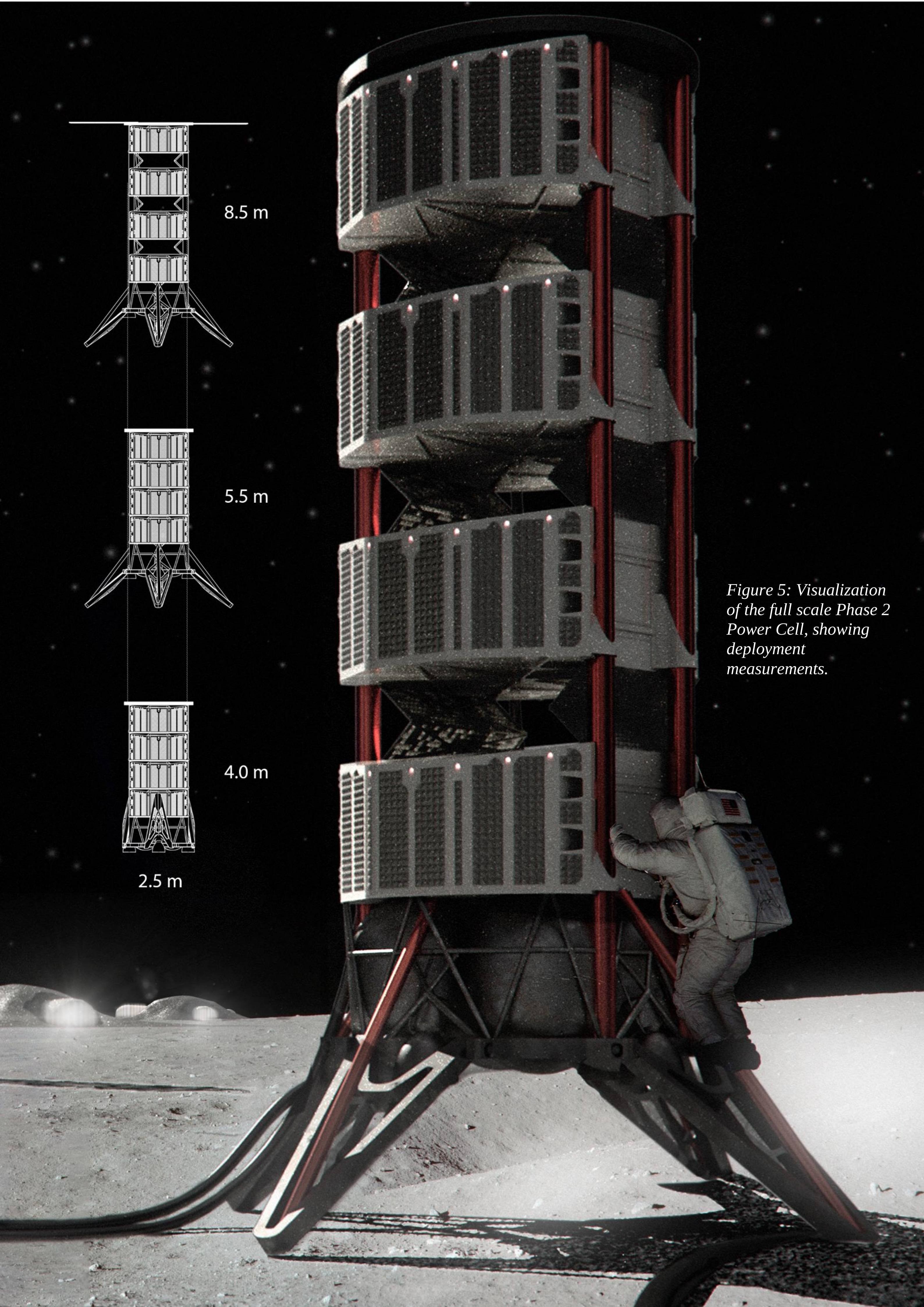


Figure 5: Visualization of the full scale Phase 2 Power Cell, showing deployment measurements.

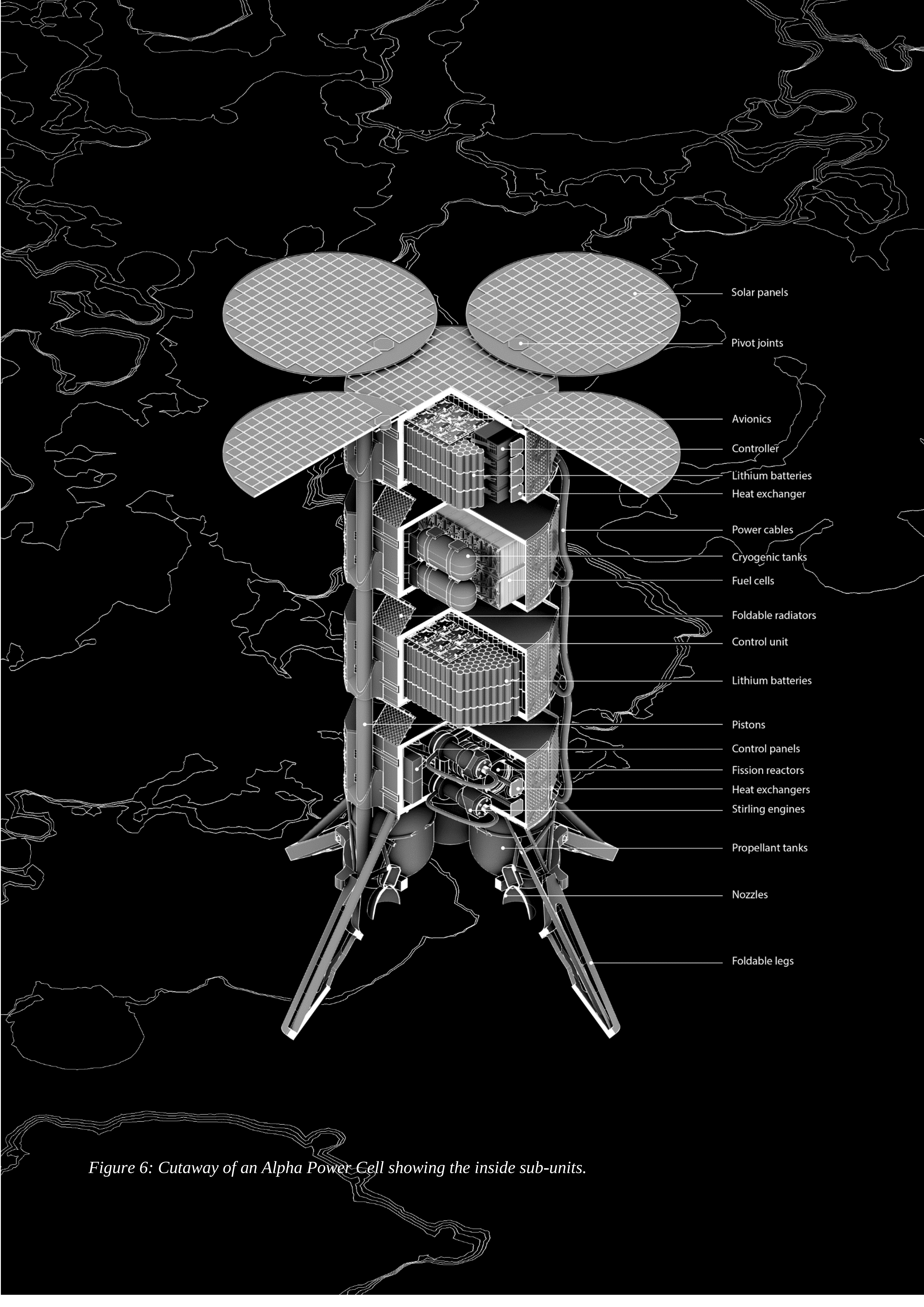


Figure 6: Cutaway of an Alpha Power Cell showing the inside sub-units.

Table 7: Description of Alpha, Beta, and Gamma cells.

Cell Type	Subunit 1 (Bottom)	Subunit 2	Subunit 3	Subunit 4	Power Output	Energy Storage Capacity
Alpha	Nuclear Stirling (Kilopower)	Batteries	Fuel Cells	Batteries and Control Circuitry	18 kW (nuclear + solar)	2,552 kWh
Beta	Batteries	Batteries	Fuel Cells	Batteries and Control Circuitry	8 kW (solar)	2,652 kWh
Gamma	Nuclear Stirling (Kilopower)	Flywheel	Batteries and Control Circuitry	Wireless Power Transmission	18 kW (nuclear + solar)	3,452 kWh

The cellular architecture for power generation and storage enables the following characteristics of our proposed solution:

Scalability: Power Cells are easily installed to meet the power demand. The architecture is scalable from several kilowatts to hundreds of kilowatts and allows simple integration of new technologies through their modular design.

Redundancy: The basic Power Cell is designed to store enough energy to support critical life support systems throughout a two-week lunar night. Generation and storage subunits all have multiple layers of redundancy with automatic monitoring and control circuitry that require little to no operator intervention.

Flexibility: The subunits within the Power Cells can be easily moved from one location to another through the use of basic forklift-like machinery or even by two-person carry, depending on the specific subunit mass. Their form factor allows for easy inspection, troubleshooting, and decommissioning.

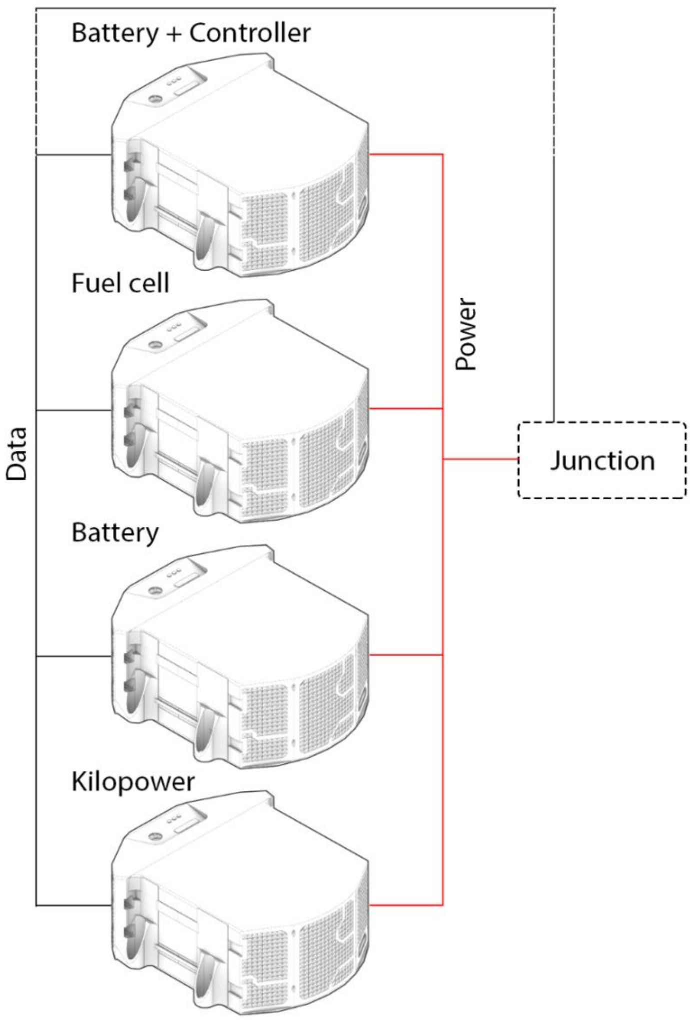


Figure 7: Functional diagram of an Alpha Cell.

Standardization: Each Power Cell and subunit have standard dimensions and design that will optimize manufacturing, the flight qualification process, and supply chain. All electrical and mechanical interfaces between subunits will be standardized for easy integration into the grid, regardless of the subunit content.

Rapid deployment: Power Cells require no assembly on the lunar surface and are commissionable at any location they are delivered to. A complete cell mass is approximately 4,500 kg, with subunits ranging in mass from 400 to 2,000 kg. They can begin generating power immediately through remote command.

3.1.1.2 Operation of the Power Cell during a lunar day-night cycle

The Power Cell is designed to operate during both day and night with no interruption. All Power Cells are equipped with a deployable 20 m^2 photovoltaic array that is able to generate up to 8 kW of electrical power during the daytime to meet instantaneous power demands, as well as recharge the on-board batteries and regenerative fuel cells with excess power produced. Each Power Cell has been designed with power storage capacity sufficient to power life support systems for six astronauts for two weeks in a worst-case failure event (that is, loss of all sun-independent power generation capabilities at the beginning of a two-week lunar night cycle). In such an event, all activities will focus on surviving the lunar night, with all non-essential activities being stopped and power being diverted to meet emergency life support and communication requirements exclusively. With our proposed design, this gives an increased power margin closer to the lunar poles due to the shorter nights than at the equator. For Alpha and Gamma Cells, their on-board Kilopower-based reactor is able to continuously generate an additional 10 kW power throughout the night cycle. For Beta Cells, additional batteries are installed in place of the reactor that is present in Alpha and Gamma Cells. Therefore, during the night time, Beta Cells rely only on batteries and fuel cells. The deployment plan for the Power Cells takes into account their relative day and night time power generation capabilities in order to maintain a minimum ratio of night-time power generation capability to on-board energy storage. This allows the system to maintain a nearly constant power output during both day and night while constantly increasing the safety margin as the network is expanded.

3.1.2 Power Cell Generation Technologies

3.1.2.1 Nuclear Stirling Engine

Stirling engines are used to convert heat into mechanical work, enabling the generation of electricity. Kilopower is a nuclear-powered Stirling engine under development by NASA, and is the basis of the main Sun-independent power generation system during Phases 1 and 2. The uranium-235 fueled reactor is designed to produce up to 10 kW of power continuously for approximately 12 years (Mcclure, 2017). Liquid sodium is used to transfer heat from the uranium core to a Stirling engine which converts it into rotational energy to drive an electrical generator. This system requires little to no operator intervention and features a simple start-up mechanism. The reactor provides inherent protection against meltdown through its ability to remove all generated heat via natural circulation of the sodium coolant, radiated out through passive cooling fins. The use of nuclear energy is required by our architecture in order to provide an economically and technically feasible power generation solution in the absence of sunlight.

3.1.2.2 Photovoltaics

Power generation from solar energy is the most common type of in-situ resource utilization. Photovoltaic (PV) solar panels are a space-proven technology and will provide the main supplemental power generation capability for the reactors. They produce electrical energy through the photovoltaic effect, where photons from incident sunlight excite electrons in a semiconductor material (or solar cell) to a higher energy level to induce an electric current. The amount of power generated is highly dependent on the type of PV technology used, and the extent to which it is possible to track the sun. Conventional space-rated solar cells have a conversion efficiency of approximately 30%, which is about twice as much as typical terrestrial solar panels. This is achieved by utilizing several layers of different semiconductor materials with different energy band gaps. This approach ensures that a larger portion of the electromagnetic spectrum from the Sun is captured, thereby converting more energy into electrical power. Ongoing research on this approach is believed to be able to increase the efficiency to 40-50% (Landis, 2016). Assuming the ability to maintain the panels in an orientation perpendicular to the solar rays, a maximum power generation of between 11.6 and 14.5 kW could be expected from a total surface area of 20 m^2.

3.1.3 Power Cell Storage Technologies

3.1.3.1 Fuel Cells

Fuel cells are devices that are able to produce electrical power from stored chemical energy. They are the primary energy storage system that will be included in the cellular design system. They are sized to a storage capacity of 2,352 kWh within each Power Cell, which is enough to power the life support systems for the longest possible two-week lunar night.

There are many fuel cell technologies. However, our design will use unitized regenerative proton exchange membrane fuel cells (Wang, et al., 2017), which are well established and can operate reversibly in order to recharge. These have a high specific energy of 1.0 kWh/kg, which accounts for both the fuel cells themselves and the cryogenic liquid hydrogen and oxygen that fuel them.

3.1.3.2 Batteries

Batteries will provide a moderate amount of power storage within each Power Cell. They will be used primarily for operating the sensors and controllers that are placed inside the subunits. However, in the event of an emergency, they will serve as a short-term backup source of power. The battery subunit contains 1,000 kg of batteries with a storage capacity of 100 kWh, enough to keep the life support systems operational for 14 hours. This period will give the astronauts time to repair the power system with the support of the Lunar Orbital Platform-Gateway (LOP-G), evacuate, or be rescued.

There are several battery technologies that may be candidates for our solution. We have employed the lithium nickel cobalt oxide (Surampudi, et al., 2017) batteries because they have a high technology readiness level, a reasonable operating temperature, and the best specific energy (100 Wh/kg) of the available options.

3.1.3.3 Flywheels

Flywheels are devices that store rotational energy through the spinning of a rotor, which can be converted to electricity on demand. They are essentially mechanical batteries with an extremely high specific energy of approximately 100 Wh/kg, and are capable of rapidly being charged to their maximum capacities within minutes. High specific energy flywheels require advanced materials and manufacturing techniques including carbon-fiber and magnetic bearings. Compact, flight-qualified versions are expected to be available by the latter phases of the project.

3.1.4 Power Distribution

Power distribution is a critical element in the power solution, which ensures that sufficient and continuous power is provided in a controlled manner for all planned activities on the Moon. The distribution system must support activities carried out during the lunar day/night cycle, and be resilient to associated environmental variations. Design of a power distribution system must consider the power supply, the supply path and the power consumption by the load (equipment and habitat, for example). It must also ensure that appropriate redundancies and fault detection are incorporated within the system.

The power distribution system will support the characteristics of power generation in Section 3.1.1.1 by having the following features:

1. Compatibility: The distribution network will support multiple types of current and future power generation sources. It will provide power at multiple voltage levels, and in both alternating current (AC) and direct current (DC).

2. Continuity: The distribution system will have a redundant network that has a robust fault detection and power management system to provide uninterrupted power in a controlled manner.

3. Expandability: The grid structure used in the network will be expandable to accommodate all power needs of the planned activities throughout the phases, regardless of location.

Several characteristics and technologies must be evaluated when designing an optimal power distribution system suitable for lunar conditions. For our power solution, the distribution architectures considered are AC/DC transmission, high voltage (HV)/low voltage (LV) transmission, wired/wireless transmission, grounded/ungrounded systems, and centralized/decentralized grid systems. The distribution system is designed by evaluating the strengths and weaknesses of each of the characteristics, including the impact of their implementation in the lunar environment, where possible. A detailed comparison of the alternative options for the distribution architectures can be found in Appendix A.

3.1.4.1 Distribution Topology and Transmission Technology

The final power distribution solution is implemented as a decentralized microgrid (Figure 8). This is a localized, distributed network of power cells (that is, power generation and storage) and loads that does not depend on a single power input. The microgrid topology enables the distribution network to operate as an independently controllable unit while minimizing interruptions and instabilities in the power supply at each load (Venkatachary, Prasad and Samikannu, 2017; Rodríguez-Molina, et al., 2014; Lanterovy, 2014). Decentralization of the grid improves system flexibility and enables the ability to provide redundant backup power to the system. (Metcalf, Harty and Robin, 1991; Schirone and Macellari, 2014; Yu, et al, 2013).

The first implementation of the microgrid is seen in Phase 2, with Phase 1 bringing in all support equipment and infrastructure that will be used in the following phase. In the early stages of Phase 2, all transmission will be conducted via wired means. This will progress to include wireless power transmission (WPT) that will augment the wired distribution at the end of Phase 2, in preparation for Phase 3. Microwave beaming is selected as the WPT technology instead of laser because of its relatively higher efficiencies over laser WPT (~45%) (Shreck and Latifi, 2011; Freid, et al., 2008).

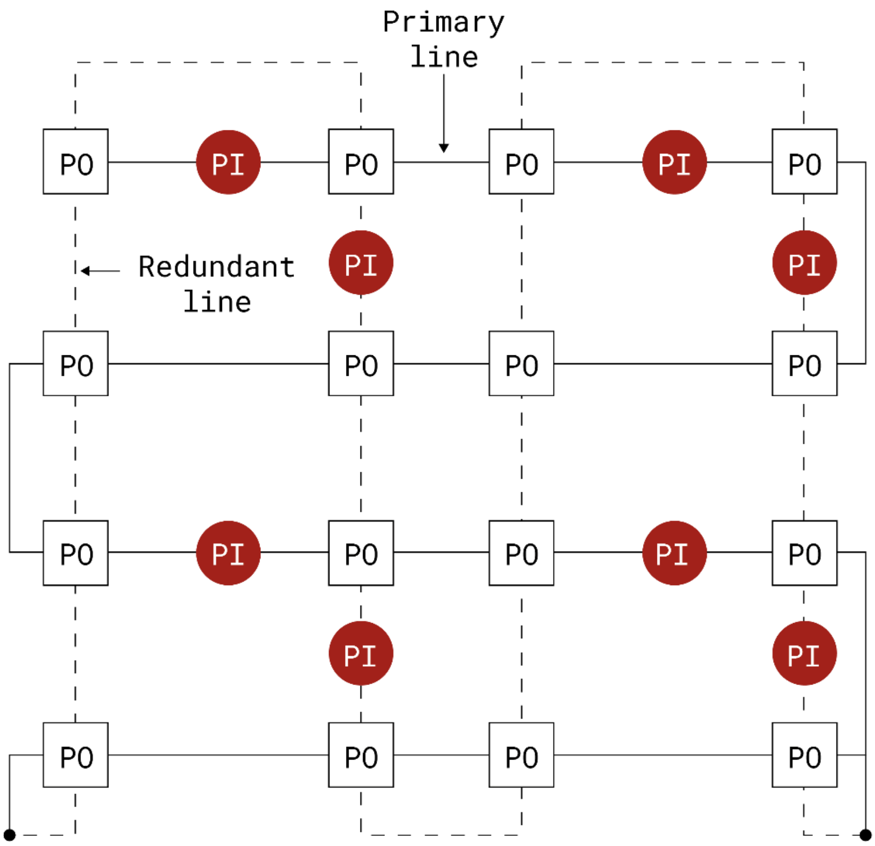


Figure 8: Decentralized microgrid for power distribution. Power input (PI) and Power Output (PO) layout.

The main power will be distributed through a high voltage AC transmission, as considered in the study by Khan, et al. (2006). As suggested in Gordon (2001), the cables in the microgrid network for wired transmission will be deployed both on and under the surface (buried). The wires will be vacuum-insulated coaxial cables having low mass and high resiliency against radiation, while also preventing leakage of the electric field (Gordon, 2001). Buried high power transmission lines generate heat which will not be dissipated by the regolith, thus requiring the re-appearance on the surface. However, these exposed cables may get damaged during planned activities, and may also be a trip hazard to astronauts. Due to this trade-off, a surface/buried combination is implemented, with surface cables being setup where EVAs/activities are expected to be a minimum. Figure 9 illustrates the cable properties required (discussed above) to ensure successful transmission of power on the lunar surface by wired means.

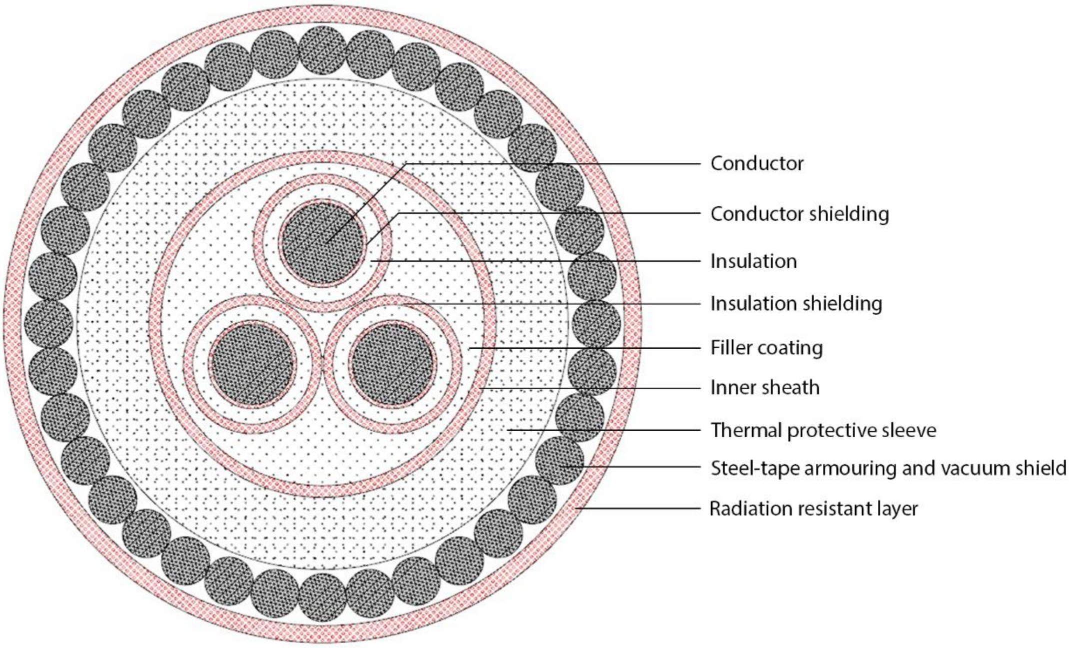


Figure 9: Cross-section of a high voltage transmission cable adapted for the lunar surface.

3.1.4.2 Voltage compatibility

While the network uses AC high voltages during transmission within the grid, the power sources and the equipment consuming the power (the loads) will operate at low voltages in either AC or DC form. Therefore, both up and down conversion of power as well as conversion between AC and DC forms have been added at each interface to the grid as illustrated In Figure 10.

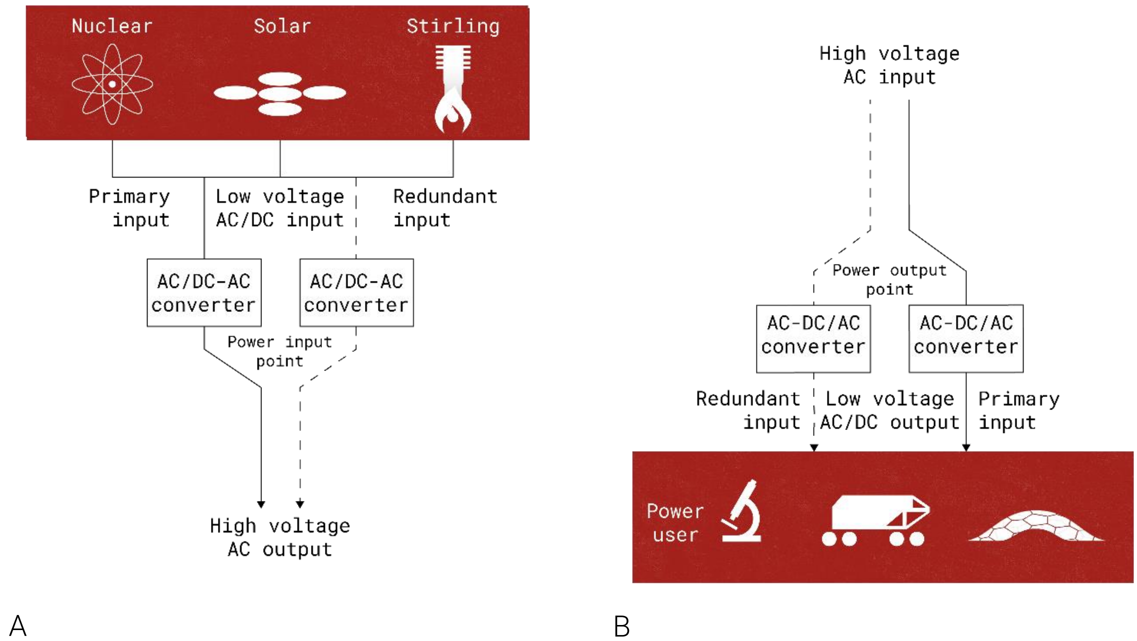


Figure 10: Voltage compatibility at the interfaces of the grid. A: between power generation and the grid. B: between the grid and the loads.

3.1.4.3 Grounding

The power system on the Moon will be ungrounded. This is partly due to the low conductivity of lunar regolith, causing grounding of electrical circuits to become a complex problem on the Moon (Freid, et al, 2008). An ungrounded system is also more resilient to grounding faults and short circuits than a grounded system, as at least two grounding points are required for large fault currents to occur. This means the likelihood of damage to equipment and power interruption is less with an ungrounded system (Bruning and Lusby, 1960). Ungrounded electrical systems can however, have large over-voltages in the event of a fault, which can be hazardous to both astronauts and equipment. This can be mitigated by integrating a neutral ground in the cabling system (Bruning and Lusby, 1960; Gordon 2001), and by adding current, voltage, and temperature monitoring sensors along the cables.

3.2 Power Management

3.2.1 Automated Power Management System

A power management system (PMS), integrated within the control circuitry of the cells themselves, is needed for the safe operation of the overall power system. Current concepts of operations (CONOPS) rely on human oversight and are labor intensive. These concepts should be updated to use advances in artificial intelligence (AI), which is a critical crosscutting technology that improves the performance and reduces risks for a wide range of applications (NASA, 2015). The PMS should be an integrated part of the power system to provide prioritized data during emergencies, monitor for anomalies, predict problems, and provide automatic safety actions when necessary. Temperature, humidity, vibration, resistance, and radiation sensors should all be incorporated to provide the PMS with the data necessary to perform its functions. Estimation of the remaining useful operating time of power system components before and after fault detection is important, together with an integrated graphical user interface (GUI) providing overall system status and diagnostic data. We estimate such a system will consume 500 W for Alpha and Gamma Cells, and 300 W for Beta Cells in our power solution.

3.2.2 Maintenance Plan

The power system architecture is designed to require minimal human oversight, as EVAs are complex and risky activities to perform. The use of advanced sensors and robotics will minimize the number of EVAs for maintenance purposes. The power solution will need to be maintainable both on the system and subsystem level, which ensures that a fault in one component does not compromise the entire power grid system. As our scenario features a system that evolves over progressive phases, it should support extensions and be adaptable to future power distribution and generation requirements.

The maintenance plan consists of:

1. Preventive maintenance where scheduled inspections are carried out to reduce the probability of failure. These inspections will be executed by rovers equipped with cameras and manipulating devices such as Spar Aerospace Ltd.'s Special Purpose Dexterous Manipulator (SPDM). The SPDM includes an end effector with several tools such as pliers, screwdrivers, grippers, hooks, and cutting mechanisms that can be rapidly interchanged according to the maintenance task (Littman, 1994).
2. Predictive maintenance that relies on low-cost sensors to monitor the power system condition performance. Once an abnormal condition or trend is identified, components will be repaired or replaced, ideally before a failure happens.
3. Replacement of damaged components, or those nearing the end of their rated lifetime.
4. Safety stock of critical spares available on site, and the ability to 3D print other spare components on demand.

3.2.3 Disposal Plan

The disposal of power generators, power storage hardware, and power system components will occur at the end of their rated lifetime or when they are irreparably damaged. The management and control of these disposable elements are necessary because of the potential hazards to human health and to the environment. We will minimize the impacts of nuclear and chemical power generators by implementing a robust disposal plan that is compliant with the safety framework addressed by the most recent legal requirements, see Section 4.1.

The disposal plan includes:

1. Transportation of power sources and power storage components to a “graveyard” when they reach their expected lifespan or need to be replaced. The graveyard will be selected to maximize distance within operational constraints and use natural shielding from the landscape if possible.

2. A low-energy sensor-suite for each subunit that monitors the status of the disposed equipment constantly and transmits the information to the control unit of the rovers, habitat, and LOP-G.
3. Documentation specifying the subunit material and component that has been disposed to ensure accountability of those items.
4. Documentation identifying potential impacts to the environment and how to mitigate them (addressed in the risk management plan in Section 2.5.4).

3.3 Power Deployment Plan

3.3.1 Phase 1

During Phase 1, a single Alpha Cell will be delivered to the desired location on the lunar surface, providing 18 kW of power during the day, and 10 kW during the night.

All equipment required to set up a basic power distribution network for early Phase 2 will be delivered to the Moon during this phase. This includes cables for wired transmission, transformers, voltage converters, and other peripheral electronics required to maintain reliable operation. Delivery of equipment will also include cable-laying robots, which can dig into regolith, lay cables, and cover trenches again with regolith. It is assumed that the TRL (Figure 11) of robots for the application of cable-laying on the Moon is greater than six. This is based on under-sea cabling techniques used for telecommunication (Figure 11).

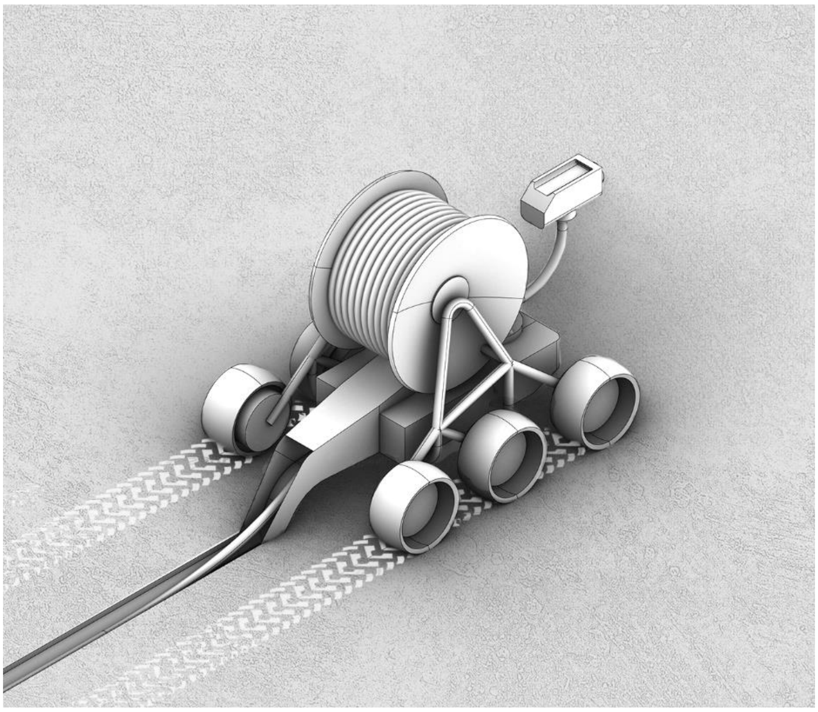


Figure 11: Concept drawing of a rover laying cable in lunar regolith.

3.3.2 Phase 2

As described in Section 2.4, the main elements of our power solution is deployed progressively in Phase 2 through three sub-phases: Phase 2A, 2B and 2C.

3.3.2.1 Phase 2A

During Phase 2A, we will deploy one Alpha Cell and one Beta Cell, bringing the total power generation capability during the day to 44 kW, and 20 kW during the night.

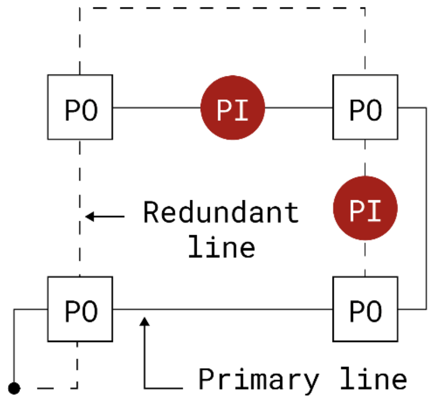


Figure 12: Fundamental unit of the microgrid.

The goal of the power distribution network in this phase is to satisfy the basic power supply need for the operation of two habitable rovers. We achieve this by setting up a 4-output grid, where each grid point is a power output (Figure 12). The grid is connected to two independent power inputs to ensure redundancy. Each input is configurable to accommodate different cell sizes, or a combination of cells. This network will provide power for four different loads at any given time, and will be the fundamental unit in the microgrid design.

3.3.2.2 Phase 2B

During Phase 2B, we will deliver an additional Alpha and Beta Cell to bring the total power generation capability during the day to 70 kW, and to 30 kW during the night. With this addition, we can expand the distribution network to an 8-output grid with four power input points to increase its capacity from that of Phase 2A. The distribution network now becomes a cluster that is composed of multiple grid units (Figure 13). This enables power distribution to support the increased presence on the Moon and related increase in activities planned for this phase as described in Section 2.4.4.

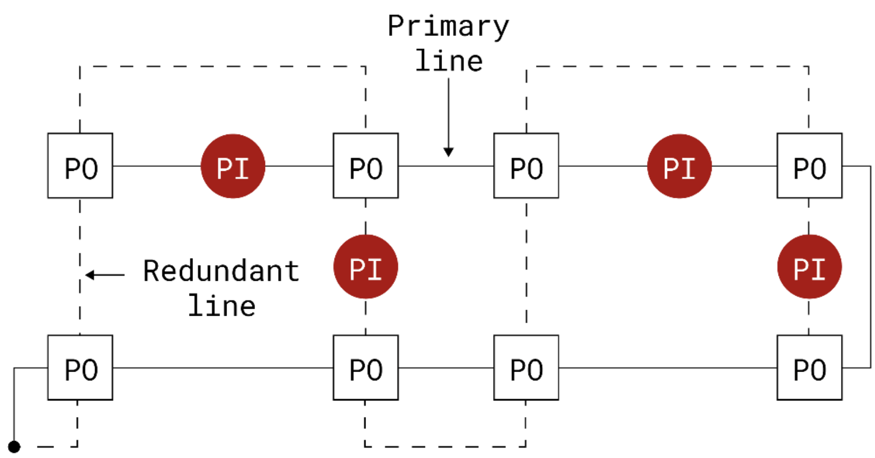


Figure 13: Expansion of the microgrid to a two-unit cluster.

3.3.2.3 Phase 2C

Phase 2 concludes with the delivery of three Gamma Cells, increasing the power generation capability during the daytime to 124 kW, and night to 60 kW, which lays the final foundation for the development of future technologies in Phase 3.

The three Gamma Cells enable the grid to expand up to a 16-output, 8-input grid (Figure 14). During this phase, the power is transmitted by both wired and wireless means, in preparation for the increased power distribution demands in Phase 3. Wireless transmission implemented in Phase 2C allows distribution of power over medium distances (~2-5km) without the need for setting up cabling and the voltage losses associated with wired transmission (Freid, et al., 2008). This is particularly important in areas where the laying out of cables may be difficult, such as over uneven surfaces having strong temperature variations. Current technology at TRL ~6 indicates that wireless transmission of power on the Moon can provide ~10 kW over a range of 2 km with microwave beaming (Freid et al., 2008). This means that we can integrate this technology into the wired grid, to allow expansion of human exploration at distances away from the habitat. In Phase 2c, we assume this distance to be 2-5 km.

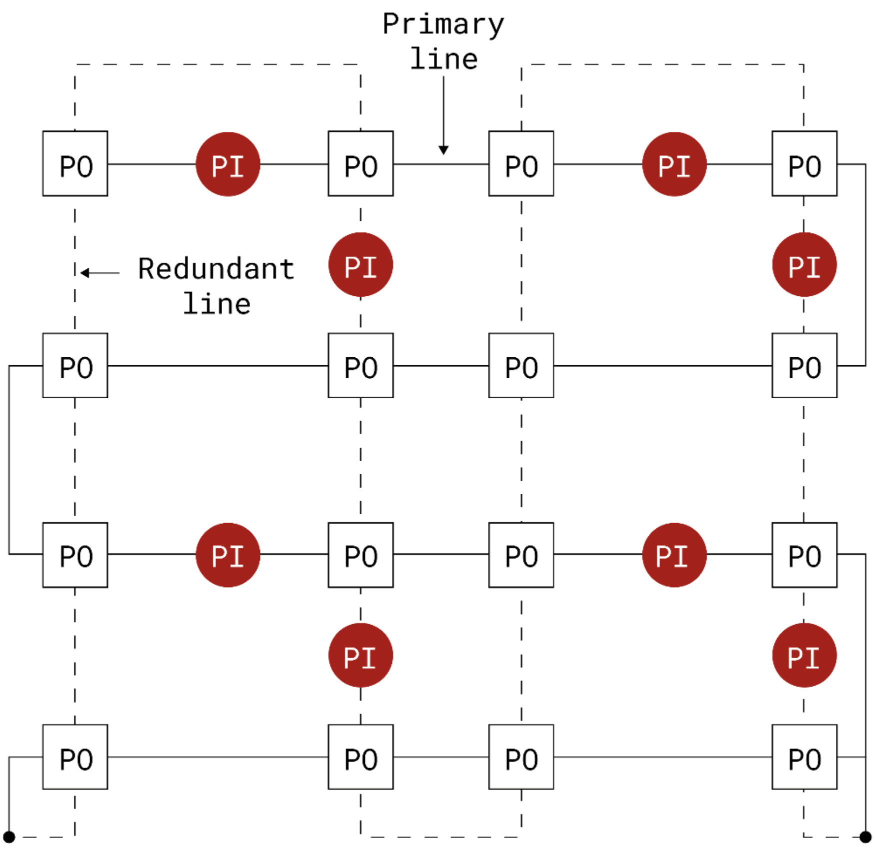


Figure 14: Illustration of a 16-output, 8-input microgrid.

3.3.3 Phase 3

As the number of Moon villages grows in Phase 3, so do the power needs, which we anticipate to be on the order of megawatts. While our proposed power solution is capable of scaling up to meet these requirements, we expect the integration of newer technologies to provide more efficient options. This includes in-situ resource utilization (ISRU) of materials, and more wide scale use of sunlight on the Moon for energy installations, generation, and storage.

In Phase 3, wireless technology is expected to mature to allow transmission over long distances of around 100 km. This would support the expansion of the grid as more Power Cells are added, and may even evolve into including higher capacity power generation technologies such as those discussed below.

We have identified the following emerging technologies for power generation and distribution that have the potential to reach maturity in Phase 3.

3.3.3.1 Concentrated Solar Power

The abundance of sunlight on the Moon and the availability of natural cold sinks in permanently shadowed craters makes thermally concentrated solar power (CSP) a potentially viable technology for larger scale power generation for a lunar base. CSP involves using heat generated by solar energy to drive a dynamo or alternator that generates electricity. This has been demonstrated on Earth with efficiencies ranging from 25-33% (International Energy Agency, 2014). This technology could be implemented on the Moon, in combination with a heat sink that can store energy through the lunar night. While CSP can produce heat during the lunar day, it will be unable to do so in the absence of sunlight. A sufficiently sized sodium or ceramic medium used as a heat sink could provide heat to a Stirling engine during the lunar night, and also be used for habitat heating without the need to convert it to electricity. We envision this application to be best suited for Phase 3 power generation for habitats with tens to hundreds of people present on the station.

3.3.3.2 Nuclear Fusion

Nuclear fusion has the ability to produce energy at approximately ten times the amount per gram of fuel as fission (Martin, 2006). Lockheed-Martin recently acquired a patent for a Compact Fusion Reactor (CFR) that is 200 cm in length, 100 cm in diameter, has a mass of 20 tons, and produces 1 MW of power with a specific power of 50 W/kg. A larger version producing 200 MW is expected to have a specific power of 1000 W/kg (McGuire and Lockheed Martin Corporation, 2014; McGuire, Font and Qerushi, 2016). Given the estimated abundance of Helium-3 on the Moon, this makes it a potentially viable fuel source for a fusion reactor (Johnson, Swindle and Lucey, 1999; Crawford, 2015) that could spur a shift in Earth’s energy economy, while also enabling higher endurance space exploration missions (Dobransky, 2013). It is difficult to predict when this source of energy could be used economically in a reliable way. Recent breakthroughs generate new hope that this could be accomplished in a reasonable timeframe (Johnson, 2018; Vyas, 2018; The Zeolots, 2018), and thus provide one possible long-term mean of energy production on the Moon during Phase 3.

3.3.3.3 Solar Power Satellite (SPS) Technology

Harvesting solar power on satellites and beaming it to a surface receiver is an emerging technology that can enable wireless power transmission over distances on the order of hundreds of kilometers. Research on this technology estimates power generation on the order of gigawatts, provided a large enough fleet is deployed (Sangster, 2014). The economical sensibility of such a system in the future will be dependent on a number of factors, including reduced lunch costs and better efficiency of photovoltaics and WPT. The main WPT technology considered for SPS is microwave transmission (Sangster, 2014; Sasaki, et al., 2007). Given the low loss of high-power microwave beams (Benford, 2008), this may be a viable option to relay power in-between settlements (via satellites), that could be set up as a back-up to distribute power in the event an entire settlement losses access to its local power system.

3.3.3.4 Electromagnetic Vibration Technology

Wired transmission of power suffers significant losses over long distances, which can limit the expansion of the lunar power distribution network. An emerging technology is the use of electromagnetic induction to convert vibration energy from the Moon's seismic activity into electrical energy. Research has demonstrated that the vibration can be transferred into rotary gears that could drive a generator to produce electricity. Placing such devices inside of transmission cables and collecting the energy produced by lunar seismic activity ("moonquakes") effectively can boost the voltage levels in the cable as power is being transmitted over large distances (Wang, et al., 2018; NASA, 2016). Given that cables are being laid out either under or on the surface, this technology would work to enhance and expand the power distribution system already established across the phases.

As Phase 3 progresses into the long-term, the evolution of human presence must consider the need for multiple habitats and power requirements over hundreds of kilometers. Assuming the above technologies are sufficiently mature by this time, there would be great potential to expand the proposed power distribution network to a large-scale high capacity macro grid that could support sustained human presence on the Moon for a multitude of activities.

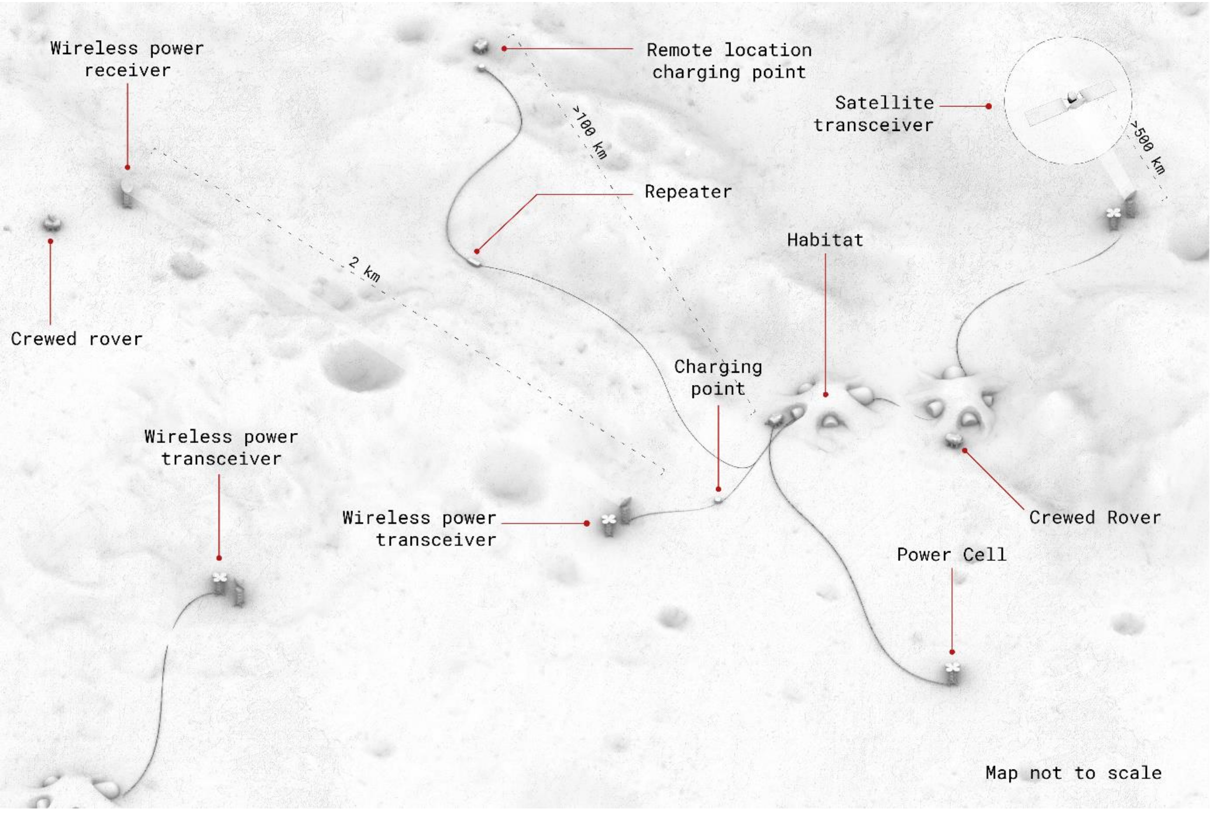


Figure 15: Long-term solution power distribution network on the Moon, for a sustained presence.

4 Legal and Business Challenges and Opportunities

The previous Section has dealt with the technical aspects of the power solution to be deployed on the Moon, allowing humans to survive the lunar night. We now turn to the legal, economic, and business aspects of the proposed solution.

The Outer Space Treaty (OST) (United Nations, 1967) determines the rights and obligations of countries who carry out activities in outer space. Although it has been in existence since 1967 and accommodates different kinds of space activities, there is ambiguity in interpreting its principles in light of the changing nature of activities in space.

Aspects of our proposed solution, such as in-situ resource utilization (ISRU), the use of nuclear power, or the long-term vision of a power grid system open to multiple users, are accompanied by several legal risks and constraints, as well as policy challenges.

The commercial space sector will play a vital role in the future of space exploration. We have therefore taken this into account in our solution. We foresee that in the future there will be a high demand for power to perform activities on the Moon. There will be a market for power, with various types of customers including space organizations, countries, and commercial companies.

In this Section, we address the different challenges and opportunities within our power solution by adopting a legal-by-design approach explained in the next section. We also propose the creation of an international body called the International Space Power Organization (ISPO) to provide access to and regulate the power generation, distribution, and its use on the Moon in an open and equitable way, for the benefit of all. This organization will also enable the financing of the power infrastructure on the Moon by allowing different stakeholders to participate and invest. Further, we address the context in which the lunar market will evolve, and we discuss ways in which businesses and governments can cooperate. We believe that the creation of a self-sufficient lunar economy is based on the availability of energy as a service.

4.1 Legal by Design

4.1.1 Legal-by-Design Way of Working

Law and regulation are often seen as barriers to innovation and progress, as their inflexibility to change is seen to get in the way of new technological developments and their applications. Legal by design is a way of working where the interests and needs of a multidisciplinary team are taken into account from the start to arrive at a solution that has legal protection as well (Hagan, 2018). In this way, the process encourages an action-oriented approach and uses "logic, imagination, intuition and systemic reasoning to create desired outcomes", (Armitage, Cordova and Siegel, 2017).

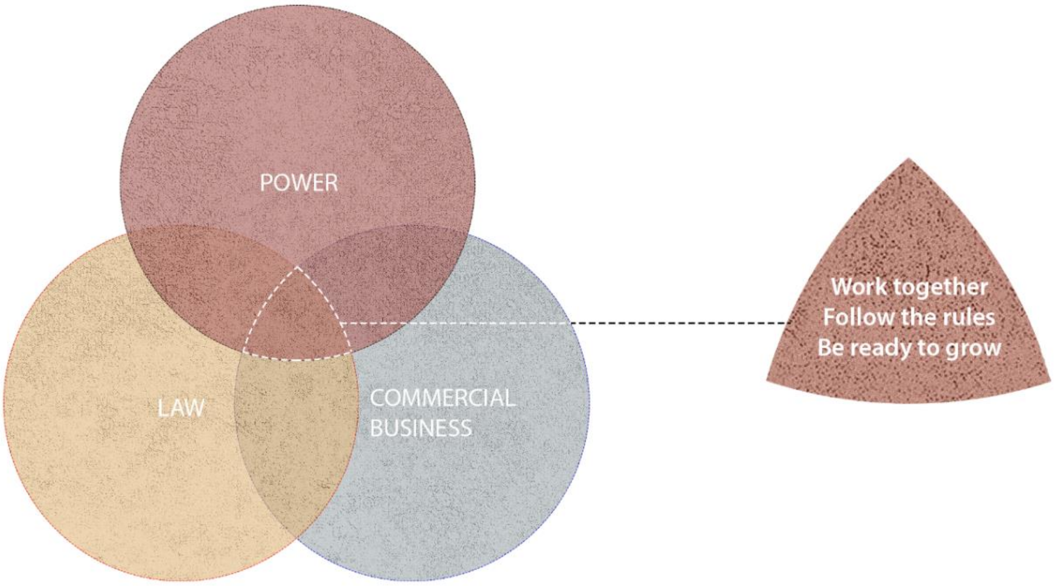


Figure 16: Legal by design.

We have taken a legal design-thinking approach to this project, where the various disciplines, such as power solution, architecture, legal, and commercial aspects, are aligned from the beginning. For example, the use of nuclear energy as a source of power on the Moon may be controversial. However, international law does not prohibit its use for peaceful purposes. The legal design thinking approach is applied in Phase 1 of the project to understand why nuclear energy is chosen as a source of power, how it interfaces with existing law, what modifications need to be made, what economic and policy aspects need to be incorporated, how to convince stakeholders, and many other relevant questions. This approach ensures that the project and its legal framework are dynamic and supportive of each other, resulting in a power solution that is legal by design.

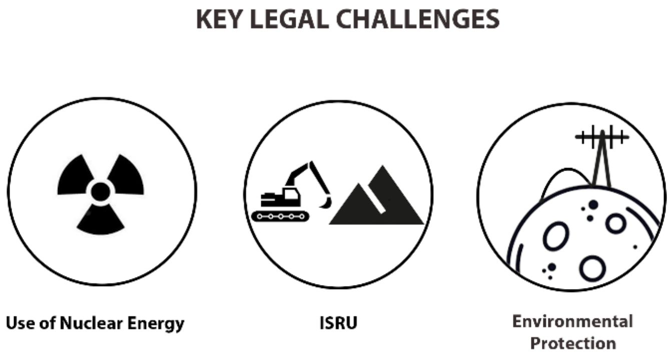


Figure 17: The major legal challenges that we address to be compliant with international law.

The technical and economic challenges to survive the lunar night also present key opportunities at a policy and societal level (Ehrenfreund et al., 2012), such as:

1. Promoting international collaboration.
2. Removing ambiguity in laws to ensure compliance.
3. Providing a scalable power solution that can boost scientific and economic activities on the Moon.
4. Ensuring participation of multiple users, to share the costs and the benefits in long-term activities on the Moon.

The OST forms the baseline reference for the legal considerations in our project. We do not use the Moon Agreement (United Nations, 1979) as it is not widely accepted in the international community. For our project, we are guided by the principles of freedom of exploration and use "for the benefit and in the interest of all countries" (OST Art. I), use of outer space "exclusively for peaceful purposes" (OST Art. IV), "cooperation and mutual assistance" (OST Art. IX), and international environmental law concepts such as the "precautionary principle" and "polluter pays principle" as will be discussed below.

4.1.2 In-Situ Resource Utilization

In-situ resource utilization (ISRU) is important for lunar activities, as it reduces the dependency on Earth's resources. In recent years, the interpretation of OST Art. II which states that "Outer space, including the Moon and other celestial bodies, is not subject to national appropriation by claim of sovereignty, by means of use or occupation, or by any other means," has been debated in light of growing interests for ISRU. Non-appropriation is considered by some as contrary to the freedom of use and exploration in OST Art. I.

The United States of America and Luxembourg have enacted national laws that authorize the commercial use of space resources, which gave rise to much debate. In an attempt to clarify the ambiguity in law, the International Institute of Space Law stated in a position paper that "...in view of the absence of a clear prohibition of the taking of resources in the Outer Space Treaty one can conclude that the use of space resources is permitted." (International Institute of Space Law, 2015)

Further, international guidelines, analogous regimes, and other forms of soft law have proven to be useful to understand how ISRU may be regulated. In our proposal, we take inspiration from the Hague Space Resources Governance Working Group. This group was created to promote international cooperation and proposes building blocks for an ISRU framework (The Hague International Space Resources Governance Working Group, 2017).

The proposed activities in Phase 1 and Phase 2 relate to exploration and scientific investigation. For this reason, we argue that the resource utilization is necessary for lunar night survival. However, it should not be unlimited. Instead, resource utilization must be regulated with regard to both non-appropriation and potential contamination of the lunar environment. We address environmental considerations in the sections below.

In Phase 3 of our mission and beyond, ISRU could occur on a larger scale and be used commercially. There have been many suggestions on how to deal with such exploitation (Lyall and Larsen, 2018), but no proposal has gained significant support to date. In Section 4.2 we propose an international body that will regulate the generation, distribution, and use of power on the Moon, in full accordance with the OST.

4.1.3 Use of Nuclear Power

Using nuclear energy on Earth is controversial, but for applications in space it is often the only viable solution (Lenard, 2001). United Nations' treaties, principles, and resolutions lay the legal groundwork for activities in outer space, including the use of nuclear energy (United Nations, 2017). The OST and the Moon Agreement only forbid the placement and use of nuclear weapons in space, but do not prohibit the use of nuclear power for peaceful purposes. The United Nations Principles Relevant to the Use of Nuclear Power Sources in Outer Space (United Nations, 1992a) requires that nuclear use must be restricted to cases where other power sources are not viable (NPSOS Principle 3).

On the Moon, we cannot just rely on solar energy, as it is not available at all times and at all places. With the current technology, nuclear power is the only alternative to ensure our survival during the lunar nights. Nuclear power is also a good option from an economic standpoint, as its specific power is high, meaning that even a small nuclear power source can provide a substantial amount of power. With uninterrupted power from a nuclear energy source, human activities on the Moon will grow.

The use of nuclear energy carries several risks that need to be mitigated, as described in the NPSOS. Hazards from radiation exposure during launch, orbit, installation, lifetime, and decommissioning must all be addressed. The dangers may affect multiple parties on Earth and the Moon, including humans, infrastructure, and the environment. The risk of contamination to the lunar environment must be minimized (OST Art. IX, discussed in the next section), but also balanced with viable exploration, use, and human safety requirements for power and infrastructure. To address these issues, a risk analysis, safety framework, and mitigation plan must be established before the activities of Phase 1. This is addressed in Section 3.2.3 and Section 2.5.5, as well as in appendix B.

National legislation takes into account how the use of nuclear power is regulated, at the same time, approaches are also developed by intergovernmental agencies such as ESA (Summerer, 2007). The Committee on the Peaceful Uses of Outer Space (COPUOS) has developed a safety framework (UN COPUOS Scientific and Technical Subcommittee and IAEA, 2009), that functions as a guide for actors wishing to pursue the use of nuclear power sources in space. However, the scope of this framework is limited, as it does not deal with protection of humans in space and planetary environments. It focuses instead on the hazards to and on Earth as a result of nuclear power use in space. In such circumstances, we use international environmental law and national legislations on nuclear energy to fill in the gaps.

While it is not easy to create a new law or a treaty on the use of nuclear power in space, it is relatively easy and convenient to have agreements between a small group of stakeholders. We propose that duties and responsibilities concerning the use of nuclear power on the Moon, can be arranged in a contract between the stakeholders of our project, so that a common code of conduct is available. With a robust safety framework, nuclear power may become the energy of choice on the Moon. Applying the legal-by-design approach, we have used legal boundaries as a guide for our missions.

4.1.4 Environmental Protection

Activities on the Moon must be carried out in a manner that does not result in harmful contamination of the lunar environment or have adverse effects on Earth's environment (OST Art. IX). Over the years, the scope of harmful contamination has extended beyond the protection of planetary environment to protection of the general space environment, geomorphological structures, and historically relevant sites on celestial bodies (Williamson, 2010).

The Planetary Protection Policy by the Committee on Space Research (COSPAR) classifies missions depending on their level of contact with Earth or other celestial bodies, requiring different levels of documentation (COSPAR, 2017). Missions to the Moon are classified as Category II missions, which require simple documentation to be shared with the international space science community. This includes creating a planetary protection plan which lays out targets, impact strategies, and mission reports, among other things. Thus, rules for environmental protection of the Moon are less complicated than those for planets and other celestial bodies.

Under these legal circumstances it is necessary to find a balance between protection of the space environment, particularly the Moon, and the exploration and exploitation of that environment. To provide clarity, planetary protection obligations can be incorporated in the contractual arrangements made between the stakeholders in our proposed international body. Establishing collective ownership of a planetary protection policy is a way to ensure that the stakeholders find the balance between environmental protection and exploration of the Moon.

There are many unknowns about the lunar environment and the impact of our activities. Considering this, our proposed regulatory framework will incorporate terrestrial environmental law principles in devising obligations on its stakeholders and users, such as the following principles:

1. Principle 15 of the Rio Declaration (United Nations, 1992b), or "The Precautionary Principle", which states that,

   "In order to protect the environment, the precautionary approach shall be widely applied by States according to their capabilities. Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation."

2. Polluter Pays Principle - This environmental law principle, adopted by OECD countries and many others, proposes taking necessary preventive measures in carrying out various activities that may have adverse impact on the environment. It suggests the establishment of control measures against any harm or degradation of the environment. It also imposes a cost penalty on the polluter, so that others' rights are not hampered.

4.1.5 Geopolitical Challenges

One of the major challenges to the solution we propose is not legal or technical, but geopolitical. Countries and their changing politics have an impact on the interpretation and implementation of international treaties. In recent times, the interpretation of principles such as freedom of use, non-appropriation etc., have been the subject of major geopolitical debates. We have addressed some of these in the previous sections, such as the topic of resource utilization and involvement of commercial partners (UN COPUOS Legal subcommittee, 2018).

When the United States of America and Luxembourg enacted their national laws permitting exploitation of space resources, some countries opposed them as they believed that their right to the freedom of exploration and use of outer space may be harmed. Similarly, when the European Union developed a code of conduct for space activities, it did not invite views from other space-faring nations such as Brazil, China, India, and Russia. At a time when many countries are actively engaged in space, it is necessary to take into consideration many perspectives in order to have a universal character to any new law or policy or business approach in relation to space activities. This will also greatly aid in converging the views of different countries, so that there is easy acceptance of new proposals.

Our proposal, as will be addressed in the next Sections, is aimed at addressing this challenge as best as possible to balance the interests of different countries, and also include the interests of commercial parties. Our legal and financial solution is unique in this sense. Yet, there is the possibility that major space players do not accept the solution, this risk is also addressed in Appendix B. Even if the legal and financial model we propose is not accepted, the existing legal framework for space activities will sufficiently support our power generation and distribution solution.

4.2 International Space Power Organization: ISPO

4.2.1 Inspiration

During the years of legislation of space law, “the main thrust of space activity was science and exploration”; therefore, “the anticipated benefits were an expansion of the scientific knowledge base and spin-off technologies.” (Gal, 1996). To this moment, no initiatives in the space sector related to the challenges addressed above have truly offered a complete solution combining legal and commercial considerations.

At this juncture, where space exploration is leading to its exploitation as well, it is necessary to think about regulatory tools that can support scientific, public, and private interests. The regulatory framework that we propose to create, from Phase 1 onwards, is a contractually established international body called the International Space Power Organization, or ISPO. We envision that this organization and the manner in which it is established will reshape the way public perceives ‘space power’. We need power to support any activity on the Moon, and it is with this power that we can achieve a sustained presence on the Moon and beyond.

ISPO takes a bottom-up approach to regulating power generation, distribution, and its use. Further, it will financially enable the establishment of power infrastructure on the Moon, by way of investments and financial transactions between various stakeholders in the stages after that.

We envision a thriving space economy with diverse players such as governments, institutional investors, private investors, and private business owning different parts of the value chain. A robust power generation and distribution industry can serve multiple users and their different power consumption needs. This model promotes new initiatives based on the availability of key resources and ready-to-use power infrastructure.

4.2.2 Description of the ISPO Framework

According to Stewart Patrick, a strong supporter of the limited agreement or "mini-lateralism" approach, “in order to promote significant global policies, the smallest number of states or countries needed to create the greatest impact on a specific subject should be brought to the table.” (Patrick, 2014). Although the OST still accommodates all envisioned activities in outer space, it is ambiguous when it comes to addressing some questions concerning exploitation, as mentioned earlier in this Section. To amend the law or create a new law is not easy in the present day, as many more space faring nations have a say in shaping policy and framework. Any effort put in this direction will be protracted. As a simple alternative, the ‘mini-lateral’ approach will look into contractual agreements between a relatively smaller number of stakeholders, who will have the most impact on the subject of the agreement.

The International Space Station (ISS) was the result of one such mini-lateral agreement. However, in the ISS model only governmental space agencies were involved. Even among them, only certain agencies played a specialized role.

As space becomes more accessible to all, there will be increased participation not only from several space agencies of developed and developing nations, but also commercial enterprises. As we move from an era of exploration towards exploitation, it becomes necessary to be inclusive.

Our proposal is to get a group of countries, space agencies, and private commercial space and energy companies, to come together to address the regulation of power infrastructure on the Moon. The stakeholders will enter into a contractual agreement that will lay down their duties, rights, and responsibilities, from Phase 1 - setting up the power infrastructure, to Phase 3 - where users can plug in and use the power grid. This international body can grow as the infrastructure and services mature. New stakeholders, such as energy companies and developing space agencies can join, making it a flexible and inclusive framework.

ISPO will be in full compliance with existing international space law and guidelines. That includes the use of nuclear power sources, carrying out activities for the benefit of all humankind, and adopting elements from international environmental law, to provide an integrated setup for conducting power-related activities on the Moon. The stakeholders will be governed by a Board, chosen on a periodic basis to make policy and governing decisions for ISPO. Specific duties concerning projects or missions of the stakeholders will be allocated to Directors. To ensure compliance to international laws, ISPO will also implement verification mechanisms. Any violation of rules will be penalized. ISPO will also have the authority to settle disputes between its stakeholders.

ISPO will consist of two sub-organizations: the Outer Space Energy Regulatory Authority (OSERA), and the Outer Space Energy Development Bank (OSEDBA), to balance the interests of the various stakeholders, and to also clearly demarcate the spheres of activity. Their respective mandates are to provide commercial and legal foundations to promote human expansion into outer space.

Figure 18 illustrates the main interactions between the two International Space Power Organization (ISPO) bodies and their key stakeholders: governments and space agencies, power and mining companies, space companies, and investors.

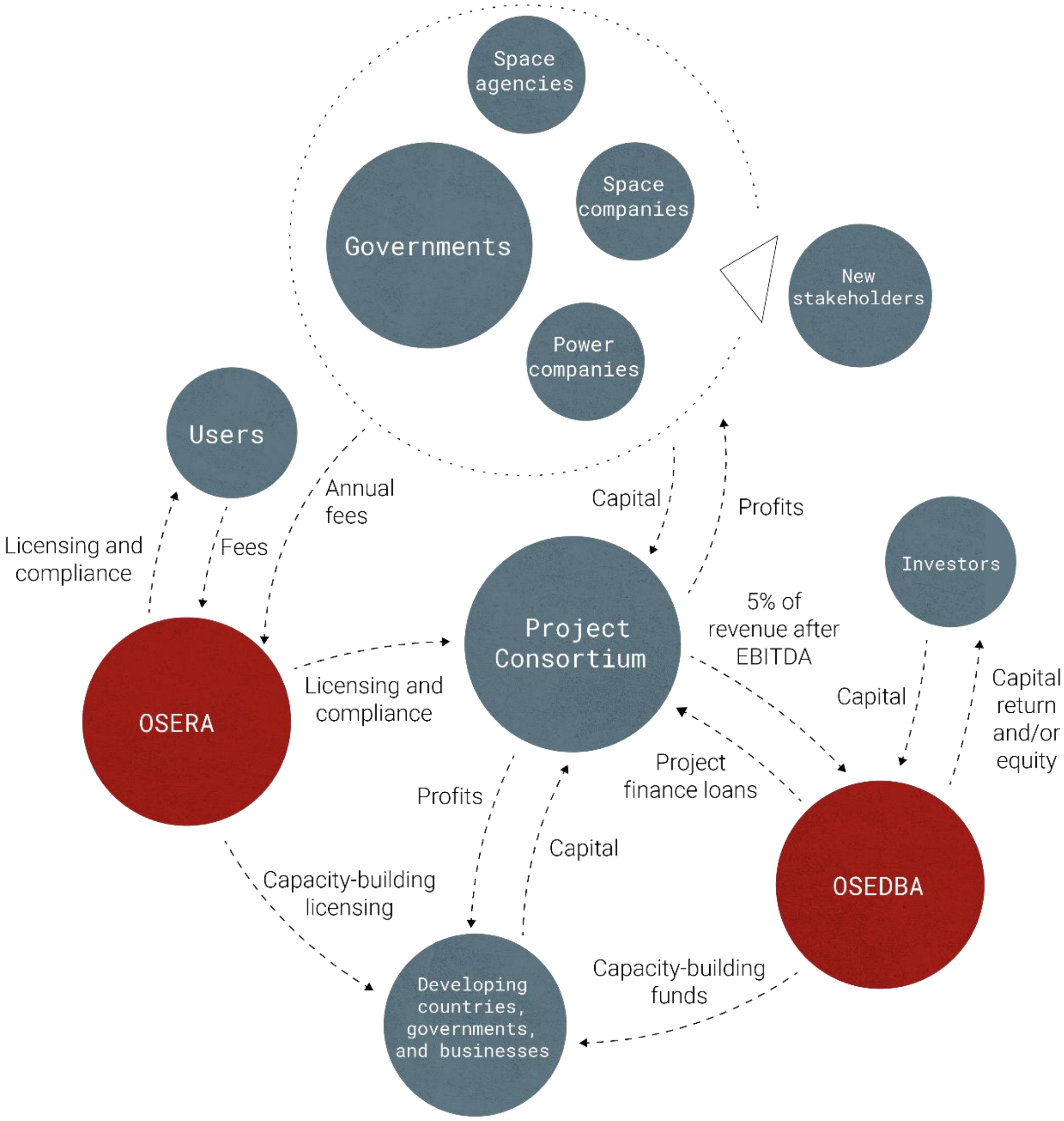


Figure 18: International Space Power Organization (ISPO) and stakeholder interactions.

4.2.3 Regulatory Framework: OSERA

The Outer Space Energy Regulatory Authority (OSERA) will exclusively deal with regulation and administration. We envision a power distribution grid that will serve multiple users. With this in mind, our framework will work on grid-based regulation. The stakeholders of ISPO and external parties can form a project consortium for a specific activity or series of activities. For each mission or project, formed either as an effort of international cooperation or individual national activity, OSERA will identify a Launching State for the purpose of selecting a State that is responsible, liable, and has jurisdiction and control for fulfilling international obligations under the OST. Within the project consortium, the stakeholders will contractually arrange further details such as insurance, liability apportionment, intellectual property distribution, and export control. The contractual agreements have to be in accordance with existing national and international law. As mentioned earlier, ISPO will have verification mechanisms to ensure compliance.

At a more mature stage of power generation and distribution, OSERA will regulate access to power infrastructure, for example landing sites and power grid, through licenses. In Phase 3 when the power infrastructure is available as a service, OSERA will be the licensing authority for users of the grid to ensure that all users comply with international laws as set within the ISPO.

4.2.4 Commercial Framework: OSEDBA

To provide an appropriate structure to facilitate trust and cooperation, the Outer Space Energy Development Bank (OSEDBA) will be modeled after the framework of the International Development Association, one of the key institutes of the World Bank Group. We believe that referencing a reputed framework will offer clarity to stakeholders, which is critical to the success of any large-scale international effort. For this reason, we also suggest that the entity is instituted as a branch body of the World Bank Group specifically dedicated to economic enablement in outer space for the benefit of humankind.

The mandate for the Outer Space Energy Development Bank (OSEDBA) is expressed in four tenets:

1. Promote space-specific project financing for a broad range of investment sources to fund various missions.
2. Allow multiple stakeholders access to funding for research, development, and use.
3. Enable multilateral contractual agreements to establish long-term support for projects.
4. Allocate a portion of revenues towards capacity building funds for developing nations, to boost technological advancement and facilitate their access to space.

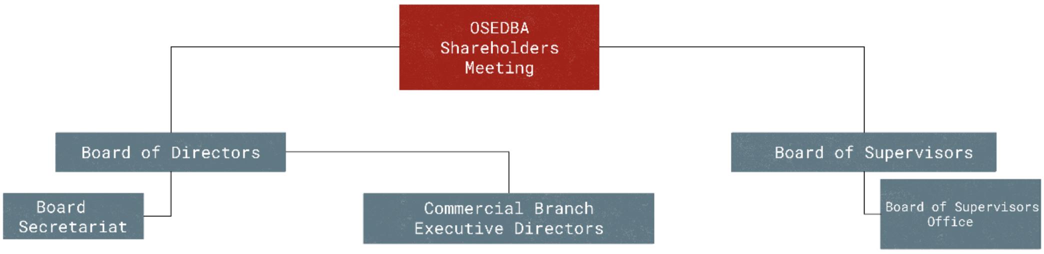


Figure 19: OSEDBA diagram showing the relationship between the influx of investment capital and the manner in which it is conveyed to the various players in the space industry.

We have studied existing organizations, economic models, trends and academic reports, in the process of finding a financial solution. First, we have international financial entities, such as the World Bank, national credit export banks and agencies, venture capital firms for space startups, and the ISS financial model have provided an experience-based perspective. Second, a review of current trends includes space-related investment, such as the Luxembourg government's fund to support and promote the use of space resources (Space Resources - Luxembourg, 2018), as well as terrestrial project financing and distribution business model solutions (Johnson, 2010). Third, other forward-thinking economic models and proposals, such as the space bank (Cahan, Marboe and Roedel, 2016), contributed in-depth analysis of potential concepts. Finally, previous ISU team projects relating to lunar settlement and of ISRU were reviewed for additional input and context.

4.2.5 Stakeholder Benefits

A series of incentives will be established to encourage participation from a wide variety of public and private stakeholders. In the short term, tax benefits offset the cost of contribution to developing infrastructure that provides benefits for all humankind. In addition, the potential to provide access to development funds and issue bonds for major project funding provides a guaranteed return on investment. In the long term, entities that participate in the funding of space-related development retain the benefit of ownership of infrastructure and related revenue sources, which have the potential for significant returns over a long period. This is similar to the incentive given by the government of Luxembourg to promote investment in the space resource utilization industry (Link, 2017).

4.2.6 Commercial Partnership Models

For the purpose of this report, Project Finance refers to a specific type of financing structure that supports the development of long-term infrastructure and industrial projects. These projects are often risky and expensive with few near-term financial benefits for a purely commercial company to undertake. Project debt and equity are used to finance the project, while the debt portion is repaid using the cash flow generated by the operation of the project. This model is commonly used for terrestrial projects that involve a public benefit, and it is similarly suited for the development of space infrastructure (Figure 19 and Figure 25 in the appendix) illustrates an arrangement for project financing of a lunar energy infrastructure project. The upper section of ***Figure 20*** illustrates how OSEDBA acts as a conduit for investment and allows multiple organizations to invest in a way that suits their interests and sensitivities. Simply put, investors will own part of the OSEDBA-financed project portfolio and not individual projects. The bottom portion of the diagram illustrates the ability of the Project Consortium to accommodate various types of stakeholders and investors using a model similar to the International Space Station.

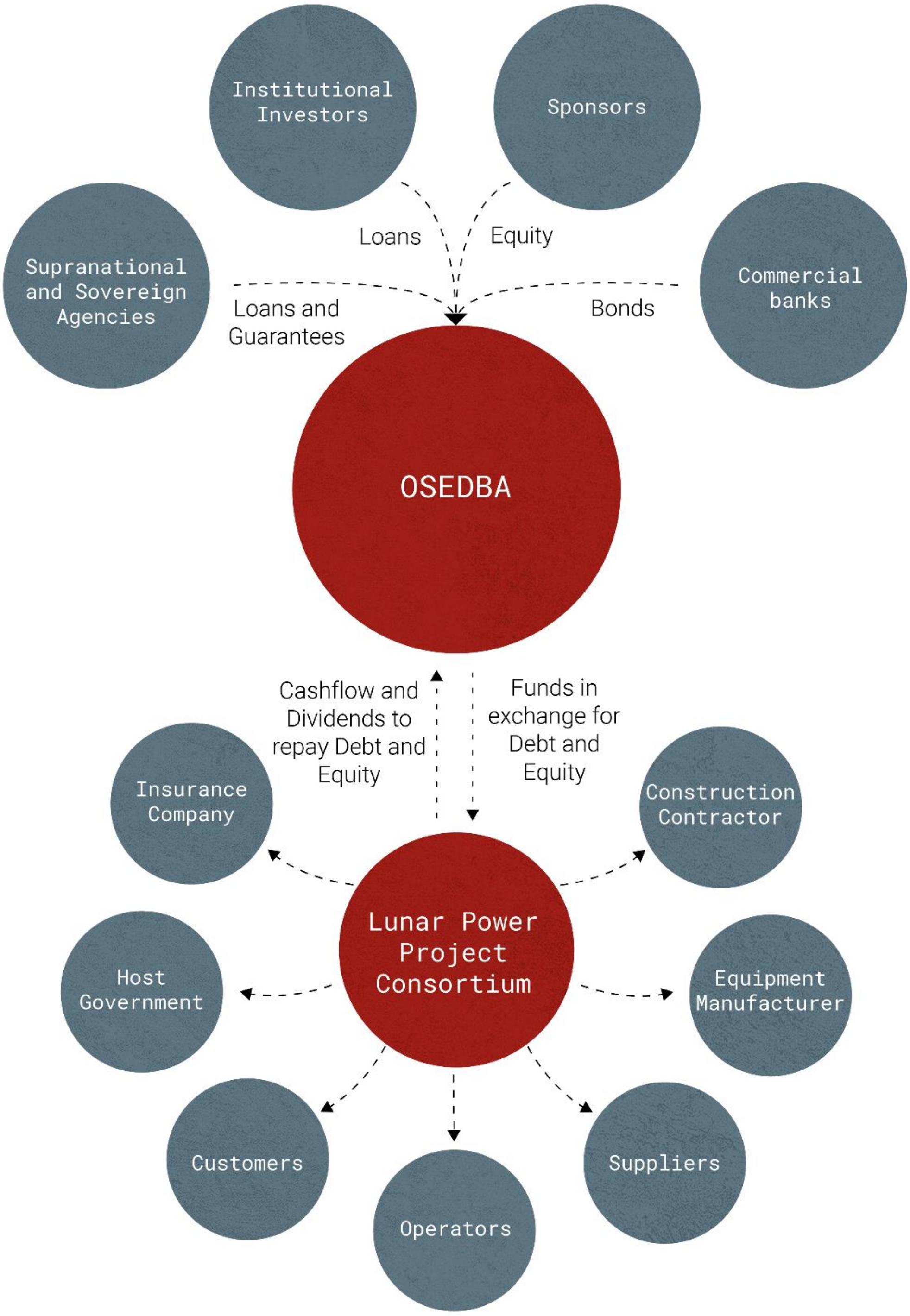


Figure 20: OSEDBA diagram showing the relationship between the influx of investment capital and the manner in which it is conveyed to the various players in the space industry.

Economic activities in outer space have three major constraints: a lack of funding mechanisms, policy and political uncertainties, and ambiguous laws. To date there is no solid business case for purely private commercial activities on the Moon. We assume that the costs related to the production, storage, and delivery of energy on the surface of the Moon are assumed to be negligible compared to capital costs to transport, build, and operate the power solution system.

We assume that in Phase 3 there will be a full-fledged power grid that will enable an increased number of lunar and cislunar missions due to the lower payloads mass and operational costs required. We also assume that this growth will lead to increased return on investment for all debt and equity investors.

4.3 Economic Considerations and Business Case

Power generation and distribution will act as a driver for development on the Moon and other planetary bodies for centuries to come. Within this context, we address how a solution can be most supportive of a long-term presence. To define such criteria for success, several factors should be considered, including increasing efficiency, growing production capability, and support for new services, new startups, and new space actors. By creating a modular and scalable system, access should be available for a variety of activities as markets develop and capacity-building activities are made possible for non-traditional space actors. In terms of efficiency, a commercial solution is often more effective than one implemented by a public entity and, by rewarding early movers, a growing lunar economy built upon the availability of dependable power sources.

4.3.1 Market evaluation: Infrastructure as a Service

4.3.1.1 Infrastructure as a Service

The term Infrastructure as a Service (IaaS) describes the process of providing customers with facilities or structures necessary to operate their business. The concept of IaaS is often referenced in the information technology industry when describing business models for services such as cloud computing and the ability to provide remotely located storage capacity for customers. In our context, IaaS refers to the provision of infrastructure and distribution of energy to consumers on the lunar surface.

From a historical-institutional perspective, our iteration of infrastructure as a service is analogous to telephone and broadband technology, which were initially provided to the general public by governments and later privatized.

Recent market trends in the software as a service industry indicate a shift towards subscription models (Pettey, 2018), based on a combination of user preference and provider interest in recurring revenue. This assessment is based on numerous examples, such as Microsoft Office and Adobe Creative Suite, which were previously sold as individual licenses, but have since transitioned to monthly and annual subscription models. Similar analogies can also be drawn for a power distribution business case, as subscription models generate a source of periodic revenue for an industry and a form of on-demand payment for the customer (Dell EMC, 2018). The application of a subscription model in our business case is discussed in the next section.

4.3.1.2 Analog for Lunar Power Generation and Distribution

To assess the potential business models for lunar power distribution it is important to consider the state of, and trends within, the energy industry on Earth. To bring a major economic driver like energy utility to an entirely new market, it is possible that future business models may mirror current models on Earth.

According to a Deloitte study titled "*Power Market Study 2025*," utility markets in the past have underperformed, their value decreased, and earnings before interests and taxes declined, leaving utilities to operate today in a low-return environment. This is in line with an overall shift from asset-based to cash-flow-based returns (Deloitte, 2015). According to Eurostat, general end-user electricity consumption in both European and US markets on Earth have declined. One reason for this is a surge in demand for new power and utility offerings, which results in the need for innovation in the energy sector (Flaherty, Schwieters and Jennings, 2017).

According to PricewaterhouseCoopers (PwC), the trend of retailization is an emerging form of a more direct consumer-to-utility relationship and is impacting industries such as consumer banking, online shopping, home energy management solutions, and real-time billing and mobile payments (Flaherty, Schwieters and Jennings, 2017). PwC's "2017 Power and Utilities Trends Report" identifies the need for power utilities to provide alternative generation sources, energy storage, equipment replacement, sensor-based energy monitoring systems, software-based data analytics, facilities management services, and infrastructure.

4.3.1.3 Potential Partners Among Energy Industry and Space Startups

Aside from some speculation regarding space-based solar power (GreenMatch, 2018; Reedy, 2017), there is very little evidence to suggest that commercial power companies are publicly exploring lunar power generation as a business interest. The lack of infrastructure, an existing market, high capital risk and long-time horizon for return on investment are certainly not appealing for near-term interest. However, if substantial support from the public sector were offered to offset the development and construction costs, it may be reason enough to generate interest.

Several entrepreneurial space companies have expressed interest in lunar power distribution and some have even incorporated it into their business models for customer payloads (Acierno, 2018) (Hendrickson, 2018). Companies such as Astrobotic, Moon Express, ispace, and Blue Origin, may potentially be interested in the use of an energy distribution network on the Moon, to proceed with their individual interests and diversify their business model on the lunar surface. These companies engage in activities that are notable market drivers, including resource utilization, scientific research, technological demonstration, education, tourism, human exploration, and use of the Moon as a gateway to other destinations.

4.3.2 Business Case for Lunar Power Supply

4.3.2.1 Model for Solution and Operation

To transition the power station from a publicly funded operation to a purely commercial system, it will almost certainly require the government to act as the primary customer to offset costs for other users. While this transition will occur over a period measured in decades, the lunar power generation and distribution system should be designed and built with the anticipation of operation by a commercial entity.

A viable lunar presence will involve a variety of actors that will require an energy source to conduct their operations. Power generation and storage are often large, complex, and expensive subsystems. By delivering this valuable utility, a mission to establish power distribution will remove one of the most significant barriers to entry for exploration and utilization of lunar resources (Zuniga, et al., 2017). An established system will also provide significant benefits and capacity-building activities for future space actors and nations without means of accessing the lunar surface.

4.3.2.2 Strategy and Implementation

On Earth, energy companies undertake power plant development projects as long-term investments and it should be assumed that the same would be true on the lunar surface. A purely commercial plant on the Moon would be a monopoly supplier by default, though the demand would not be quite as guaranteed or constant as on Earth. Public sector support for projects of this scale is quite common, especially in cases where a technology is not fully developed or demonstrated, or where a market may not have yet fully matured. In these scenarios, public-private partnerships are of use to both the commercial industry and governments, as they provide an opportunity for mutual benefit, shared risk, and offset costs (Miller, et al., 2015). Major public infrastructure projects, such as railways, highways, dams, information technology (IT), airports, energy systems, and defense projects are frequently initiated and funded by public spending and carried out in cooperation with private contractors. In effect, by assisting in the development and eventual procurement of a product, a government is able to ensure a cost-effective and continual supply of a desired resource.

A lunar power station could provide power to both public and private customers of all types as soon as it is established. Given a sufficient market where demand for power on the lunar surface matches supply, it could even operate as a private commercial company by Phase 3 of the deployment mission. At that point, given that the public sector would not likely have an interest in bearing the responsibility of upkeep, a privatized model would benefit the system.

A privatization model for the utility might resemble the commercialization and privatization of Intelsat, which was originally formed as the International Telecommunications Satellite Organization (ITSO), an intergovernmental organization with eleven partner nations (Miller, et al., 2015). The privatization of ITSO coincided with the development of a commercial market for satellite manufacture and launch. It operated as a private company for nearly sixteen years before an initial public offering in 2017.

NASA’s Commercial Lunar Payload Services (CLPS) is somewhat analogous to the successful Commercial Orbital Transportation Services program in which commercial launch companies filled a capability gap to launch NASA science payloads into Earth orbit and beyond. CLPS aims to develop a commercial capability to provide a similar service for payloads destined for the lunar surface at a lower price point and to support the growth of private sector partners (Clark, 2018).

4.3.2.3 Business Models

A sufficient and reliable power source is the keystone of a functional long-term lunar economy. Models would use the public sector as a primary customer to offset costs for other users of power. In a model of anchor tenancy, a major customer with higher demand is integral to maintaining a market from which smaller customers benefit. Without the demand of a primary customer, there is no viable market and little incentive for a commercial entity to provide a service at an affordable price.

In the case of long-term established entities with near-constant demand, a subscription-based model might be most sensible. For this model, demand and supply are far more predictable. In a consumption-based model, which would be more appropriate for non-constant users or temporary users such as science missions and rechargeable rovers, demand would experience a temporary spike before returning to its baseline.

4.3.2.4 Roles for Partners in the Energy Industry and Startups

While energy companies have not historically participated in space exploration activities, future development may draw a beneficial analogy from energy activities on Earth. Business models could incorporate the expertise of energy companies on Earth to provide a utility for activities on the Moon. They could also contribute their financial means and management knowledge to broaden the economic base. A generation and distribution system would provide opportunities for partner companies to participate in multiple elements of the energy business model. This includes generation, maintenance, software, transmission, retail, distribution, and disposal. These roles could foreseeably be filled by space startups seeking to provide logistical and technical support for lunar missions.

4.3.2.5 Cost of System Upkeep

Maintenance, parts replacement, and expansion will be the major cost components of a lunar power business model once the facility is established. The following cost estimates can be assessed annually as basic maintenance and replacement costs:

Table 8: Estimated cost of system upkeep.

Phase	Cost per year (USD)
1	$50 million
2A	$150 million
2B	$250 million
2C	$350 million

Using Kilopower systems as a reference, several mission studies were performed. Based on a ten-year flight program, a $690 million estimated cost is assessed with an additional $145 million for recurring systems (Mason, Gibson and Poston, 2013). With a cell cost primarily dictated by the reactor, $500 million was taken as a conservative average estimate for system cost and maintenance, amortized over a ten-year lifetime.

4.3.2.6 Revenue Sources

Depending on the size of the established customer base, the revenue model would be subject to change. In the early years of development, before a third-party market becomes fully established, the primary customers would likely be publicly funded missions. In a commercial model, these missions, including human habitation, could procure energy at cost. As the market grows to include a greater number of customers, revenue would also be generated by providing a utility to commercial customers.

4.3.2.7 Risks, Gaps, Challenges, and Limitations

There are many challenges in creating a business case for technology that has not been fully demonstrated. Our main challenge is ensuring enough demand to close the business case for a power generation and distribution platform. While it is feasible to assume that there will be continued interest from the public sector in lunar exploration, there are still relatively few concrete reasons for private exploration that will result in a return on investment. Long periods for return on investment and high development costs are barriers to commercial activity in space.

4.4 Conclusion

We have addressed in this Section how a design thinking approach combined our legal considerations with other project aspects to create a complete power solution to the problem of lunar night survival. We have discussed the legal challenges of ISRU, nuclear energy and environmental protection, which are a source of much debate. With adequate risk assessments and mitigation plans in place, we feel that these challenges can be solved, both technically and legally. We have proposed the creation of an international body, the International Space Power Organization (ISPO), which will regulate power generation, distribution and use on the Moon. Based on a power grid structure with equitable access, this system will allow benefits for all initial and future stakeholders of lunar exploration. ISPO will balance regulatory and licensing responsibilities with a funding body for further development. The future lunar economy that we envision will involve partnerships between private and public entities of all sizes and levels of development. By providing a vital utility upon which businesses will be established, our solution will provide a long-lasting impact necessary for development and sustained presence on the lunar surface.

5 Implementation Considerations

5.1 Mission planning

This Section presents our strategy and plan to deliver, install, and initialize our power solution at our selected location near the South Pole of the Moon. Our focus is on Phase 2, while taking into consideration the impacts of Phase 1 and the possibilities foreseen for Phase 3. There is no specific planning discussed for Phase 1 and we anticipate development of Phase 3 based on what is achieved in Phase 2C.

We have developed our mission design based upon space agency methodologies, following these seven factors (Figure 21).

1) Payload: identification of the mass and dimensions of our Power Cell.
2) Rocket and lander: choice of the rocket to suit the mission and the design of the lander to be integrated with our Power Cell.
3) Trajectory: choice of optimal trajectory from Earth to Moon.
4) Launch: recommended launch site based on operational capability and legal criteria.
5) Landing: maneuvers to deliver our payload to our selected site near the lunar South Pole.
6) Installation: deployment of our solution and installation at the South Pole site.
7) Initialization: operation of the Power Cell commences.

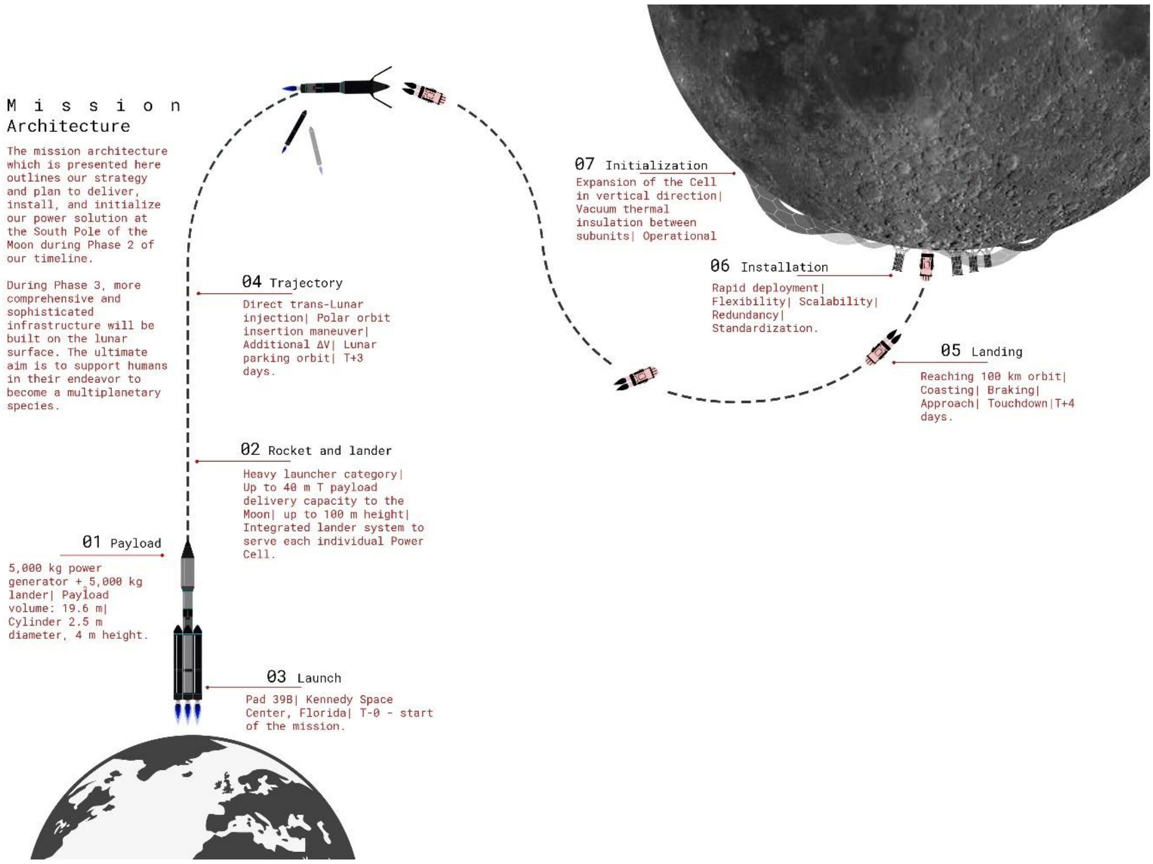


Figure 21: Mission planning scenario for moving to the Moon.

5.1.1 Payload Mass

We designed our mission treating the payload mass and dimensions as the key, driving factors in our mission design.

The design of the Power Cells could be physically integrated with a lunar lander to enable each Power Cell to land as a single assembly without a complicated deployment process after touchdown.

Our payload has two main components that contribute to its total mass: the Power Cell and the lander.

We accounted for the following mass and dimensions of each Power Cell:

Power cell:
Total mass: 4500 kg
Dimensions: 2.5 m diameter, 4 m height
Volume: 19.6 m^3

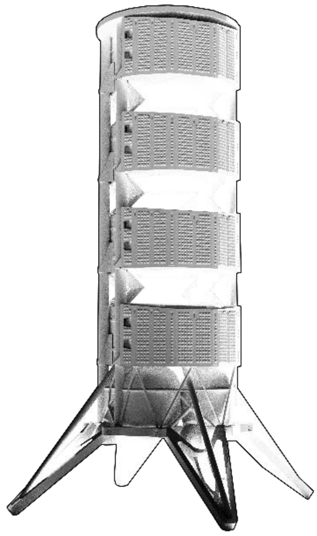


Figure 22: Fully deployed Power Cell.

5.1.2 Rocket and Lander

5.1.2.1 Rocket

The total mass of the power solution is the principal driver to identify the most feasible rocket for this mission. There are several launch vehicles available, or in development, that are considered in Table 1. For this project, the launch vehicles considered fell into either the heavy or super heavy launch vehicle classes.

Table 9: Rocket payload mass capacities available in the public sphere relate to a range of capacities, from GTO, to Moon, to Mars. For our purposes here we have collated available information to provide a high level comparison noting that the values are related to different delivery orbits and locations. (Xudong and Lehao, 2016), (NASA, 2018), (ULA, 2018a; 2018b), (SpaceX, 2017), (Blue Origin, 2018), (Arianespace, 2018).

Rocket	Developed by:	Payload Capacity in Metric Tons (mT) *
Long March 9	China Aerospace Science and Technology Corporation	50 mT (to Moon)
Space Launch System (SLS)	NASA	37 to 40 mT (to Moon)
Falcon Heavy	SpaceX	26.7 (GTO) to 16.8 mT (Mars)
Vulcan	United Launch Alliance (ULA)	16 mT (GTO)
Delta IV	United Launch Alliance (ULA)	14 mT (GTO)
New Glenn	Blue Origin	13 mT (GTO)
Ariane 6	European Space Agency (ESA)	5 mT (GTO)

Considering both our payload mass and the ability of the launch vehicle to deliver the payload to the Moon, our analysis indicates that a super-heavy launcher, such as NASA's Space Launch System (SLS), is the most viable choice to support an Earth-to-Moon launch. Our selection is based upon:

1. Payload capacity for missions to the Moon
2. Availability of landers that have been optimized for SLS or Falcon Heavy
3. Established supply chains supporting the launch architectures.

It is worth noting that the Long March 9 is also currently in development and is designed to have a larger payload capacity than SLS. In comparison to SLS, Long March 9 is in an earlier development stage. In order to support a deployment of our proposed power solution in the near term, the SLS is a more viable launch vehicle at this time due to it being further along in its development. The current climate of rapid innovation in rocket technology is also likely to broaden our rocket options for missions to the Moon and beyond in the upcoming decades.

While we assume that LOP-G will be operational in Phase 1, our mission design will account for tradeoffs between Earth-to-Moon launch trajectories and Earth-to-Gateway followed by Gateway-to-Moon missions.

5.1.2.2 Lander

We plan to procure a lunar lander from industry to meet our specific requirements. One option, depicted in our diagrams, is an integrated lander system to serve each individual Power Cell. Such a design is consistent with our power system's rapid deployment strategy, which will minimize delivery time and cost.

A request for proposal to the commercial sector offers the opportunity to outline the parameters that we require this lander to meet, such as mass, fairing dimensions, throttle requirements, abort constraints, telemetry, protective components, compatibilities, and other critical features.

The following Table 10 outlines the key features of Blue Origin's Blue Moon lander compared with the XEUS lander system being developed as a collaboration between Masten Space Systems Inc (MSS) and United Launch Alliance LLC (ULA). Such landers can be adapted to our specific needs.

Table 10: Comparison of available landers (Masten, 2018) and (Swarts, 2017)

	Blue Moon	XEUS
Company	Blue Origin	MSS / ULA
Rocket Compatibility	SLS New Glenn Atlas V	SLS Compatible Vulcan/ Advanced Cryogenic Evolved Stage (ACES) compatible
Features	Vertical Takeoff Vertical Landing (VTVL) Technology proven on the New Shepard vehicle 4.5 mT payload capability Short development time & risk	VTVL Multi-engine distributed propulsion landers allow precision horizontal landing Improves on schedule and cost drawbacks of single-engine landers Versatility given low center of gravity Proven cryogenic propulsion lowers cost

5.1.3 Launch

We recommend the use of launching sites that align with the needs of our stakeholders, ESA and NASA, and ensure consistency between the liability of launching states and the responsibility countries have for their national space agencies under the space-related treaties.

As the launch infrastructure for SLS is currently being developed at Kennedy Space Center in Florida we are planning our mission based on a launch from the United States for both operational and legal reasons.

Table 11: Scheduled launches during each phase.

Phase	Delivery	Mass Delivered (Kg)
Phase 1	Delivery 1	4,500
	Delivery 2	4,500
Phase 2A	Delivery 3	4,500
	Delivery 4	4,500
Phase 2B	Delivery 5	4,500
	Delivery 6:	4,500
	Delivery 7:	4,500
	Delivery 8:	4,500
Phase 2C	Total	36,000

5.1.4 Trajectory

For the trajectory selection, we analyzed several planned missions, including the ESA's Lunar Lander and the Indian Space Research Organisation's Chandrayaan 2, which will be sent to the South Pole of the Moon by 2019. Since the mission aims to land on the South Pole, the trajectories available are constrained by the final polar orbit to be reached. On the other hand, SLS will be capable of a direct trans-lunar injection (TLI) trajectory. We chose the ideal trajectory based on two aspects: the vehicle selection and intended landing site. The travel time depends heavily on the TLI maneuver, which defines the apogee of the orbit, and can vary from 34 hours to five days.

After booster separation, the vehicle will reach a circular Earth orbit before injecting into a trans-lunar orbit. The payload will then coast freely until a braking phase is initiated to circularize its orbit around the Moon. A plane change will then insert the payload into polar orbit. The payload will then reach the lunar South Pole after a series of course corrections and landing maneuvers.

This proposed trajectory is illustrated in the following diagram:

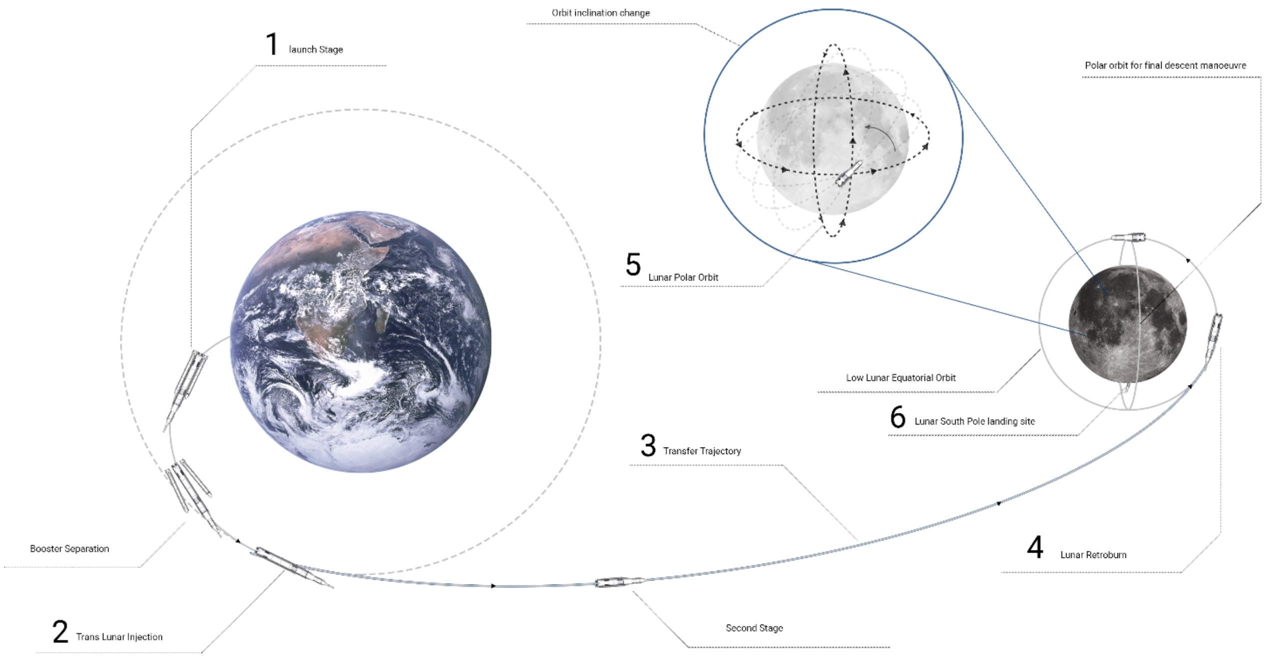


Figure 23: Trajectory diagram of launch for polar lunar orbit.

To reach this recommendation, we evaluated two options that we concluded were not suitable.

First, the Apollo approach, through which a spacecraft is inserted in an Earth-parking orbit and reaches a TLI through a later maneuver. This option was disregarded because the SLS is will be capable of a direct trans-lunar injection.

Second, the low-energy transfer (LET), through which a spacecraft is inserted into an elliptical Earth orbit, is affected by the solar perturbation that aligns the Earth and Moon orbital axes. This results in a reduction in velocity, which creates an unstable orbit that does not permit a polar landing (Loucks, et al., 2005). For this reason, the LET is not a viable option.

5.1.5 Landing

There are three phases that comprise a landing on the lunar surface: direct descent, Earth orbit rendezvous, and lunar orbit.

Direct descent incorporates the launch, a direct insertion through TLI, and a landing without first orbiting around the Moon. The Earth orbit rendezvous adds a parking orbit around the Earth to allow the docking of two spacecraft for refueling. The final phase involves the payload entering into lunar orbit before it commences its descent, without first entering a parking orbit around the Earth.

Although the most appropriate landing method can only be determined once our lander system is designed and integrated with our Power Cells, we envisage that the lunar orbit will be used (NASA, 1992).

Once the spacecraft enters the lunar orbit, a maneuver will be needed to insert the spacecraft into a polar orbit to allow the lander and payload to descend to the surface of the Moon. The payload would be inserted into the orbit through a series of braking actions. Once it has reached an altitude of 100 km, the landing steps of coasting, braking and approaching the surface are performed (Fisackerly, 2011).

During the de-orbiting phase, the lander reaches a lower altitude, which is determined by the landing site constraints. The lander then enters a coasting phase to reduce the fuel consumption en route to the landing site. Finally, the rover conducts a propulsive landing to soften the impact and maintain a proper descent path (Mathavaraj, Pandiyan and Padhi, 2017). In particular, different types of sensors can provide the lander with information about the feasibility of a successful landing, such as cameras and image processing software.

5.1.6 Installation

Following the landing, the installation of our power solution will commence. Each subunit of the Power Cells can be removed from the Power Cell structure, transported using a rover, and reassembled at the new location with minimal technical work.

To meet future power demand, each unit will have a plug-in architecture to connect more Power Cells or subunits into the grid. Cables required for the distribution of generated power will be deployed using autonomous rovers.

To lay down the required cabling on the Moon, we will adopt a similar approach to the intercontinental underwater fiber optic cable installation on Earth.

5.1.7 Initialization

Initialization of each Power Cell can be performed remotely or on site.

After the initialization process commences, the entire unit expands vertically to create vacuum insulation between subunits of our Power Cell. After powering on, the Power Cells will reach their nominal power levels quickly, becoming operational within a matter of minutes. This was a key goal of our power solution: to enable rapid deployment to allow energy supply to the range of users in a timely manner.

By the end of Phase 2, we envisage that we will be able to transmit power wirelessly to desired locations, overcoming logistical challenges and ensuring the rollout of an efficient mission design.

5.2 Human Factors

5.2.1 Health Hazards and Risks

The hazards that exist in the lunar environment and pose medical risks to humans can be broken down into four categories: the lunar environment itself, extravehicular activities (EVAs), events that impact the habitat or rover, and other general hazards (Figure 24). General hazards are those that could occur independently from the environment and are predominantly mitigated by selecting out individuals with chronic diseases or those with an increased likelihood of developing a medical condition. Risks during an EVA or those inside the habitat and rover heavily depend on the technology that is used in those protective structures. The severity of medical conditions may be impacted by the potential interactions between the categories.

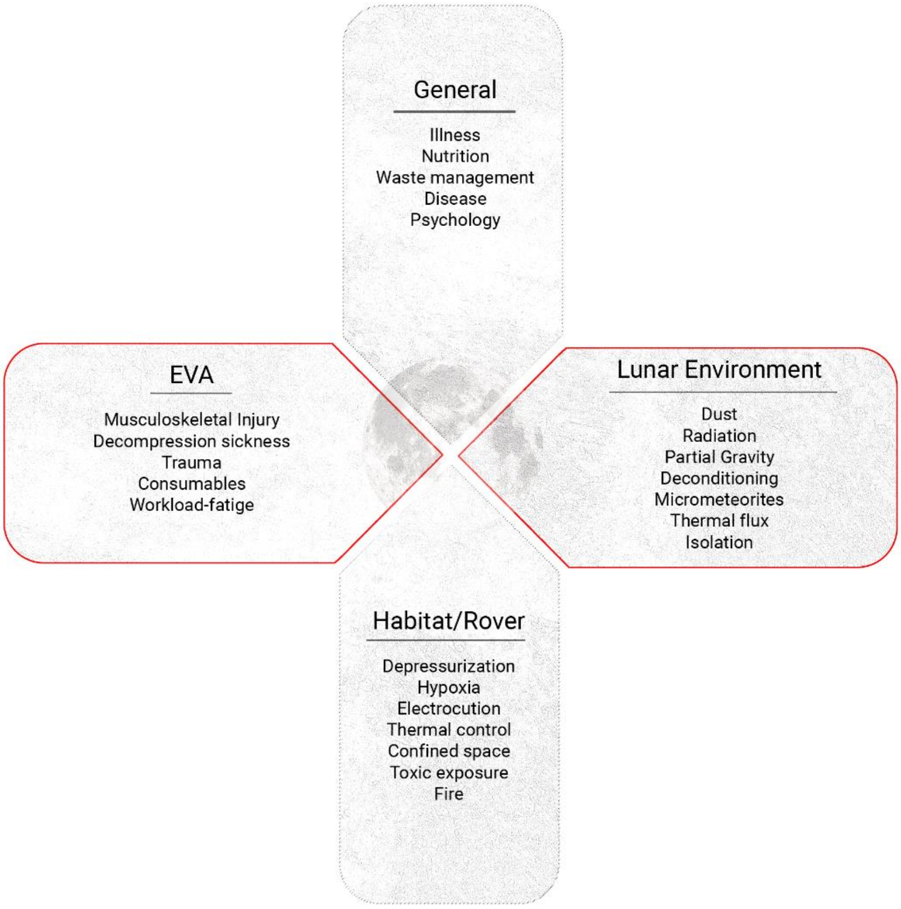


Figure 24: The four sub-categories where medical risks could manifest. Each environment has its own associated medical risks, but they overlap and can affect susceptibility to risks in other areas.

An appropriate Crew Health Care System (CHeCS) should be included when considering what medical risks are most likely to occur from the risks identified. In a rover, where space is a premium, any medical kit will be minimal, but as missions become longer in duration with increasing numbers of astronauts, the likelihood of any medical incidents also increases. Life support systems should include, at very least, the ability to perform baseline observations and monitoring of vital signs, such as heart rate, oxygen levels and blood pressure. In addition, gases should be available to deliver hyperbaric treatment in the event of decompression sickness and a defibrillator to treat cardiac arrhythmias caused by electrocution. The power requirement assumed for CHeCS is 0.11 kW (Anderson, et al., 2015)

The medical risks are even greater during an EVA, when only a few layers of material protect from the lunar environment. In addition, for a return to the Moon, astronauts will be expected to undertake far more EVAs than is currently the norm for ISS operations, up to 80 hours per week, increasing the likelihood of an incident. For EVAs, each astronaut requires a pressurized spacesuit with its own small-scale ECLSS, the Space Portable Life Support System (SPLSS). Each astronaut carries a finite supply of their own consumables, such as oxygen, Lithium Hydroxide (LiOH) canisters for carbon dioxide removal, and diapers for urine and waste collection. An active cooling vest is worn to dissipate heat and maintain a comfortable thermal environment. The EVA suit itself requires power for operation, with backup batteries to be used in the event of loss of the primary power system (Chappell, et al., 2017); the importance of redundancy is discussed in section 2.1.1.2. An astronaut is far more vulnerable to risks such as decompression sickness, thermal extremes, radiation and fatigue (Chappell, et al., 2017), assuming current space suit design.

5.2.2 Psychology

Space exploration is a challenge for the human psyche. Such an austere and remote environment can cultivate a sensation of isolation, but effective selection and training can reduce how susceptible an individual is to psychological stress. Strong relationships within a well-integrated and cohesive crew will be useful in coping with, and performance under, high-stress situations, such as performing a lunar EVA to repair critical power systems (De La Torre, et al., 2012) (Karasek and Theorell, 1990, Suedfeld, et al., 2016).

5.2.3 Human Factors in Architecture and Design

Our architectural design approach is human centered, taking into consideration potential lunar activities, physiological limitations, and above all, safety. In the design of our Power Solution, we appreciate that astronauts will be working in cumbersome spacesuits under potentially stressful conditions. In addition, the Moon's gravity is approximately one sixth of the Earth's and a far greater factor than the microgravity environment of low Earth orbit, where all human space flight has been undertaken since the Apollo program. Operating in partial gravity alters the way astronauts mobilize. Therefore, when constructing a habitat and deploying the power solution, we must consider how humans will function in this unfamiliar environment.

For the Power Cell itself, considering a human operator, it will have an interface that allows two astronauts to easily service the deployed cell and exchange power units without the use of specialized tools. Each Power Cell has an external structure with handles to enable repositioning. This comes at a cost of mass, volume and complexity in construction, but introduces enormous flexibility for various situations in which the power systems may need to be deployed.

To facilitate easy assessment and diagnostics by astronauts, a simple digital display indicating the status of each Power Cell will be incorporated into the design. This way, assessment of the systems can be made from a distance and will reduce the demand for frequent and unnecessary EVAs.

6 Conclusions

The global pursuit of space agencies, governments, and commercial partners to develop technologies to return to space is an inspiring goal. To support this endeavor, we were tasked with developing a power solution, to support a variety of human and robotic activities on the Moon. In addition to the challenging problem of developing a power solution, we have identified a number of auxiliary issues that need to be addressed in order to provide a feasible power solution, including: the lunar environment, the desired lunar activities, the international business case for power supply, the legality of our proposed solution, the associated human needs and factors, and the deployment method of delivering the power solution to the Moon.

We have developed and proposed our Power Cells as a viable solution that is capable of supporting both an initial and sustained presence on the Moon. Our proposed Power Cells are scalable, redundant, flexible, standardized, and rapidly deployable. By selecting an architecture that takes the whole supply chain into account, we are able to provide a reliable human-centric power generation, storage, and distribution capability that can both be realized with current technology and accomplished in an economically feasible manner. Though we have proposed specific activities that are supported by this system, it is by nature adaptable to any other activity in the austere lunar environment that requires energy.

To make this power solution truly viable, the difficulties associated with regulation of activities beyond our planet cannot be understated. We have presented the foundations of a regulatory body that can act on behalf of all humankind to police all space faring nations during their endeavors into space. This framework will be equally controlled around the globe and will ensure that access to space and the Moon will be regulated in the future. The issue of how to incentivize private investment into the space industry has also been addressed with OSERA and OSEBDA. These institutes collectively generate the required funding support to generate more interest in space.

While the scope of the proposals described here are broad, they were considered and designed with the humankind at the heart of the solution. We look forward to future space and lunar activities and anticipate not just lunar night survival but sustained prosperity for all.

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Appendices

Appendix A – Power Distribution Architecture

Table 12 below shows a comparison of alternative options for different power distribution architectures. Both current and emerging technologies (where applicable) are considered together with the impact of their implementation in the lunar environment.

Table 12: Table of power distribution information.

Description	Power Distribution Ability	Power Parameters	Strengths	Weaknesses
Alternating Current (AC) vs. Direct Current (DC) (Metcalf,Harty and Robin, 1991; Khan, et al., 2006; Barave and Chowdhury, 2007)				
AC	Suspended: >600-800 km Buried: <40-60km	N/A	1. Simpler voltage transformation; 2. Less switching losses; 3. Simpler power generation equipment	1. Transmission losses (skin effect and capacitive current)
DC	Suspended: >600-800 km Buried: <40-60km	N/A	1. More common load interface; 2. More efficient transmission line (no skin effect and capacitive current losses); 3. Low cable cost; 4. Less layout space	1. Complex voltage transformation; 2. Difficult to interrupt safely
High Voltage (HV) vs. Low Voltage (Metcalf,Harty and Robin, 199; Khan, et al. 2006)				
High Voltage	Greater than 300 V	N/A	1. Lower current; 2. Lower mass; 3. Higher transmission efficiency; 4. Lower energy losses	1. Need more insulation; 2. Higher isolation requirements; 3. Higher mass and volume
Low Voltage	Less than 300 V	N/A	1. TRL 9; 2. Reduced safety hazard; 3. DC-DC converters easier to manufacture; 4. Minimal insulation	1. DC-DC conversion less efficient; 2. High energy losses; 3. High switching losses
Wired Vs. Wireless (Freid, et al, 2008)				
Wired Power Transmission	1. High voltage AC/DC capability; 2. ~100kW over long distances (5km or greater); 3. Distribution of power from multiple sources; 4. Via above surface, on surface or buried cables.	1. Power transfer efficiency - 60%; 2. Power transmission loss - 2.4kW	1. Proven technology on Earth; 2. High power transfer efficiency; 3. Low power transmission losses; 4. Cable distribution may be implemented above surface, on surface or buried; 5. Distribution across large distances; 6. Capable of combining multiple power sources	1. Large mass/high cost (incl. launch); 2. Difficult to reconfigure; 3. Require complex temperature management along the cable between source and load; 4. Require additional shielding against radiation/lunar dust; 5. Grounding of cables a primary concern; 6. Potential safety hazard
Wireless Power Transmission	1. High DC voltage; 2. 10s of kW over medium distances (up to 5km); 3. Primarily solar power distribution; 4. Via transmission towers or satellite transmitters - microwave or laser.	1. Power transfer efficiency - 45%; 2. Power transmission loss - 5.5kW.	1. Low Mass/Low Cost (incl. launch) 2. Easily reconfigurable; 3. Resilient against temperature variations between source and load; 4. Resilient against lunar radiation; 5. Resilient against poor grounding of regolith; 6. Resilient against lunar dust.	1. Lower power transmission efficiency; 2. High power transmission losses; 3. Initial infrastructure may be complex (transmission towers/satellites) 4. Limited distances per relay 5. Primarily solar power only 6. Potential safety hazard for EVAs in the presence of the beam
Grounded Circuits Vs. Ungrounded Circuits (Freid, et al., 2008)				
Grounded	N/A	N/A	1. Protection against faults in the power lines for both humans and equipment; 2. Particularly important for human safety with high voltage systems	1. Easy to short circuit – only requires 1 point of grounding contact; 2. Regolith is a poor conductor, therefore difficult to ground power cables.

Ungrounded	N/A	N/A	1. Difficult to short circuit systems – 2. Require at least 2 points of contact 3. Easy to set up on the Moon due to poor grounding capability of 4. Regolith	1. High risk for humans from large over voltages
Centralized Vs. Decentralized Power Systems (Metcalf,Harty and Robin, 1991)				
Centralized Power System	200kW	1. 100V-5V DC 2. 240V/115V/28V AC(400Hz/20kHz/50 kHz); 3. input node:20, output node 20	1. Power utilization ratio is high; 2. Low maintenance cost 3.Economies of scale can be generated.	1. Risk of a single-point failure; 2. Low system redundancy capability; 3. High reliability requirements; 4. Difficult to supply remote areas and special applications 5. High construction cost. 6. Single mode of energy supply
Decentralized Power system	10kW/node	1.100V-5V DC; 2. 240V/115V/28V AC(400Hz/20kHz/50 kHz); 3. input 5/node, output 5/node.	1. Improved system flexibility; 2. Ability to meet needs of special users; 3. Ability to apply to different bases in the distribution network; 4. Ability to provide redundancy; 5. Improved power supply stability; 6. Save cost on cable infrastructure	1. Dynamic grid connection of different loads may lead to power grid fluctuation (control required); 2. Distributed and high maintenance cost; 3. Low power utilization ratio 4. Several power supply modes can be used.

Appendix B – Risk Mitigation

<table>
<tr><td>Risk Manager</td><td>Cian O’Regan</td><td>Probability (0-1)</td><td>Impact (1-10)</td><td>Risk Level (Probability x Impact)</td></tr>
<tr><td>Risk No</td><td>TP-LNR-RSK-MA-01</td><td>0.2</td><td>9</td><td>1.8</td></tr>
<tr><td colspan="5">Description of the Risk
Since the settlement base and landing site are not at the same location on the Moon, transportation between landing site and base site may result in harm to humans, the power supply, or both.</td></tr>
<tr><td colspan="5">Root Cause of the Risk
Unfamiliar and steep terrain, poor path planning</td></tr>
<tr><td colspan="5">Risk Mitigation Plan
Ensuring that the distance between the landing site and base site is minimized (e.g., landing as close to the base site as safely as possible). Ensuring that the information used to identify landing and base sites is accurate and well understood.</td></tr>
</table>

<table>
<tr><td>Risk Manager</td><td>Cian O’Regan</td><td>Probability (0-1)</td><td>Impact (1-10)</td><td>Risk Level (Probability x Impact)</td></tr>
<tr><td>Risk No</td><td>TP-LNR-RSK-MA-02</td><td>0.01</td><td>8</td><td>0.08</td></tr>
<tr><td colspan="5">Description of the Risk
The proximity of astronauts to a nuclear power source and the effects this may have on crew health and safety</td></tr>
<tr><td colspan="5">Root Cause of the Risk
The influence of the lunar environment such as unfamiliar terrain combined with potential for damage of the nuclear power hardware infrastructure and its shielding during activities and transportation on the Moon. Also, degradation of the protective shielding caused by exposure to radiation and micrometeorite impacts</td></tr>
<tr><td colspan="5">Risk Mitigation Plan
Ensuring the nuclear power supply to be used is configured in such a way that the probability of breaching its shielding is as low as possible and that it is tested to withstand the harsh environment of the lunar surface, e.g., temperature flux, roll pitch and yaw maneuvers during transportation</td></tr>
</table>

<table>
<tr><td>Risk Manager</td><td>Tuva Atasever</td><td>Probability (0-1)</td><td>Impact (1-10)</td><td>Risk Level (Probability x Impact)</td></tr>
<tr><td>Risk No</td><td>TP-LNR-RSK-MP-01</td><td>0.5</td><td>7</td><td>3.5</td></tr>
<tr><td colspan="5">Description of the Risk
Potential launch delays caused by problems with launch vehicle and payload development efforts</td></tr>
<tr><td colspan="5">Root Cause of the Risk
Launch vehicles that will be used in our mission, which are in development right now, pressurized rovers, habitation modules and actual power generation and distribution system elements might experience significant delays after the mission commissioning</td></tr>
<tr><td colspan="5">Risk Mitigation Plan
Adequate project management and planning best practices should be developed and followed to prevent delays in the completion of the project</td></tr>
</table>

Risk Manager	Andre Fonseca Prince	**Probability** *(0-1)*	**Impact** *(1-10)*	**Risk Level** *(Probability x Impact)*
Risk No	TP-LNR-RSK-Power-03	0.15	5	0.75
Description of the Risk Failure in one of the power sub-cells				
Root Cause of the Risk Malfunction of system causing unavailability of the power to be supplied by one sub-cell. Cables that interconnect the sub-cells damaged and unable to redistribute the power. Poor maintenance leading to failure of the sub-cell power system.				
Risk Mitigation Plan Redundancy on the cell system. In case of failure of up to 2 sub-cells, the third sub-cell can operate and supply enough power for critical operations.				

Risk Manager	Andre Fonseca Prince	**Probability** *(0-1)*	**Impact** *(1-10)*	**Risk Level** *(Probability x Impact)*
Risk No	TP-LNR-RSK-Power-04	0.06	7	0.42
Description of the Risk Sub-cell overheating.				
Root Cause of the Risk Poor design of the cooling system.				
Risk Mitigation Plan Design radiators around each sub-cell with enough capacity to dissipate the heat. Ability to connect sub-cells to their neighbor sub-cells that have extended heat dissipation capacity.				

Risk Manager	Andre Fonseca Prince	**Probability** *(0-1)*	**Impact** *(1-10)*	**Risk Level** *(Probability x Impact)*
Risk No	TP-LNR-RSK-Power-02	0.05	5	0.25
Description of the Risk Leakage of chemical components from batteries/fuel cells or nuclear power solution.				
Root Cause of the Risk Malfunction of system. Meteorite collision. Crash of lander on surface.				
Risk Mitigation Plan Material of the container of each sub-cell can retain the leakage not allowing it to spread out on the environment.				

Risk Manager	Chris Beauregard	**Probability** *(0-1)*	**Impact** *(1-10)*	**Risk Level** *(Probability x Impact)*
Risk No	TP-LNR-RSK-BusEcon-01	0.2	10	2.0
Description of the Risk Political risks are essentially unavoidable for a mission and may have significant impacts on continued funding and, in the direst circumstances, can result (and have resulted) in program cancellation, even for flagship missions				
Root Cause of the Risk When administrations change, priorities change and a variety of other factors may impact funding allotted to specific missions				
Risk Mitigation Plan The only way to even partially mitigate this risk is to ensure support through public outreach and government affairs efforts				

Risk Manager	Chris Beauregard	**Probability** *(0-1)*	**Impact** *(1-10)*	**Risk Level** *(Probability x Impact)*
Risk No	TP-LNR-RSK-BusEcon-02	0.3	4	1.2
Description of the Risk Failure of a commercial market for power distribution on the Moon is certainly possible and would result in significant government support being required over the long term. It would not cause the mission to fail in the short term, but would result in the lack of long-term mission success				
Root Cause of the Risk Commercial success is partially dependent upon investment and commercial missions to the lunar surface to utilize a power generation and distribution. If business cases cannot close, even with the power source in situ, there will not be a market to purchase services.				
Risk Mitigation Plan Maintaining a backlog of future commercial and government missions is helpful in preparing for power needs, as well as informing public sector customers of the burden they may be expected to bear to keep expectations realistic				

Risk Manager	Chris Beauregard	**Probability** *(0-1)*	**Impact** *(1-10)*	**Risk Level** *(Probability x Impact)*
Risk No	TP-LNR-RSK-BusEcon-03	0.4	2	0.8
Description of the Risk Cost overruns are a common occurrence in high technology industries, especially when public funding is used and low TRL missions are undertaken. If the miscalculations are significant, mission cancellation or re-scoping may be required and public support may be lost				
Root Cause of the Risk The most common cause is poor cost estimation or intentional underestimation of costs to garner support for a mission. To some extent, it is unavoidable				

<table>
<tr><td colspan="5">Risk Mitigation Plan
Proper and meticulous cost estimation, frequent re-evaluation, and third-party analysis are the most effective ways to mitigate. Partnerships to share cost are helpful.</td></tr>
<tr><td>Risk Manager</td><td>Deepika Jeyakodi</td><td>Probability (0-1)</td><td>Impact (1-10)</td><td>Risk Level (Probability x Impact)</td></tr>
<tr><td>Risk No</td><td>TP-LNR-RSK-Legal&Policy-01</td><td>0.01</td><td>8</td><td>0.08</td></tr>
<tr><td colspan="5">Description of the Risk
Release of human-made radioactive materials during launch or lunar surface operations resulting in a health hazard to humans or pollution of the lunar environment as well as a negative impact on public perception.</td></tr>
<tr><td colspan="5">Root Cause of the Risk
Inadvertent activation of the reactor prior to or during launch followed by a launch failure. Penetration of the reactor pressure vessel once on the lunar surface.</td></tr>
<tr><td colspan="5">Risk Mitigation Plan
The use of nuclear power source is to be justified with sound technical reasons on why no other source of power can be used instead. Disposal plans for nuclear power source elements, at end of life, will be suggested.</td></tr>
</table>

<table>
<tr><td>Risk Manager</td><td>Deepika Jeyakodi</td><td>Probability (0-1)</td><td>Impact (1-10)</td><td>Risk Level (Probability x Impact)</td></tr>
<tr><td>Risk No</td><td>TP-LNR-RSK-Legal&Policy-03</td><td>0.5</td><td>8</td><td>4</td></tr>
<tr><td colspan="5">Description of the Risk
Clarity on In-Situ Resource Utilization (ISRU) and its scalability is not available. Permanent survival of lunar nights also requires the permanent establishment of comprehensive infrastructure through ISRU</td></tr>
<tr><td colspan="5">Root Cause of the Risk
The Outer Space Treaty does not make an explicit mention of ISRU. It neither allows it nor prohibits it, and the Moon agreement, which addresses resource exploitation on the Moon, is not accepted widely by the international community</td></tr>
<tr><td colspan="5">Risk Mitigation Plan
A plan will be suggested for an international agreement between as few parties as possible to resolve this issue, in full compliance with and without amending the Outer Space Treaty. An agreement with key stakeholders is proposed to achieve clarity on how ISRU is to be carried out and manage the process</td></tr>
<tr><td>Risk Manager</td><td>Deepika Jeyakodi</td><td>Probability (0-1)</td><td>Impact (1-10)</td><td>Risk Level (Probability x Impact)</td></tr>
<tr><td>Risk No</td><td>TP-LNR-RSK-Legal&Policy-02</td><td>0.65</td><td>9</td><td>5.85</td></tr>
<tr><td colspan="5">Description of the Risk
Stakeholders identified in the TP do not ‘buy-in’ to the Regulatory & Commercial framework proposed</td></tr>
<tr><td colspan="5">Root Cause of the Risk</td></tr>
</table>

Conflicting interests of the various stakeholders, and opposing external parties (nation States & commercial parties)
Risk Mitigation Plan Pitch made based on 'international cooperation' and 'benefit of mankind', as strong rationales to adopt a regulatory and commercial framework that gives equitable access to stakeholders, and those that will come there afterwards

Risk Manager	Sebastian Frederiksen	Probability *(0-1)*	Impact *(1-10)*	Risk Level *(Probability x Impact)*
Risk No	TP-LNR-RSK-Arch-01	0.1	7	0.7
Description of the Risk Dust in airlock leading to possible leaks in pressurized cabins				
Root Cause of the Risk Dust can get into the hinges of airlocks and EVA suits				
Risk Mitigation Plan Frequent maintenance, detailed inspection after every 5 EVA's				

Risk Manager	Sebastian Frederiksen	Probability *(0-1)*	Impact *(1-10)*	Risk Level *(Probability x Impact)*
Risk No	TP-LNR-RSK-Arch-02	0.2	7	1.4
Description of the Risk Major pressure leak caused by material fatigue due to severe environmental conditions such as temperature variations and exposure to solar radiation				
Root Cause of the Risk Wear and tear, radiation, oscillating movement				
Risk Mitigation Plan Inspection through non-destructive diagnostics tools				
Risk Manager	Bonnie Posselt	Probability *(0-1)*	Impact *(1-10)*	Risk Level *(Probability x Impact)*
Risk No	TP-LNR-RSK-HPS-01	0.1	8	0.8
Description of the Risk As the number of EVAs on the Lunar surface is expected to be 80 hours per crewmember, the demanding aspects of lunar surface activity and its impact on human health is hard to anticipate				
Root Cause of the Risk Corrosive and toxic nature of Lunar dust to the respiratory system				
Risk Mitigation Plan Providing adequate life support systems and training. Running analogue missions on Lunar regolith testbeds on Earth for symptom recognition, so that medical conditions would be easy to address				

Risk Manager	Bonnie Posselt	Probability *(0-1)*	Impact *(1-10)*	Risk Level *(Probability x Impact)*

Risk No	TP-LNR-RSK-HPS-02	0.05	8	0.4
Description of the Risk Changes in crew dynamics such as conflicts, arguments or stress leading to mission abortion				
Root Cause of the Risk Austere Lunar environment, isolation and confinement, increased fatigue and stress due to alteration of the circadian rhythm				
Risk Mitigation Plan Designing human centric habitats and tools helps in mitigating well-known human factors before flight.				

Appendix C – Lunar analogue simulation

A lunar analogue mission exercise was performed by 35 participants of the International Space University (ISU), exclusively the lunar team project group (TP). It was conducted at the European Astronaut Centre (EAC) of the European Space Agency in Cologne (Germany), taking advantage of their facilities, in particular the virtual reality suite, which added fidelity to the simulated mission. A specific team within the TP group was assembled to create the analogue scenario and ensure that the mission ran smoothly. The full group benefits from having individuals from many different countries and from across a wide range of professions; aerospace, mechanics, physics, marketing, medicine, chemistry, and other fields.

The aim was to simulate lunar surface operations, undertaking a maintenance EVA to review a power system that suffers a sudden failure following a micro meteorite storm. For the exercise the whole team was split into three groups; the lunar surface maintenance team, a proximity team in a space craft orbiting the Moon and a ground control team. The roles of each team are detailed in Table 13. This set up enabled us to incorporate the real life challenges that occur with communicating information between all the groups, and experiencing how human factors have a significant role in the efficiency and accuracy of such a process. Replicating a potential scenario that could arise during a human mission on the Moon allowed ISU participants to experience, hands on, how to work on an analogue mission, and to reflect on critical practices associated with mission planning and implementation. The simulation lasted approximately 2 hours, and was repeated twice during the day to allow all group members to play a part and be involved.

Table 13:Breakdown of team structure for analogue mission.

Team	Location	Tasks	Communication
Ground Team (GT)	Earth	Monitoring of PT and MT resources. Remote 3D printing capabilities.	GT cannot communicate directly with MT.
Proximity Team (PT)	Cislunar	Interface of communication between GT and MT. Teleoperation of a rover on the lunar soil.	PT can communicate with GT and MT at separated time.
Maintenance Team (MT)	Lunar soil	Direct access to power generation on Lunar soil. MT can go on surface exploration EVA.	MT cannot communicate directly with GT.

Mission scenario:

A meteorite shower impacted areas around the lunar base causing power fluctuations and damage to one solar panel. The failure of the power generation system on the lunar soil is detected from Earth. The three teams started to work on different procedures to address the problem, while facing additional challenges, such as medical emergency on EVA and estimating the extent of the damage using a tele-operated rover. The ultimate solution was to create a 3D printer replacement component of the solar panel damaged part, and perform the maintenance in virtual reality.

All team members experienced some psychological stressors to a degree, such as anxiety, stress, and isolation associated with difficult communications. In addition there was some tension observed between the groups as a result of misunderstanding and miscommunication. Valuable lessons were learnt about the importance of clear and effective communications. It also was clear that a power solution should be easily accessible and simple to maintain, highlighting the importance of a effective human –machine interface. For the organizing team, many lessons were also learnt, particularly about the importance of pre-mission training and familiarizing, and how best to set up the mission.

Appendix D – Overview of OSEDBA

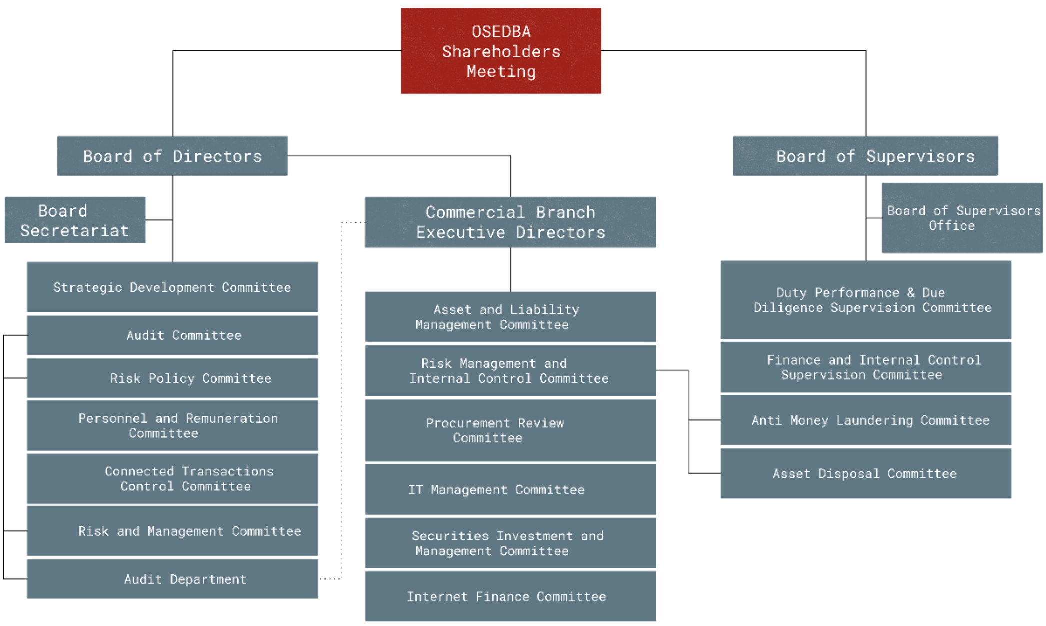

Figure 25: Extended. OSEDBA diagram showing the relationship between the influx of investment capital and the manner in which it is conveyed to the various players in the space industry.

Outreach for Lunar Night Survival

Developing a sustained presence on the Moon is a challenge that involves various actors and will have a long-lasting influence on all life on Earth. We believe it is important to work on an outreach campaign to share the results of our project and pursue a future full of cooperation and benefits for all humankind.

Value proposition

In order to promote our project and its results, we began by reflecting on what potential value it could add. Our proposed solution is a scalable power generation and distribution system to use during lunar days and nights to enable a sustained presence on the Moon. At the same time, we explore innovative business models for providing the power for Moon activities, and evaluate topics critical to mission success, such as legal matters, commercial opportunities, maintenance, and human performance requirements. We believe our ability to consider all these elements is enhanced by the fact that our diverse team is comprised of 35 participants from 16 different nations and from a wide variety of professional fields. This aligns with the international, interdisciplinary and intercultural spirit of the International Space University, offering a unique opportunity for innovation.

Strategic plan and operations

With a clear value proposition, we worked on a strategic plan to create awareness about our Lunar Night Survival project, to share its results and contribute to the international space community. With these goals in mind, we identified our main audiences: the space industry and the ISU community, the general public and especially children.

We developed an action plan using different promotional tools. First, we prepared a presentation to illustrate our project results in a clear, simple, and original format to the ISU participants, staff, stakeholders, and guests. This was done through the use of a theatre format, integrating the technical challenges of our Lunar Night Survival project with humor and narrative. By adopting such an approach we wanted not only to present our findings but to excite and inspire others.

To promote our work and final presentation, we have created and disseminated posters to announce the production and engage our audiences. At the same time, we built a public relations campaign within our team, ESA, and NASA. We also created a website where our project is described and each one of our team members is presented. LinkedIn and Facebook are among the other channels we are using to share the key messages about our project and team. In addition to sharing our Lunar Night Survival messages across the world, we want to maintain contact with our fellow team members to generate and consolidate this network of experts and enthusiasts.

We also have a mascot that represents our team, our values, and has accompanied us throughout the project. We named him Mati to honor the newborn (space) baby of one of our Israeli colleagues. In Hebrew culture, the name Mati symbolizes wisdom, leadership, and bravery. We believe these ideals are emblematic of our team as well. Mati has since become a symbol of our team spirit, caring for each other. At the same time, we have created an Instagram page for him (@MatiTheMoon) with the intention to create awareness and engagement with kids and the general public about space.

Looking forward

The adventure does not end as the Space Studies Program 2018 comes to a close. We plan to continue to expanding knowledge, fostering our enthusiasm for space and maintaining the relations between our team members. We intend to start a campaign with our mascot, Mati, visiting each one of us, in each respective country. For that, we have created an online map to identify our countries and communicate where Mati is. We will also continue with our website and social platform communications. In addition, we will be presenting our work at a number of high profile international space conferences. Several of our team members will attend the International Astronautical Conference, held in Bremen, Germany this October, and the 'Lunar Night workshop' to be held in held in Maryland, USA in November. We will continue to adapt our outreach strategy according to available opportunities and team suggestions along the way and hope that you will join us.


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