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# Lunar Night Survival

Supporting future exploration and activities on the Moon with a scalable power generation and distribution system

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**Abstract**

Future lunar exploration will involve a combination of human and robotic elements engaging in a variety of activities. Reliable, scalable power 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 extreme temperature variations create an inhospitable environment. As part of the International Space University Space Studies Program 2018, the Lunar Night Survival Team Project proposed a scalable power generation and distribution system for utilization during lunar days and nights to enable a sustained presence on the Moon. The proposed power solution, termed Power Cell, is a modular structure of stackable subunits from which a grid of Power Cells will initially support up to six crew members on the lunar surface for an extended period of time and can be extended to megawatt-scale in the long term. The Power Cell is based on space-proven power systems, such as photovoltaics, fuel cells, batteries, and on the newly demonstrated Kilopower fission technology. In support of this solution, a legal and economic framework is formulated to enable future power-related activities in outer space under a regulatory and financial body called the International Space Power Organization (ISPO). New business models, fueled by private-sector innovation and public-sector support, are also presented to allow new industries to thrive on the lunar surface and in cislunar space.

## 1. Introduction

Spacefaring nations have recently revived the vision of establishing a sustained human presence on the Moon. This renewed interest has been adopted by both commercial and governmental space actors that have independently expressed a desire to explore beyond Earth's traditional orbits in a manner that is economically feasible, and with the intensity necessary to achieve goals in a reasonably short timeframe. Private space endeavors are entering the industry and can support public space agencies that are also pursuing their own means to access the lunar surface. China is building the Long March 9 rocket for sample return missions, Roscosmos is advancing its super-heavy lift capabilities for lunar robotic missions, and NASA, in partnership with ESA, is developing the Space Launch System (SLS) for supporting human missions to the Moon.

With these activities in mind, the International Space Exploration Coordination Group (ISECG) has prepared a Global Exploration Roadmap (GER), which defines a potential suite of activities that will eventually enable a human presence on Mars. The most recent 2018 update to the GER defines the role of the Moon as a strategic stepping stone towards the mission of reaching Mars. The increasingly important role of the Moon as a mechanism to support more complex missions is driving much of the present activities towards establishing a sustained presence on the lunar surface.

As momentum builds toward a sustained lunar station, many agencies have begun funding research and development of the various technical challenges that must be solved to accomplish such a mission. This has led to a variety of activities, as a long-term return to the Moon will manifest in a context that differs from the geopolitical motives present during the Cold War.

## 2. Material and methods

To address the many important technical and non-technical questions, this International Space University (ISU) Team Project identified creative solutions that can improve access to space in a technically reasonable and legal manner that encourages international collaboration and partnership between public and private organizations. This project is framed in the context of developing a power solution that is capable of sustaining a long-term human presence on the moon. To this end, it also creates a framework that will enable the solution's deployment in a manner that is legal and commercially feasible.

This paper is structured as follows:

- Presentation of the requirements and technical solution to power a lunar base that can continuously support up to six astronauts, including power supply throughout lunar nights
- Discussion of how collaboration between space faring nations can be regulated in a way that maintains collective oversight and ensures that all activities are legal prior to deployment
- Presentation of a model by which all organizations can access funding to advance their space exploration activities
- Discussion of the mission plan to deliver the solution to the lunar surface.

## 3. Requirements for a Sustained Lunar Presence

There are many essential scientific and technological advances that must be made to enable a continuous human presence on the Moon. The knowledge required for this explorative endeavor determines the nature of the activities on the lunar surface. This section discusses these activities, reviews criteria for potential lunar base locations, and presents the scenario for the development of a sustained presence on the Moon. These aspects will prescribe the requirements for and development of the proposed power solution.

### *3.1 Lunar Science*

In determining the scientific activities that will be performed on the Moon, the Lunar Exploration Roadmap (Lunar Exploration Analysis Group, 2016) is used as a guide. This document is composed by a collective of experts, including planetary scientists and engineers, to outline a coherent plan for lunar exploration. The main scientific goals are similar to the prioritized science concepts and findings listed by the National Research Council (2007) and the opportunities defined by ESA (2015). The following list of objectives from the Lunar Exploration Roadmap (2016) sets the stage for scientific activities on the lunar surface:

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.

The opportunities for scientific research are by no means limited to these objectives, but they illustrate activities that will provide baseline knowledge to inform decisions regarding a sustained human presence on the Moon.

### *3.2 Technology Demonstration for ISRU*

Vital resources, such as oxygen, water and propellant for reusable landers, are continuously required for a sustained human presence on the Moon. The collection and use of these and other resources from local environments is generally termed In-Situ Resource Utilization (ISRU) and its technology is currently under development. It was determined that the proposed power solution must provide sufficient power to support the development, demonstration, and eventual utilization of ISRU technologies on the Moon. Activities in the Team Project scenario that define these power requirements include excavation, transportation, the processing of lunar regolith, and the mining of volatiles and water ice from permanently shadowed craters. The development of these technologies will be staged [8]. First, the critical design factors must be verified, unknowns must be assessed, and the environmental impacts must be evaluated. Second, the production rate, reliability, and long-term operations must be demonstrated and validated. Third, the facilities must integrate with other surface assets. Processing of these resources may be performed as they are extracted, or excavated material can be transported to separate processing facilities, possibly at distant locations.

Currently, technology for ISRU on the lunar surface is still in development, but shows significant promise for reductions in cost, the creation of new capabilities, and the promotion of commercial activity on the Moon. It is one of the many activities that can be developed by the public sector to support private actors by adopting initial cost and risk before a mature market is established. This reasoning is also supported by the sustainability principles of affordability and partnership, as described in the Global Exploration Roadmap [13].

### *3.3 Preliminary Site Selection*

The lunar South Pole is the primary landing site in this scenario based on five selection criteria for a base site on the Moon [4]: 1) accessible terrain, 2) favorable lighting conditions to minimize the length of lunar nights, 3) minimal thermal variation, 4) reliable access to communication, 5) and availability of resources for ISRU. These criteria, and the fact that exploration of the South Pole Aitken Basin is a priority of the National Research Council (2007), made the South Pole the ideal starting point. It is at this location that permanently shadowed regions are believed to harbour water ice and volatiles. It should be noted that, despite the shorter lunar night at the South Pole (only 48 hours), the power solution must still be able to provide power for the duration of a lunar night at the equator, which may last up to fourteen Earth days.

*3.4 Phases Description*

The establishment of sustained human presence on the Moon is divided into three consecutive phases. Each phase is defined by the activities proposed within it, of which the power requirements must be supported by the power solution. The amount of power required by these activities will 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. Such activities will include scientific research, deep space science monitoring, ISRU, mining, access to cislunar space, and launching and landing of spacecraft.

In **Phase 1**, satellites will map the surface of the Moon to identify possible landing sites, based on the site selection criteria previously defined, similar to the purpose of the SMART-1 mission [7]. Satellite data will be used for selecting three potential landing sites for small robotic rovers. Robotic lander and rover missions can be performed through public-private partnerships, as specified by NASA and ESA. By the end of Phase 1, two multi-purpose two-person habitable rovers will be delivered to the selected site, prior to astronaut arrival. Redundancy is chosen for safety. If one rover fails, all four astronauts must be able to shelter in the other rover.

In **Phase 2**, humans will return to the lunar surface. Eventually, six astronauts will be able to undertake missions from the Lunar Orbiting Platform-Gateway (LOP-G) to the Moon, with two support astronauts remaining in orbit. To facilitate this, it is recommended that LOP-G should have the capacity to support at least eight astronauts. Though this is beyond the current LOP-G architecture, it is viewed by this Team Project as a preferred condition to bring humans and materials to the Moon in a sustained manner. This capacity is in line with the current commercial efforts to develop landers by private companies such as Moon Express, Astrobotic, iSpace, and previous efforts by NASA to develop a lander that could carry four astronauts. Phase 2 is divided among three chronological subphases (2A, 2B, and 2C) based on the activities that will be performed.

**Phase 2A** begins with the first crew of two astronauts landing at the same location as the rovers that were delivered in Phase 1. Astronauts will then inspect and initialize both rovers. If necessary, they will be able to live in the ascent lander for three to four days [2]. With both rovers operational, crews of four astronauts will be able to perform short-duration missions on the lunar surface during the lunar day. A third habitable rover will arrive at the end of Phase 2A, enabling two additional astronauts to travel to the lunar surface once operational. This increases crew size to six astronauts, defining the start of Phase 2B.

In **Phase 2B**, a permanent habitat for up to six astronauts will be delivered to the landing site. During this phase, astronauts will prepare a permanent habitat for later use. 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 demonstrate technologies, such as the excavation and processing of resources from lunar regolith.

During **Phase 2C**, the astronauts will complete the setup of 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 occupy the permanent habitat, and the power supply must support continuous surface habitation over the course of consecutive lunar nights.

In **Phase 3**, it is envisioned that a single habitat will be developed into multiple habitats, similar to the ESA Moon Village concept. This will require an increase in the power supply from the kilowatt to megawatt scale. A lunar base with up to 50 people “engaged in mining and manufacturing activities” requires a power system of 10 MW [14]. The power solution presented in this paper could be scaled to meet this requirement. In this phase, a diverse community of public and private organizations will cooperate on the Moon, with available resources used to create potential markets for commercial activity, including water, oxygen, power generation, and mining [24].

*3.5 Mission planning approach and assumptions*

In designing the mission plan, several fundamental assumptions were made. It is assumed that all infrastructure, such as rovers deployed to study the selected landing site, are still accessible before the first crewed mission to the surface. Finally, a cost-conscious approach has been adopted to ensure feasibility. A series of key strategic aspects were also included in the design: the acknowledgement of the 2018 Global Exploration Roadmap (GER) as a foundation of the mission; the innovative developments in the commercial sector to support the space supply chain; the use of launch technologies based upon both current availability and pipeline of vehicles being developed by innovative commercial space actors [3]; the interoperability of rockets, landers, and components considering future mission support, maintenance, and replacement of parts; the adoption of a rapid-deployment approach to the delivery of lunar payloads, minimizing delivery time and cost; the legal framework applicable to launching States and the need to ensure strategic alignment between a range of stakeholders so that the mission finds broad international support; and finally, 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.

With regard to stakeholders, which include spacefaring nations, international nuclear energy organizations, and the general public, a high-level analysis was used to define the relationship between the mission's objectives and values, and those of key stakeholders. By undertaking this "House of Quality" analysis, a better understanding of stakeholder principles and needs ensures that their interests are considered [10]. These values are then prioritized by calculating their scores, the highest of which guide the mission design choices. In the analysis, these 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.

Finally, a risk analysis was conducted to identify events that might impact the successful delivery of the power solution. The analysis articulates a mitigation plan and calculates risk levels by multiplying the probability of an adverse event occurring (0-1) with the magnitude of its potential impact on mission objectives (1-10). This metric provides an overview of the risk landscape of the whole mission. To address risks that are identified as potentially catastrophic, the mission design recommends the development of a disaster recovery plan (DRP). A proper DRP will assist in ensuring that the long-term success of the mission is not jeopardized by technical issues, as well as non-technical matters, such as public opposition and political challenges. While the development of a detailed DRP is beyond the scope of this paper, the importance of a plan to document such processes and procedures cannot be understated. In addition, to ensure support from key stakeholders, assurance must be provided that the risks associated with nuclear energy have been mitigated to the greatest extent possible.

### *3.6 Power Requirements*

The requirement to provide reliable and uninterrupted power is primarily driven by life support systems, as the fundamental physiological needs of a human, regardless of environment, will remain the same. For Phase 2, it is assumed that resource availability will be similar to that of the International Space Station (ISS). Therefore, human power requirements are based on those of the ISS and adapted for a small pressurized rover [1]. These values are summarized in Table 1 and they do not only account for basic survival, but also for exercise, a comfortable thermal environment, a health care system, lighting, communications, and adequate amounts of food and water. Table 1 differentiates between living within a habitat or habitable rover, and performing a surface exploration extravehicular activity (EVA). Based on existing technologies, the estimated total power requirement for a two-person habitable rover, including EVA, is 5.92 kW, which is within the range of 1 to 7 kW for a two-person lunar habitat identified by Di Capua et al., 2009. Each crewmember (CM) may be expected to perform up to 80 hours of EVA per week [1], so the power requirements will vary based on the number of CM performing EVAs and on the efficiency of the EVA life support systems. Furthermore, variations in environmental conditions, such as the absence of light and presence of lunar dust, are expected to increase the estimated power cost per CM.

| | | 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 |

Table 1. Human power requirements for a habitable rover and EVA. The reference case is taken from Anderson, et al. (2015), showing the normalized power requirement per crewmember (CM).

The environmental control and life support system (ECLSS) is comprised of seven main subsystems that each have unique power requirements [1]. For example, the health care system requires 0.11 kW, the solid waste management system requires 0.274-0.445 kW [6], the thermal control system requires 2.5 kW, the carbon dioxide removal system requires 0.10 kW and water processing requires 1.49 kW [23]. These specific power requirements correspond to 1.92%, 6.28%, 43.65%, 1.75%, and 26.05% of the entire system capacity, respectively. The efficiency of these systems is expected to increase as new technologies emerge.

The reliability of any ECLSS is determined by each subsystem and the life span of its component parts (Anderson, et al., 2015). In the event of a subsystem failure, a back-up system should be activated to enable continued operations, increasing the time available for maintenance. Habitable rovers and permanent habitats on the Moon are expected to have high-redundancy systems as a way to counteract contamination that could arise from Lunar dust.

Power is also required for lighting systems, which are not only practical, but can be used as a psychological countermeasure. The lunar night has similarities with missions undertaken at polar stations on Earth, particularly in the winter months, where prolonged periods of darkness affect mood, sleep, and circadian rhythm [27]. Lighting can be used to counter the negative psychological effects of extended darkness experienced during the lunar night. Simulating the Earth day-night cycle is possible with the Solid-State Lighting Module developed by NASA. Variable spectrum lighting, requiring 30 W of power per module and blue-enriched white light could be incorporated to improve sleep quality [11].

Based on the presented scenario, Table 2 provides a conservative estimate for the total amount of required power per phase. The numbers for habitable rovers and habitat are taken from Table 1, assuming 6 kW per two CMs (including EVA) and 1 kW for locomotion per rover [16]. The numbers for science and technology activities are based on values for an excavation rover (maximum power of 500 W) and oxygen production demonstrator (1.6 kW) [26]. The number of activities, and therefore the power operations, are assumed to double between consecutive phases. Half of the power budget is conservatively reserved for unforeseen contingencies.

| Phase | 1 | 2A | 2B | 2C |
|---|---|---|---|---|
| Permanent habitat (kW) | 0 | 0 | 0 | 18 |
| Habitable rovers (kW) | 0 | 14 | 21 | 21 |
| Science and technology (kW) | 1 | 2 | 4 | 8 |
| Power operations (kW) | 0.5 | 1 | 2 | 4 |
| 50% contingency (kW) | 0.8 | 8.5 | 13.5 | 25.5 |
| Total required power (kW) | 2.3 | 25.5 | 40.5 | 76.5 |

Table 2. Conservative estimate for the amount of power required per phase. Power operations is the estimated consumption by the power system itself. Science and technology refers to robotic rovers and demonstrators.

## 4. Power Solution

Lunar night survival requires a robust power generation and storage solution for up to 336 continuous hours of darkness at a time. The proposed solution uses reliable present-day technologies that are scalable to meet increasing power demand over time.

### *4.1 The Power Cell*

Power Cells are comprised of four "subunits" (Fig. 1), each being dedicated to either power generation, energy storage, or system control. The initial architecture involves three different types of Power Cells, each with a unique combinations of subunits (Table 3). The following design drivers were major factors in identification of the solution:

**Scalability -** Power Cells are easily installed to meet an increasing power demand. The architecture is scalable from several kilowatts to hundreds of kilowatts and allows simple integration of new technologies through a 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.

**Standardization -** Each Power Cell and subunit have standard dimensions and design that will optimize their manufacturing, 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 within hours at any location. A complete Cell mass is approximately 4,500 kg, with subunits ranging in mass from 400 to 2,000 kg.

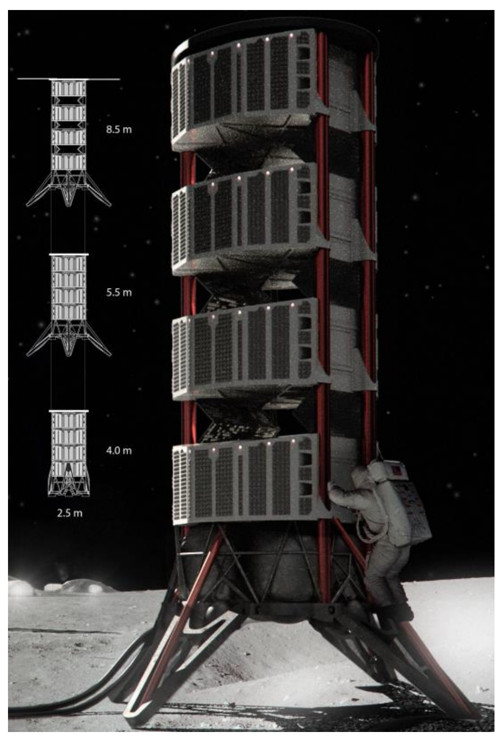


Fig. 1. Power Cell (Shown in deployed, landing, and stowed configurations)

| 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 |

Table 3. Types of Power Cells

*4.2 Power Cell Operation*

The Power Cell is designed for uninterrupted operation during both day and night. All Power Cells are equipped with 20 $m^2$ of deployable 8 kW photovoltaic cells to provide the primary power generation means during the day. Excess power is used to maintain the onboard regenerative fuel cells and to keep batteries fully charged for power supply during the night. Alpha and Gamma Power Cells also contain a Kilopower-based fission reactor to provide a constant 10-kW supply of power during both day and night. All Power Cells contain enough energy storage capacity to power an ECLSS system for six astronauts throughout an entire lunar night at the equator (equivalent to 14 Earth days) in the event of failure of all sun-independent (nuclear) power generation capabilities.

*4.3 Power Generation and Storage Technologies*

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 [21]. The use of nuclear energy is required by the architecture in order to provide an economically sized and technically feasible power generation solution in the absence of sunlight.

Photovoltaic (PV) solar cells are a space-proven technology and will provide the main supplemental power generation capability for the reactors during the lunar day. The amount of power generated depends on the type of PV technology used and the ability to track the sun. Conventional space-rated solar cells have a conversion efficiency of approximately 30%. Ongoing research in this area is believed to be able to increase the efficiency to 40-50% [17]. With panels in an orientation perpendicular to the solar flux, a maximum power generation of between 11.6 and 14.5 kW could be expected from a total surface area of 20 $m^2$.

Fuel cells are able to produce electrical power from stored chemical energy. They are the primary energy storage system that will be included in the Power Cells. The design will use unitized regenerative proton exchange membrane fuel cell technology, which are well-established and can operate reversibly in order to recharge [5]. Furthermore, they have a high specific energy of 1.0 kWh/kg.

Batteries will be used primarily for operating the sensors and controllers that are placed inside the subunits, and for powering the uncrewed rovers. 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 for 2 CMs operational for 14 hours. The Cells will employ lithium nickel cobalt oxide [25] batteries because they have a high technology readiness level (TRL), a reasonable operating temperature, and the best specific energy (100 Wh/kg) of the currently available options.

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 being rapidly charged to their maximum capacities within minutes. The later-deployed Gamma Power Cell is designed to take advantage of this developing technology.

*4.4 Power Distribution*

The component of the final power distribution solution is a decentralized microgrid [18]. This is a localized, distributed network of Power Cells and loads that does not depend on a single power source. The microgrid enables the distribution network to operate as an independently controllable unit while minimizing interruptions and instabilities in the power supply at each load [19]. The first implementation of the microgrid is seen in Phase 2, with Phase 1 delivering all support equipment and infrastructure that will be used. Wired power transmission will be used in the initial stages of Phase 2, with an eventual introduction of wireless power transmission (WPT) by the end of Phase 2 to lay the groundwork for more rapid expansion in Phase 3. Microwave beaming is selected as the WPT technology rather than laser WPT due to its relatively higher efficiency of approximately 45% [8, 30].

The main power will be distributed through a high voltage AC transmission, as considered in a study by Khan, et al. [15]. The cables in the microgrid network for wired transmission will be deployed both on top of and buried underneath the surface. The wires will be vacuum-insulated coaxial cables having low mass and high resiliency against radiation, while also preventing leakage of the electric field [9].

*4.5 Power Management*

A power management system (PMS), integrated within the control circuitry of the cells themselves, is required for the safe operation of the overall power system. The power system architecture is designed to require minimal human supervision, as EVAs are risky activities to perform. The use of advanced sensors and artificial intelligence will minimize the number of EVAs for maintenance purposes. The PMS will provide prioritized data during emergencies, monitor for anomalies, predict problems, and provide automatic safety actions when necessary. The estimated PMS power consumption for each cell is about 500 W.

The disposal of power system components will occur at the end of their rated lifetime or when they are irreparably damaged. The disposal plan includes the transportation of these units to a graveyard located at a safe distance, implementation of low-energy sensor-suite for each subunit to monitor the status of the disposed equipment, documentation specifying the subunit material and component that has been disposed to ensure accountability of those items, and a risk assessment plan to identify and mitigate potential impacts to the environment.

## 5. Legal and Business Challenges and Opportunities

The proposed solution encompasses some elements, such as ISRU, the use of nuclear power, and the vision of an open, multi-user power grid system, which carry with them legal constraints, risks, and policy challenges, which can be summarized as follows.

### *5.1 In-Situ Resource Utilization (ISRU)*

The Outer Space Treaty (OST) mandates that there can be no appropriation of the Moon and, at the same time, gives the freedom of use and exploration. In an attempt to clarify this ambiguity, 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." [12]. Therefore, it can be concluded that ISRU is allowed within the constraints posed by the OST.

### *5.2 Use of Nuclear Power*

Among the currently deployable technologies, nuclear power is the only alternative power source to solar energy, which is not available at all times and in all places. The OST and the Moon Agreement forbid only 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 (NPSOS) [22] requires that nuclear use must be restricted to cases where other power sources are not viable (NPSOS Principle 3). Therefore, nuclear energy is permissible as a power source, subject to having risk mitigation and end-of-life disposal plans.

### *5.3 Environmental protection and prevention of contamination*

The Moon is classified as a Category II body under the Committee on Space Research (COSPAR) planetary protection policies, requiring only a planetary protection plan discussing the mission, impacts, if any, and mitigation actions. To find a balance between protection of the space environment, particularly the Moon, and the exploration and exploitation of that environment, the regulatory framework proposed will incorporate terrestrial environmental law principles such as the Precautionary Principle, and the Polluter Pays Principle.

### *5.4 International Space Power Organization*

To regulate activities, a contractually established international body called the International Space Power Organization (ISPO) is proposed to support scientific, public, and private interests. ISPO will consist of two sub-organizations: the Outer Space Energy Regulatory Authority (OSERA), and the Outer Space Energy Development Bank (OSEDBA).

### *5.5 Regulatory Framework: OSERA*

The Outer Space Energy Regulatory Authority will exclusively deal with regulation and administration of a power distribution grid that will serve multiple users. It will license and authorize activities on the Moon beginning in Phase 1 for infrastructure development. At a more mature stage, OSERA will regulate access to power infrastructure, such as landing sites and power grid. In Phase 3, when the infrastructure is available as a service, it will license users of the grid to ensure and verify compliance to laws.

### *5.6 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. The intention of OSEDBA is to:

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.

*5.7 Stakeholder Benefits*

In the short term, tax benefits offset the cost of contribution to developing infrastructure that provides a useful service for all humankind. In addition, the potential to provide access to development funds and issue bonds provides a guaranteed return on investment. In the long term, entities retain the benefit of ownership of infrastructure and related revenue sources.

*5.8 Commercial Partnership Models*

Project debt and equity are used to finance the projects, while the debt portion is repaid using the cash flow generated by the operation of the project. Investors will own part of the OSEDBA-financed project portfolio and not individual projects (Fig. 2).

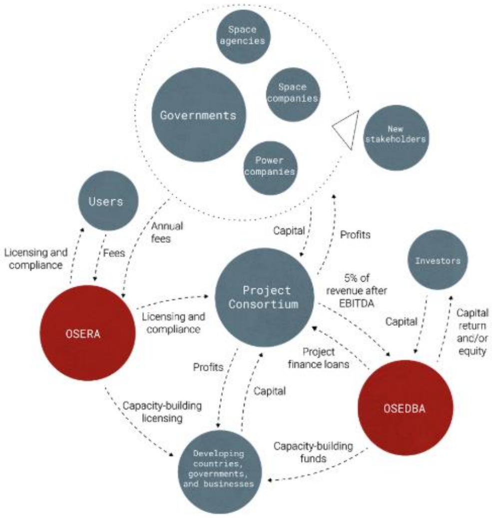


Fig 2. Commercial and Legal Interrelations

*5.9 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, the proposed power solution will facilitate a long-term lunar presence. 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.

*5.10 Potential Partners Among Energy Industry and Space Startups*

The lack of infrastructure, an existing market, high capital risk and a long-time horizon for return on investment are certainly not appealing for near-term commercial 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 activity. Several entrepreneurial space companies engage in activities that are notable market drivers, such as resource utilization, scientific research, technological demonstration, education, tourism, human exploration, and use of the Moon as a gateway to other destinations.

*5.11 Model for Solution and Operation*

The lunar power generation and distribution system is designed with the anticipation of operation by a commercial entity. Successful business models would likely use the public sector as a primary customer to offset costs for other users of power. After the research and development of the power solution are complete and infrastructure is in place, the system can be privatized and commercialized so that the public sector can procure its services. By acting as a primary customer the public sector will establish a market for power distribution as a service and enable other users to access the utility. The generation and distribution system would provide opportunities for commercial companies to participate in multiple elements of the energy business model. These roles could foreseeably be filled by space startups seeking to provide logistical and technical support for lunar missions.

*5.12 Cost of System Upkeep*

The following cost estimates can be assessed annually as basic maintenance and replacement costs (in U.S. dollars): Phase 1: $50 million; Phase 2A: $150 million; Phase 2B: $250 million; Phase 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 [20]. With a cell cost primarily dictated by the reactor, $500 million is assumed as a conservative average estimate for system cost and maintenance, amortized over a ten-year lifetime.

## 6. Mission Planning

*6.1 Approach and assumptions*

In designing the mission plan, a cost-conscious approach has been adopted to ensure feasibility. A series of key strategic aspects were also included in the design: the acknowledgement of the GER 2018 [13] as a foundation of the mission; the innovative developments in the commercial sector to support the space supply chain; the use of launch technologies based upon both current availability and pipeline of vehicles being developed by innovative commercial space actors [3]; the interoperability of rockets, landers, and components considering future mission support, maintenance, and replacement of parts; the adoption of a rapid-deployment approach to the delivery of lunar payloads, minimizing delivery time and cost; the legal framework applicable to launching States and the need to ensure strategic alignment between a range of stakeholders so that the mission finds broad international support; and finally, 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.

With regard to stakeholders, which include spacefaring nations, international nuclear energy organizations, and the general public, a high-level analysis was used to define the relationship between the mission's objectives and values, and those of key stakeholders. By undertaking this "House of Quality" analysis, a better understanding of stakeholder principles and needs ensures that their interests are considered [10]. These values are then prioritized by calculating their scores, the highest of which guide the mission design choices. In the analysis, these 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.

*6.2 Delivery*

In order to deliver the necessary equipment to the lunar surface, for Phase 2 especially, payload mass and dimension are critical considerations as they influence factors such as the type of launch vehicle, lander, and number of launches. To simplify the deployment process of the Power Cell, the lander will be developed with Power Cell integration in mind. The total mass, dimension and volume of the Power Cell, including the lander, are assumed to have measurements of 4,500 kg, 2.5 m in width, 4 m in height and a volume of 19.6 $m^3$. There will be a total of eight deliveries divided equally among Phases 1, 2A, 2B, and 2C with a total delivered mass of 36,000 kg.

As the mass of the payload is the principle driver in determining the most feasible launch vehicle, the options considered are classified as heavy or super heavy. The super-heavy launch vehicle chosen, currently under development by NASA, is the Space Launch System (SLS) Block 1B. SLS has a payload capacity between 37 to 40 metric tons, which meets the mass requirements of this mission. As the launch site for SLS will be at the Kennedy Space Center in Cape Canaveral, Florida, this same location is assumed for both operational and legal reasons.

The mission aims to initially land on the South Pole, thus the trajectory is constrained to a final polar orbit before landing, so that the launch vehicle can perform a trans-lunar injection. The payload will then reach a circular orbit, at which point, through a plane change, it will insert itself into a polar orbit around the Moon. The landing method depends heavily on the final lander system that is designed for the mission. However, it is assumed that a lunar landing will occur after a series of braking maneuvers and will be propulsive.

Finally, upon landing, the installation phase of the mission shall require minimal additional work and can be done at different locations by rovers, based on the desired landing sights. The modular power cell structure enables each subunit to be removed, transported and reassembled. The cables required for distribution of power generated can be distributed by autonomous rovers, which will use similar techniques to those that install intercontinental underwater fiber optic cables. The initialization phase is intended to enable rapid deployment of the power system, so that power unit will become operational within minutes.

*6.3 Risk Analysis*

A risk analysis was conducted to identify events that might impact the successful delivery of the power solution. The analysis articulates a mitigation plan and calculates risk levels by multiplying the probability of an adverse event occurring (0-1) with the magnitude of its potential impact on mission objectives (1-10). This metric provides an overview of the risk landscape of the whole mission. To address risks that are identified as potentially catastrophic, the mission design recommends the development of a disaster recovery plan (DRP). A proper DRP will assist in ensuring that the long-term success of the mission is not jeopardized by technical issues, as well as non-technical matters, such as public opposition and political challenges. While the development of a detailed DRP is beyond the scope of this report, the importance of a plan to document such processes and procedures cannot be understated. In addition, to ensure support from key stakeholders, assurance must be provided that the risks associated with nuclear energy have been mitigated to the greatest extent possible.

## 7. Conclusions

As the world's spacefaring nations advance toward a long-term lunar presence, they will require a reliable source of power. The proposed solution to this challenge is a modular, scalable generation and distribution system that will support up to six crew members on the lunar surface for an extended period of time. Furthermore, they will have the power supply to accommodate a high volume of EVAs to support extensive scientific endeavors, system and habitat maintenance, and ISRU activities.

The envisioned Power Cell is an extremely versatile and durable solution. It can be delivered to a variety of locations on the lunar surface and supply kilowatts of power after a brief period of initialization. To support a human presence, up to 10 kW can be delivered to crew members continuously for at least 12 years, including lunar nights, which can last up to 14 Terrestrial days. The first missions will occur near the lunar South Pole, and a detailed mission plan illustrates the delivery of the Power Cell to this region. Additionally, an anticipated timeline of necessary activities for establishing such a base includes activities such as rover deployment, scouting areas for potential ISRU and habitat accommodation, and the associated power requirements.

A critical element of establishing a long-term lunar station is the important requirement to do so legally. The Outer Space Treaty very clearly describes that space can be freely explored by all actors, and that no celestial bodies shall be appropriated by any individual or organization. With this in mind, the proposed legal body will oversee and regulate lunar activities, including power generation and distribution. In this way, it can be ensured that all space activities will be undertaken for the benefit of all humankind. Finally, a financial body has been proposed to increase access to funding opportunities for commercial organizations and spacefaring nations, including developing nations. This body is modeled with the intention of decreasing the burden of space exploration by defraying upfront costs and risks, while sharing proceeds from commercial activities.

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The executive summary and final report of our project can be found at https://isulibrary.isunet.edu/. Please also follow our outreach campaign www.lunarnightsurvival.com.

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