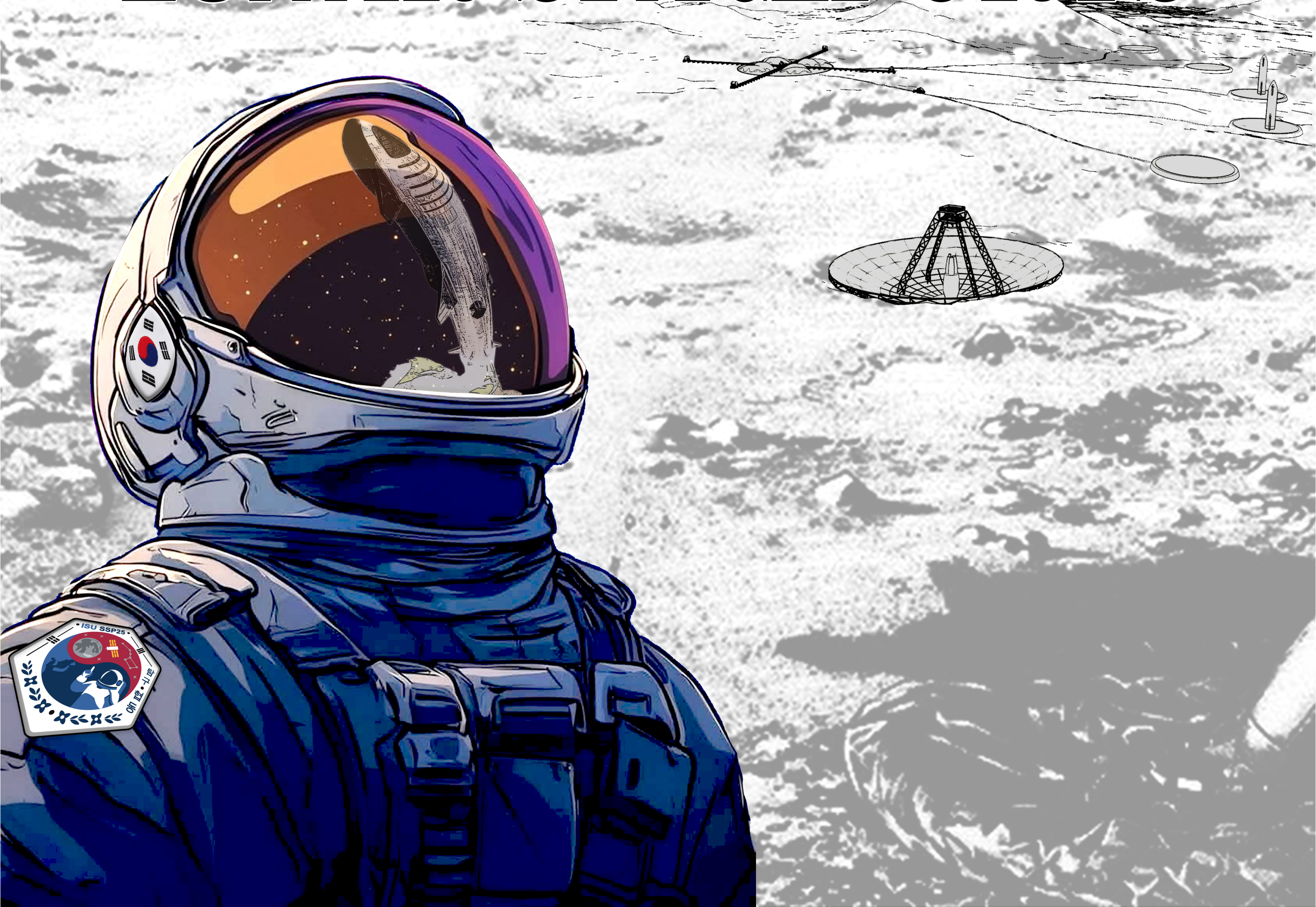
INTERNATIONAL SPACE UNIVERSITY

SPACE STUDIES PROGRAM 2025

SUSTAINABLE LUNAR SPACEPORTS



This SSP25 Team Project work was conducted at the ERICA Campus of Hanyang university in Ansan, South Korea.

The TP Final Report may be found on the ISU Library web site at: isulibrary.isunet.edu in the "Collections/Student and Participants Reports"

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Acknowledgments

This report stands as a powerful testament to the collaborative spirit, valuable insights, and exceptional guidance contributed by countless individuals at the International Space University (ISU) during its development. The ability of ISU team members and participants to work together in an interdisciplinary, intercultural, international (3Is) and innovative (emerging 4^{th} I) environment has enriched this project and marked a groundbreaking achievement in advancing research on the future of lunar spaceports and ensuring sustainable human presence on the lunar surface.

We sincerely thank Eric Dahlstrom, TP Lunar Chair, and Joshua Kassulke, TP Lunar Teaching Associate, for their invaluable support and resources. Their insightful feedback played a critical role in achieving the depth and clarity that this work required. Furthermore, we would like to thank the ISU staff and faculty for their dedication, expertise and support during this summer. In particular, we would like to thank Anna Cordrey and Arif Göktuğ Karacalıoğlu, SSP25 Co-Directors, and Claudiu Mihai Tăiatu, SSP25 Academic Coordinator, as well as Vanessa Stroh and Carol Carnett, our Editing Liaisons.

We greatly appreciate the invaluable contributions of experts from diverse fields, Angel Abbud-Madrid, John Connolly, Bernard Foing, Andre Fonseca Prince, Cheryl Gramling, Diego Guerra, Eszter Gulacsi, Damien Pietrusiak, Antonio Stark and Madhu Thangavelu, whose insights and support have been essential in steering our research. Their guidance has played a critical role in navigating the complexities of this intricate project, ensuring we remain on a successful path.

A special acknowledgement goes to Maria Paula Pulido González and Maxim Luc Mommerency, our project managers. Their exceptional leadership, patience, and unwavering support have significantly impacted the successful completion of this extensive project.

We extend our deepest gratitude to the dedicated participants of our project team, consisting of outstanding professionals and students from various fields. Their collaborative spirit and stimulating discussions have been pivotal in advancing the future of lunar initiatives. The invaluable insight and encouragement from this team have been unparalleled and need a special mention to make this research work an achievement.

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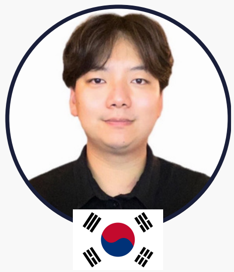

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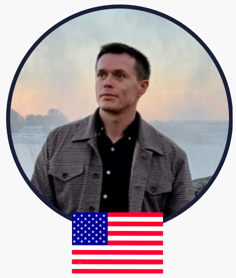

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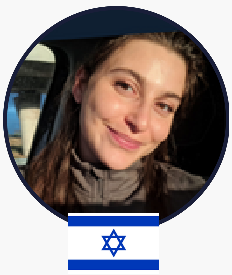

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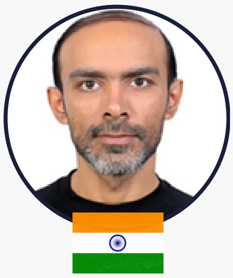

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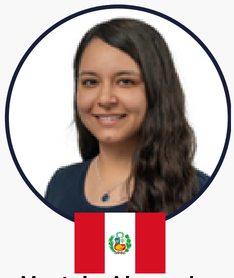

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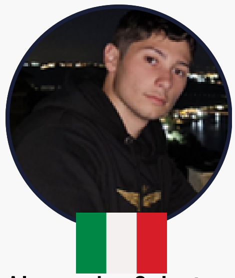

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LUNAR INFRASTRUCTURE
SSP2025

Faculty Preface

This report examines the future of sustainable infrastructure on the Moon. Fifty years after the Apollo missions, preparations are being made for humans to return to the Moon with unprecedented international cooperation and commercial participation. The Artemis program, led by NASA, is preparing for sustained lunar operations near the south pole. China and Russia are developing the International Lunar Research Station, while numerous other national and commercial entities are planning lunar activities. This convergence of government and private sector initiatives presents both tremendous opportunities and significant coordination challenges for establishing sustainable infrastructure that can support diverse lunar operations.

How should lunar infrastructure be designed to accommodate this variety of activities? How can spaceports and supporting systems be developed to enable everything from scientific research and resource extraction to emerging lunar tourism while ensuring long-term sustainability? These were some of the central questions addressed by the authors of this report.

The 37th edition of the Space Studies Program (SSP), SSP25, took place from June 30 to August 22, 2025, in Seoul, South Korea, hosted by Hanyang University ERICA Campus in partnership with the Korean Federation of Science and Technology Societies (KOFST). The SSP is an intensive eight-week interdisciplinary program covering all aspects of space activities, from technical and scientific foundations to policy, business, and societal implications.

The team project serves as an important culmination of the program, requiring participants to integrate their diverse backgrounds and apply interdisciplinary knowledge to address complex space challenges. This year, 43 international participants from 25 countries contributed to this report on Sustainable Lunar Infrastructure. The team brought expertise spanning physics, engineering, architecture, information technology, life sciences, economics, business, management, policy, and law, and worked together to identify opportunities to bridge the gap between public and private lunar initiatives.

The participants exhibited remarkable enthusiasm and creativity, generating more than 200 initial ideas during brainstorming sessions. From this wealth of concepts, they chose to focus on the future of spaceports on the Moon, examining both near-term practical requirements and long-term visionary possibilities. The team also identified that lunar spaceports will serve as critical convergence points for the diverse activities they envision: international scientific missions, commercial mining and manufacturing operations, and the emerging field of lunar tourism. While united by this common focus on spaceport infrastructure, participants were able to pursue their individual interests by examining different technical, operational, and policy aspects of sustainable lunar infrastructure development, while identifying logistics as a core enabler for a sustained presence on the surface of the moon.

We hope this comprehensive examination of sustainable lunar infrastructure, produced through genuine international collaboration, will contribute valuable insights toward establishing a robust foundation for humanity's expanding presence on the Moon.

Eric Dahlstrom, Chair
Joshua Kassulke, Teaching Associate

Participants Preface

This report reflects the work of an extraordinary group of human beings from different cultures, nationalities, and backgrounds who chose to dream together and contribute, each from their own perspective, to a shared vision: establishing sustainable plans for lunar spaceport infrastructure in both the short and long term.

Lunar spaceports are a key enabler of sustainable human activity on the Moon. They will act as the physical liaisons between Earth, the lunar surface, and our destinations beyond our natural satellite. Spaceports will act as a transportation hub for (cis)lunar supply chains, logistics and tourism. They will act as a hub of robotic and human activity, a (temporary) home and workplace for tens to hundreds of humans. Because of that, the aspects of sustainability and human-centric design play a key role when imagining lunar spaceports. We hope that this work serves as a starting point for continued exploration, and that in the years ahead, some of these ideas may take shape in the lunar infrastructure.

This report became a blank canvas on which each participant left their mark, exploring topics that connect not only to the chosen research area but also to their own passions. Every contribution that made this project possible comes from professionals who dared to dream and, through their own fields of knowledge, committed themselves to this common goal. By approaching the subject of spaceports through both short- and long-term perspectives, we created spaces in which all members of such a diverse team could feel represented and contribute their strengths, turning this report into an exceptional piece of work despite the time limitations we faced. We acknowledge the individual dedication of every contributor to this report who ensured we are adding value to the future of lunar exploration.

In this report, the three Is of the ISU - international, intercultural, and interdisciplinary - truly shine. The diversity of our nationalities and cultural backgrounds was a powerful driver of creativity and pushed us to step outside our comfort zones, while the interdisciplinary nature of this project gave the report its distinctive character.It is precisely this diversity in every sense that makes it clear that the future of space exploration will only be possible if we work together.

In the end, this report is not only about presenting professional research. It is also a reminder that we are space dreamers who aspire to make a lasting impact, not just in the space sector, but for all humanity.

Ad lunam et astra!

Nomenclature

Δv delta-v

ADD Architecture Definition Document

AFS Augmented Forward Signal

AI Artificial Intelligence

AoA Angle of arrival

ARCHES Autonomous Robotic Networks to Help Modern Societies

ATS Air Traffic Services

C-LNS CisLunar Navigation System

C-STCM Cislunar Space Traffic Control and Monitoring

CHeCS Crew Health Care System

CLTM Cislunar Traffic Management

CO_2 carbon dioxide

COMM Mission Control and Communications

DARPA Defense Advanced Research Projects Agency

DLS Deployable launch system

DoA Direction of arrival

ECLSS Environmental Control & Life Support Systems

EM Electromagnetic

ESA European Space Agency

EVA Extravehicular activity

FBO Final Base Operator

FLOAT Flexible Levitation-on-track

GCRs Galactic Cosmic Rays

GNSS Global Navigation Satellite System

GPR Ground-penetrating radar

GPS Global positioning system

HAB Housekeeping / Habitation

HMI Human Machine Interface

HRI Human Robotic Interaction

ILRS International Laser Research Station

IMU Inertial measurement unit

IOC Initial Operational Configuration

ISRU In situ resource utilization

ISS International Space Station

ISU International Space University

ITU International Telecommunications Union

JPL Jet Propulsion Laboratory

KPLO Korea Pathfinder Lunar Orbiter

LANS Lunar Augmented Navigation Service

LCROSS Lunar Crater Observation and Sensing Satellite

LED Light-emitting diode

Lidar Light Detection and Ranging

LLP Launch and Landing pad

LMIG Landing–Moving Integrated Gear

LNSS Lunar Navigation Satellite System

LOX Liquid oxygen

LRO Lunar Reconnaissance Orbiter

LSP Lunar South Pole

LSPF Launch Site Processing Facilities

LSS Lunar Surface System

LUPEX Lunar Polar Exploration Mission

maglev Magnetic Levitation

METERON Multi-purpose End-To-end Robotic Operations Network

MI&CT Maintenance, Integration & Cargo Transfer

MLI Multi-layer insulation

MMNs Mobile Mesh Nodes

MOB Surface Mobility

NASA National Aeronautics and Space Administration

NHV Net Habitable Volume

NRHO Near-Rectilinear Halo Orbit

OST Outer Space Treaty

P&GI Propellant Transfer Systems & Ground Infrastructure

PadOps Pad Operations

PMAD Power Distribution & Management

PMS Power Management System

PNT Positioning, navigation, and timing

PSR Permanently shadowed region

RFCESS Regenerative Fuel Cell Energy Storage System

RTB Reverse turbo-Brayton-cycle

RTG Radioisotope Thermoelectric Generators

RUL Remaining useful life

SM Service Module

SMAC Spacecraft Maximum Allowable Concentrations

SNR Small Nuclear Reactors

SOFIA Stratospheric Observatory for Infrared Astronomy

SRC Scent recreation capsule

SSP Space Studies Program

SSPS Space Solar Power Systems

TCS Thermal Control System

UHF Ultra high frequency

UN	United Nations
UV	Ultra-violet
VIPER	Volatiles Investigating Polar Exploration Rover
VOC	Volatile organic compound
WAC	Wide Angle Camera
ZBO	Zero boiloff

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Executive Summary

This paper presents the methodology, analysis, and key findings from the 2025 International Space University (ISU) Space Studies Program (SSP) team project on sustainable lunar infrastructure. Through an interdisciplinary approach spanning the space sciences, engineering, applications, human performance, humanities, management, law, and policy, we conduct a systematic examination of critical infrastructure requirements for long-term lunar presence that are environmentally and operationally sustainable long-term lunar presence.

This report explores the design and infrastructure for a lunar spaceport and its immediate surrounding infrastructure in the short-term ("the mission"), starting from the initial Artemis and ILRS concepts, and in the long term ("the vision"). Central to this report is the evolution from an initial Launch and Landing Pad (LLP) to a multifunctional and multipurpose hub with five LLPs and a human-centric habitation environment, effectively enabling scientific, commercial, and strategic activities on the Moon and beyond.

The report opens with an investigation into site selection near lunar poles for access to water ice, processing systems to convert raw materials into usable forms, and autonomous maintenance technologies. The team proposes de Gerlache Rim 2 as the location, primarily for its proximity to the South Pole. Subsequently, the report addresses the phased construction of an LLP, outlining a paved, sintered regolith floor, and taking lunar dust mitigation into consideration through an internal and external berm and a plumb redirection system. The suggested design progresses from an Initial Operational Configuration (IOC) to a Final Base Operator (FBO) model, reflecting operations at terrestrial airports while being designed for the specific conditions of the lunar environment. A phased hybrid transport architecture focusing on low-power rail systems enables scalable offloading and logistics. Furthermore, we propose a holistic communication and navigation infrastructure, complemented by existing proposals such as NASA's LunaNet and the use of a multi-purpose radio tower for integrated telecommunications, navigation and solar power generation. For governance, this report proposes the creation of an international Lunar Council, composed of public and private actors, as well as a Lunar Credit System to ensure fair, sustainable, and collaborative lunar development. Finally, a Lunar Tribunal will complement governance, establishing a framework for dispute resolution in accordance with existing international law.

Based on the findings from the short-term case study, this report subsequently focuses on the long-term vision of a sustainable cislunar future. It investigates the requirements for a multipurpose spaceport capable of servicing up to 10 daily launches and landings, which supports an external permanent settlement. The project team proposes a comprehensive lunar communication system, integrating radiofrequency and optical networks, satellite constellations,

and mobile relays for continuous low-latency, high-throughput links. The CisLunar Navigation System (C-LNS) could combine legacy constellations with advanced future technologies, such as quantum inertial sensing for reliable location, navigation, and timing. We envision the Cislunar Space Traffic Control and Management (C-STCM) system as an AI- and quantum-enabled framework ensuring safe and efficient operations in the Earth-Moon corridor. Furthermore, we intend the long-term spaceport to serve as the core of a multi-layered, high-capacity transportation network that connects polar hubs, resource locations and communities, and is supported by advanced infrastructure including orbital depots, fueling stations, and maglev trains. Integrating flywheels, solid-state batteries, and regenerative fuel cells will meet energy needs, which will be supported by a hybrid generation mix including space solar power satellites. Moreover, this report found that a crucial enabler for a sustained, long-term human presence is a human-centric design approach, ensuring physical and psychological well-being on the Moon. The proposed human-centric design integrates architecture with neuroscience and bioengineering to optimize space, safety, and wellbeing through dynamic lighting, ergonomic zones, and immersive biophilic elements such as natural sights and scents. This report also designs an autonomous, digital twin-enabled Environmental Control and Life Support System (ECLSS) for real-time monitoring. Finally, the report proposes leveraging blockchain technology for transparent resource tracking, transaction regulation, and rights allocation, while implementing smart contracts to further streamline operations. This spaceport economy would incorporate legal, commercial, and technological frameworks to facilitate sustainable governance, resource management, and tourism. Complementing this economic discussion is a modeled exploration of lunar tourism packages that would facilitate the financial sustainability of the lunar spaceport.

This ISU SSP team project contributes a comprehensive, interdisciplinary perspective on lunar infrastructure development that can inform both near-term mission planning and commercial lunar development. It also explores long-term visions for humanity's sustainable presence beyond Earth. The findings support the acceleration of in-space industry by envisaging a short-term spaceport design that paves the way for a long-term multipurpose spaceport capable of serving as a hub for logistics and human activity, which will be crucial for establishing a space-based economy.

Introduction

"We do not obtain knowledge by standing outside of the world; we know because we are of the world. We are part of the world in its differential becoming." - Meeting the Universe Halfway, Karen Barad (2007).

Humanity's evolution beyond our planet and into interstellar spaces is a reality within proximity. As we aim to return to the Moon, we not only hope to revisit but also to nurture a grounded presence of humans on the lunar surface, driven through sustainable practices. Building upon the established phases of the Artemis and China–Russia ILRS programs, this report curates a vision of humanity's progress and growth on the first visited extraterrestrial surface. With this intention, we address the establishment of a spaceport, being the epicenter of all the continued operations. With the vision of the spaceport as an enabler for all future work on the Moon, transportation is identified as a link between lunar, cis-lunar, and beyond-the-Moon exploration for humanity. This multifunctional facility can serve as a central hub for mobility, logistics, and operations. Considering the initial aspects that are required for a sustainable lunar presence, we identified research gaps in literature and existing mission proposals, particularly on the issue of lunar dust stirred in motion during landing or launching operations. Additionally, multiple international stakeholders such as governmental, non-governmental, and commercial are now developing critical technologies for the Moon. These include landers, rovers, power systems, and communication systems. However, there is limited research on how to integrate these efforts into a shared, scalable spaceport. A coordinated approach is needed to support multi-user surface operations. In particular, there is a gap in planning for a modular spaceport that will allow transportation to the Moon, back to Earth, and into deep space. Despite humanity's dreams for a sustained lunar presence, existing mission concepts focus on short stays and temporary structures, without addressing long-term requirements for a permanent human presence such as energy solutions, connectivity, autonomy, economics, and law. Addressing this gap through a thriving and sustainable lunar spaceport is essential to guide the transition from temporary exploration to enabling a long-term transportation link that supports cislunar travel.

This proposal aims to define the foundations of such a multipurpose lunar spaceport. It emphasizes the significance of modularity, interoperability, and early compatibility with international frameworks. The goal is to support initial surface activities while allowing for long-term expansion and sustainable use. By focusing on shared infrastructure and international collaboration, this research supports a more efficient and inclusive lunar presence. These inquiries/questions are approached by dividing the research focus in the framework of a timeline-based study. The vision of a spaceport infrastructure is divided into two focal points:

developing humanity's progress post-Artemis/ILRS missions in the short term, followed by a futuristic vision of humans living on the Moon. Both of these case studies are built on specified points of departure to ground the proposals in the specified timeline. Short term mission is built on the following guiding principles:

- Artemis and ILRS programs exist and are successful
- Current lunar governance and legislations will be preserved
- Government and private companies are working together and a relationship has been established
- Habitat module exists and can support life
- There are antennas on Earth that can communicate with the lunar base only intermittently so there are also satellites in lunar orbit to support and continuously maintaining it

Long term vision is built on the following assumptions:

- Same location as the short term case study
- External infrastructure of the spaceport has been further developed during the short term timeframe
- The spaceport includes five launch pads; there will be five landings and five launches per day, four of the rockets being for cargo and one for passengers
- The spaceport services an external permanent colony of 1000 people
- Legislations established in the short term guide new space missions/activities

It is notoriously difficult to predict the future. To ground our assumptions regarding the short-term and long-term scenarios we are working with in this report, we have referred to a strategic foresight study by (Kunzeman et al., 2021) in which the authors have conducted a futures model analysis that provies four archetypes of future storylines: growth, collapse, discipline, and transformation. Based on several drivers, trends and signals relating to the development of the space industry, the authors provide four scenarios for future spaceflight:

- Growth: Modest Expansion of Lunar Capabilities
- Collapse: No Escape Velocity from Earth's Problems
- Discipline: Risk Drives Robots (Not Humans) to Mars (and the Moon)
- Transformation: Space Serving Abundance for Humankind

For the purpose of this study, we will assume two scenarios. For the short-term mission, we will assume the growth scenario, while we will assume the transformation scenario for the long-term vision. Within the growth scenario, technology advances predictably, the space economy triples in size but stays dependent on government support, and benefits from lunar activity are not widely recognized as solutions to terrestrial problems (Kunzeman et al., 2021). Within the transformation scenario, revolutionary space technology is developed, international efforts allow for safe and sustainable exploration, humans and robots work together harmoniously

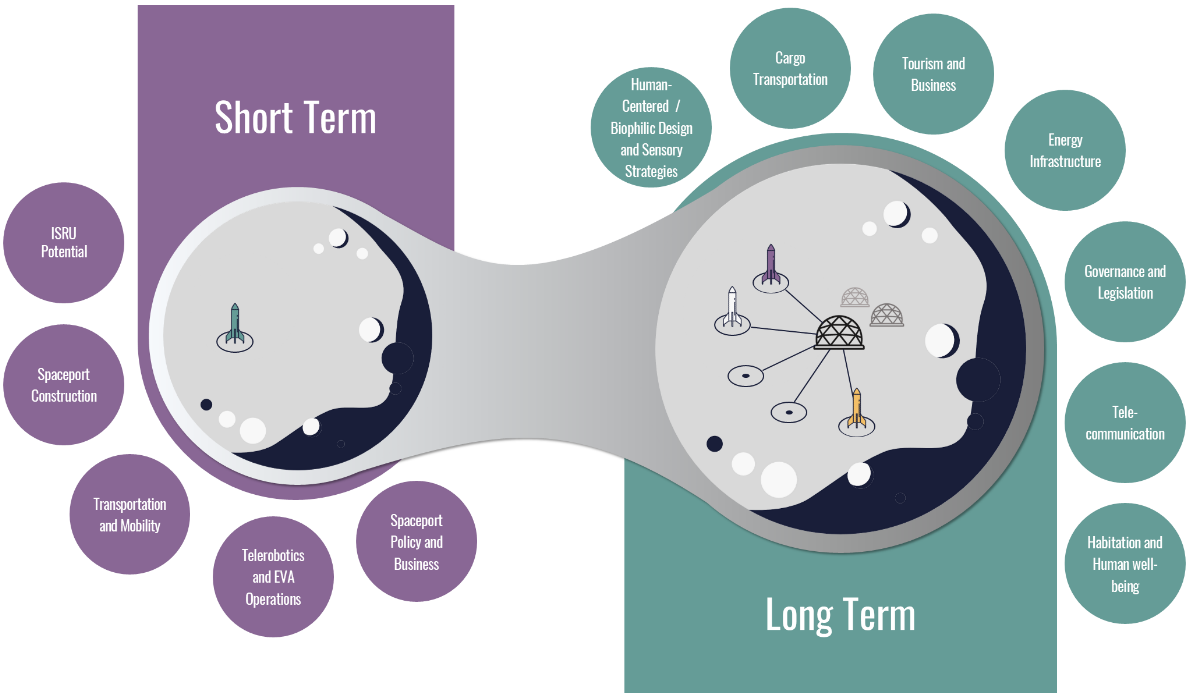

Figure 1: Interdisciplinary vision of Short- and Long-Term case studies.

and efficiently, and lunar spaceports become key resources for energy, communication and other critical space-based technologies (Kunzeman et al., 2021). Designing a paradigm for interplanetary human exploration requires an interdisciplinary vision. The short term case study (see Fig.1) addresses major topics to create the groundwork for spaceport infrastructure, including construction, ISRU potential, spaceport policy & business, telerobotics & EVA operations, and transportation & mobility. Developing this groundwork further, the long term case study reimagines humanity's growth in the future, beyond the establishment of the spaceport, and focuses on human-centered and biophilic design principles in addition to sensory strategies, cargo transportation, tourism and business models, energy infrastructure, governance and legislation, habitation and human well-being, and telecommunications. The research design curated for this project intended to address the research questions through interdisciplinary, creative, and critical approaches. The methodological approach involves propositions in the form of model-building and experiment design. This report is also complemented with a website as an extension composing multimedia content. Collectively, they form a hybrid publication, developed with the intention to compile and transmit any evolving propositions and exist as a living document shared and nurtured by the authors.

Alongside the exploratory nature, the role and significance of sustainability in the context of lunar infrastructure are addressed here. The approaches proposed in the short term intend to provide an action plan beyond the currently established lunar exploration missions and investigate ways in which sustainability in the context of survival may be approached. Alternatively, the long term based its propositions on the sustainable living of humanity in a lunar habitat while maintaining interconnectivity with Earth. Fig. 2 illustrates a reimagination of the UN sustainability goals applied to the lunar society, recognizing the aspects that would facilitate humanity's return to the lunar surface and nurture a meaningful and sustainable

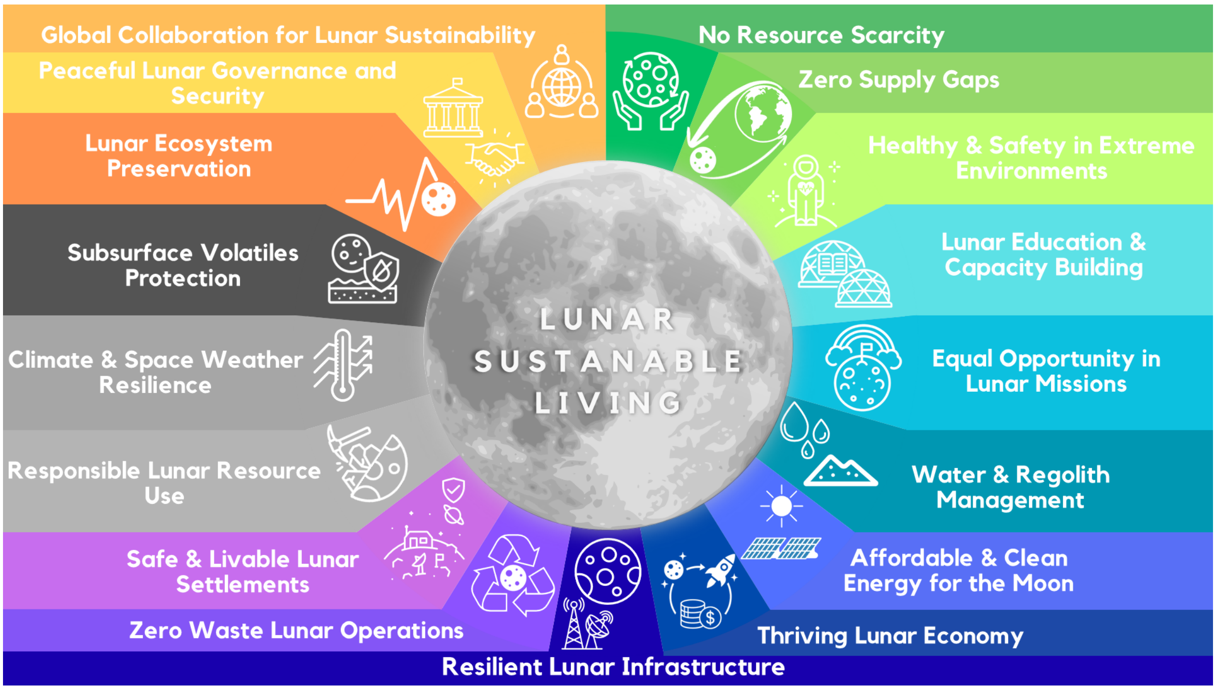

Figure 2: Re-imagining the UN Sustainability Goals for Sustainable Lunar Living.

relationship with other members of our solar system. This framework addresses different considerations of sustainable living in the context of developing a lunar society. The notion of sustainability takes form in three main domains: *collaboration, continuity, and cultivation.*

The collaboration goal involves creating peaceful lunar governance and security as well as promoting equitable opportunities in lunar missions across nations; realizing the vision of lunar society necessitates harmonious collaboration between all members of the emerging space economy. Continuity domain considers approaches for survival, including space weather resilience, subsurface volatiles protection, and security of lunar settlements. Furthermore, it responsibly addresses the concerns of lunar ecosystem preservation and responsible use of lunar resources by conducting zero-waste lunar operations and water and regolith management. Assuring affordable and clean energy for the Moon is one of the factors that fall under the third domain, Cultivation, which supports the vision of a beyond-survival scenario, which entails no resource scarcity with no supply gaps. This is the stage in which humanity has established a thriving lunar economy that fosters knowledge building and an unprecedented trans-terrestrial capability.

Short Term Mission

1.1 Spaceport Architecture and Infrastructure

1.1.1 Introduction

Humanity's return to the Moon marks a crucial step toward a sustained presence beyond Earth. As exploration programs shift from short-duration visits to permanent outposts, the development of robust surface infrastructure becomes essential. A lunar spaceport, capable of supporting frequent landings, launches, and logistics operations, will serve as the central piece in an emerging transportation network. The spaceport is more than just a launch and landing site. It will eventually become a place where scientific activity and ISRU are conducted. Designing this type of complex facility requires an integrated approach that balances environmental constraints, engineering requirements, and operational capabilities.

The process begins with site selection which is shaped by several technical criteria. These include power availability, resource access, surface safety, communication links, and terrain suitability for construction and transport. The Lunar South Pole (LSP) has emerged as a focus for international exploration efforts due to its unique environmental and geological characteristics. Locations in this region offer extended periods of sunlight for power generation, proximity to permanently shadowed regions (PSRs) that may contain valuable volatiles, and natural topographic features that could support infrastructure placement. Environmental factors such as abrasive dust, extreme temperature fluctuations, and difficult lighting conditions must also be considered because they influence how the spaceport is designed at the selected site.

Once a site is identified, considerations are taken to determine how to construct infrastructure that is capable of withstanding repeated operations in the Moon's harsh environment. Building infrastructure on the Moon requires strategies that can be implemented in both the short term to support early missions, and the long term to provide durable, sustainable facilities. This infrastructure construction topic considers two broad approaches for the development of lunar launch and landing pads (LLPs). The first is deployable or temporary systems, which can be quickly set in place using prefabricated or modular components delivered from Earth. The second is permanent structures built using ISRU techniques, particularly through the processing of lunar regolith. Within this topic, we consider the mechanical and thermal demands placed on LLPs, the methods for mitigating surface erosion, dust dispersion and radiation exposure, and potential ways to integrate natural features such as craters into the construction plans. The layout and spatial organization of the spaceport, including consideration for safe distances between operational zones and provisioned zones for future expansion are also explored.

Advanced robotic systems are central to both site preparation and ongoing operations.

Autonomous and teleoperated machines will perform tasks critical to the spaceport's lifecycle, including initial environmental surveys and infrastructure assembly. Robotic systems can operate in conditions that are hazardous or impractical for human crews, which enables nearly continuous activity in the challenging lunar environment. These systems will transport materials, build landing pads, install utilities, and maintain equipment, while minimizing human exposure to lunar hazards. Their integration into the spaceport's implementation ensures that infrastructure can be constructed, maintained, and adapted.

This case study considers all these aspects together to form the framework for developing a spaceport capable of supporting the next era of lunar exploration. The proposed framework builds off the NASA Artemis program and the ILRS. The case study strives to expand beyond these two plans to create an original and useful guide for short-term spaceport success.

1.1.2 Lunar Spaceport Location, Resources, and Environmental Challenges

Site selection criteria and environmental context

The main criteria for establishing ideal landing sites for permanent bases on the Moon vary as priorities change over time, especially as missions progress from Foundational Exploration to Sustained Lunar Evolution (NASA, 2023a). General requirements can be summarized as (NASA, 2025c):

- *Scientific and Exploration Value*: entails accessing and sampling volatiles and reaching diverse geological formencompasses proximity to and potential for IRSU, such as water ice, regolith-based oxygen, metals, and silicon
- *Power Availability* (e.g., solar or nuclear)
- *Accessibility and Landing Site Safety*
- *Line of Sight to Earth*: considerations for direct communication with the Earth for early missions (before establishing a relay)
- *Thermal Environment*
- *Surface Mobility and Logistics Support*: considerations for rover and lunar transportation designs

For the spaceport location in the near-term horizon, access to cost-effective and abundant power is the most critical factor. The other priority is the ability to explore ISRU in terms of the extraction of hydrogen and oxygen from water ice, even though performing this from PSRs in the lunar poles is likely to be technically challenging due to extremely low temperatures and remote access solutions that would be able to operate in such conditions to drill and extract the volatiles.

It is worth considering that launching and landing on the south pole of the Moon requires aligned launch windows with Earth, which brings its own set of technical challenges. These include larger delta-v requirements, environmental concerns and communication needs. Some of these aspects, especially communication, will be explored in detail in the following chapters. We are assuming that the spaceport facility will service a small research base facility with a rotating crew.

Focus on the Lunar South Pole

The LSP is the primary planning focus of NASA's Artemis program, the Chinese Lunar Exploration Program (Chang'e) and the future ILRS. This case study builds on the Artemis plans and their projected time frame. The study assumes a successful return of human missions to the Moon and continued progress in scientific research. It also expects that robotic and human field work will continue to focus on the LSP, including successful sample return programs from the PSRs.

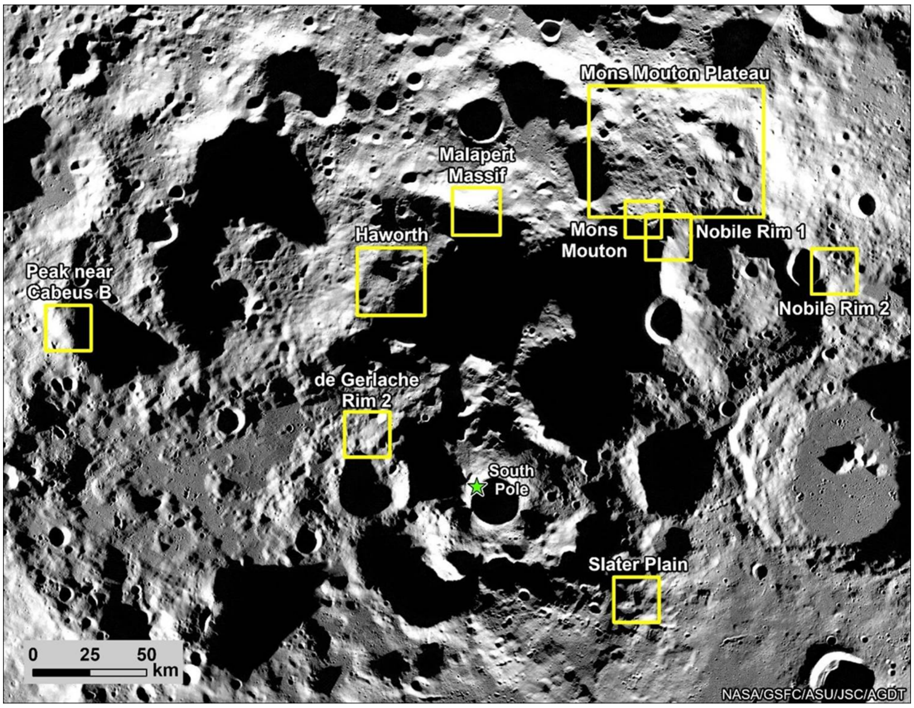

Figure 1.3: The image shows nine candidate landing regions for NASA's Artemis III mission. Background image of the LSP terrain within the nine regions is a mosaic of Lunar Reconnaissance Orbiter(LRO) Wide Angle Camera(WAC) images. (NASA, 2024b)

The case study proposes adopting one of the selected 2024 Artemis III locations (See Fig. 1.3) as a representative location for the spaceport. The selected site in the LSP is *de Gerlache Rim 2* (See Fig. 1.4). This site has been selected with the criteria described above in mind, primarily for its proximity to the LSP at approximately 88°S. It offers access to volatile-rich PSRs and benefits from near-continuous sunlight during the lunar summer, providing extended illumination periods on an elevated terrain. The site topography provides many structural options for large-scale shielding between the spaceport and a future base or habitat. Additionally, due to its position on the near side of the Moon, the site allows opportunities for direct line-of-sight to Earth, which enables high-bandwidth communications without the need for orbital relays.

Resource Availability and Utilization Potential

Surface-Accessible Volatiles

Beyond the inherent geological and environmental advantages, the LSP also offers a key operational asset for establishing a sustainable lunar spaceport: its richness in surface-accessible

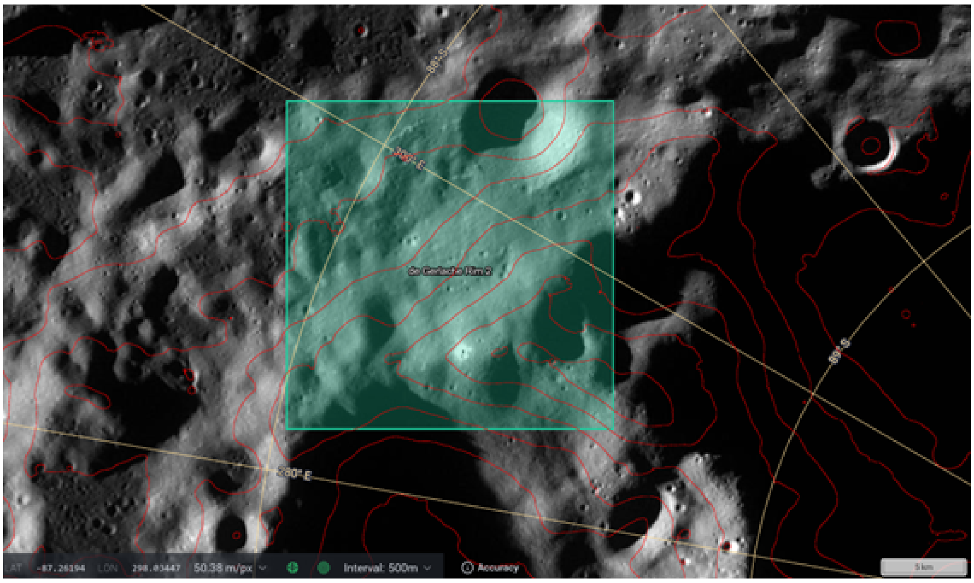

Figure 1.4: Detailed view of the *de Gerlache Rim 2* location showing topographical variability and abundant impact craters of all sizes. Orthographic projection of the LSP with LROC WAC base map. Credit: ATC Lunar/LROC

volatile deposits, particularly water ice, concentrated in PSRs (Kring et al., 2021). While these volatiles hold significant scientific value for answering vital questions for both terrestrial and in-space applications, their practical utility for sustaining and expanding lunar operations is equally compelling. These volatiles consist of chemical elements and compounds that evaporate, sublimate, or flow at very low temperatures, including substances such as hydrogen (H), water (H_2O), helium (He), carbon dioxide (CO_2), and carbon monoxide (CO) (CLRN, n.d.). Their presence is highly variable depending on the surface analyzed, reflecting diverse chemical processes that impact soil conditioning and biogeochemical absorption-loss cycles (Shearer et al., 2024).

Remote sensing and impact probe data from missions such as NASA's Lunar Reconnaissance Orbiter (LRO) Mission; Lunar Prospector Mission; Lunar Crater Observation and Sensing Satellite (LCROSS) Mission; Stratospheric Observatory for Infrared Astronomy (SOFIA) Mission (See Fig. 1.5); and India's Chandrayaan-1 Mission all confirmed the presence of water ice and other volatiles in south polar PSRs (Lucey, et al., 2022; Mahoney, 2022; Sharghi, 2023).

These deposits are thought to be remnants of ancient cometary and meteoritic impacts, as well as elements carried by the solar wind and outgassing from the Moon's interior, preserved for billions of years in regions that never receive direct sunlight. The extreme cold, often below –200°C, prevents sublimation, allowing significant quantities of volatiles to remain trapped within the regolith just centimeters to meters below the surface. PSRs therefore serve as natural laboratories to study the effects of temperature (in illuminated surfaces) and volatile abundance (most likely enhanced in the PSRs) on the Moon's regolith evolution.

Utilizing volatile deposits is central to the objective of establishing a spaceport at the LSP. Water ice is particularly important because it can be split into its constituent hydrogen

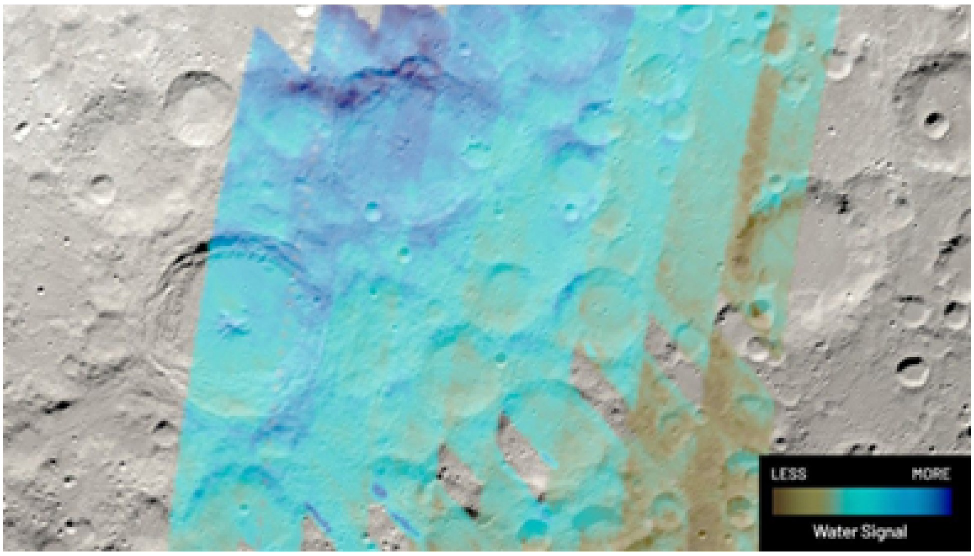

Figure 1.5: SOFIA map of potential water ice near the Moon's South Pole (Sharghi, 2023)

and oxygen through electrolysis, providing essential resources for life support and rocket propellant. From a sustainability perspective, these deposits can be transformed into operational enablers through ISRU, thus drastically reducing dependence on Earth-based supply chains (Kring et al., 2021). Lastly, to fully understand the potential of these deposits, robotic in-situ measurements, including drilling and sampling, will be needed to determine the exact nature and extent of the ice and other cold-trapped volatiles at or just below the lunar surface.

Current and Future Missions

Landing sites that allow access to potential volatile deposit areas are the current target of many robotic missions and are proposed in the Artemis human exploration program (Kring et al., 2021). The most relevant missions are described on our website.

These robotic missions play a critical role in preparing the groundwork for establishing an LSP spaceport. The missions provide valuable scientific and engineering data to support lunar surface infrastructure design by mapping the distribution of volatiles, characterizing regolith properties, and testing extraction technologies. Missions such as Chandrayaan-3 and the Korea Pathfinder Lunar Orbiter (KPLO) Mission contribute high resolution surface and subsurface data, which refines understanding of PSRs and their resource potential. Other missions like Lunar Polar Exploration Mission (LUPEX) and Chang'e-7 aim to directly sample and analyze volatiles in-situ, which validates remote sensing observations and advances ISRU capabilities.

Technological Challenges

Turning PSR volatiles into usable fuel presents some challenges. ISRU technologies must be adapted to the Moon's harsh environment where extreme cold, abrasive dust, and limited solar exposure complicate mining and processing operations (Rapp, 2006). Technologies under development include heated augers for regolith extraction, microwave or thermal mining to release volatiles, and cryogenic storage systems to contain liquid hydrogen and oxygen (Shearer et al., 2024). Current robotic platforms also have difficulty in these extreme environmental conditions which limits exploration of the PSRs. For example, NASA's Volatiles Investigating Polar Exploration Rover (VIPER) rover, despite its advanced payload for volatile detection, remains restricted in PSR access due to its reliance on batteries and solar power, which are ineffective in areas without sunlight. Fully characterizing these regions would require rovers capable of extended traverses, equipped with instrument suites equivalent to those deployed on Mars exploration missions.

Regolith and Dust: Hazards and Engineering Considerations

Physical and Chemical Properties of Lunar Dust

Lunar regolith is composed of extremely fine, angular grains with high energy, making it both abrasive and electrostatically sticky (Abbas et al., 2008; NASA, n.d.-h). In the Moon's ultraviolet-rich airless environment these particles acquire charge and can levitate (producing the observed horizon glow), creating a persistent charged dust layer near the surface (Abbas et al., 2008). In practice this clingy dust scourges hardware: Apollo crews found spacesuit fabrics and boots eroded within hours, and cameras and vacuum cleaners jammed by adhered fines (Hong et al., 2024). Dust coating solar arrays, thermal radiators, and optics degrade their performance significantly reducing power output and sensor sensitivity (Hong et al., 2024). Moreover, lunar dust's nano-scale metallic iron and fractured surfaces, with particles below 10 μm that are respirable, can induce lung-inflammation, oxidative stress, and other health issues when lifted by lander plumes or rover wheels (Hong et al., 2024). Dust can also infiltrate airlocks, abrade seals, filters, joints, and even rover mobility suffers when settled dust reduces traction and progressively wears wheel treads and actuators. Apollo mission reports noted that surface dust was so pervasive it "impeded crew health and operations" (NASA, 2020).

These challenges become even more critical in the context of developing a lunar spaceport, which must accommodate repeated landings, surface mobility, and human presence over extended durations. Each landing event risks lofting high-velocity dust that can erode landing pads, degrade nearby infrastructure, and endanger arriving or docked vehicles. Over time, dust accumulation could compromise thermal systems, power generation, and mechanical reliability across the facility. Therefore, any lunar spaceport design must integrate comprehensive dust-mitigation strategies including hardened landing surfaces, protective enclosures, dust-tolerant mechanisms, and environmental sealing, to ensure long-term operability, crew safety, and sustainable infrastructure on the Moon (Abbas et al., 2008; NASA, 2020).

Dust Mitigation Strategies for Spaceport Operations

In the design and operation of a sustainable lunar spaceport, dust mitigation strategies fall into four interdependent categories: dust generation avoidance, passive mitigation, active mitigation and dust-tolerant design. Each of them addresses a different stage of the dust lifecycle and must work in concert to be effective.

Dust generation avoidance aims to reduce the creation of dust at the source. Techniques include the construction of hardened landing pads, using sintered regolith or ceramic spray, and adding berms to deflect rocket plumes (Swiney & Hernandez, 2022). Operational measures, such as minimizing engine throttle near the surface or reducing rover speed, also reduce dust lofting (Miranda et al., 2023; Swiney & Hernandez, 2022). However, these measures can only limit - not eliminate - dust dispersion during high energy-operations like landings and launches.

Passive mitigation focuses on preventing dust from adhering to surface or entering systems. Hydrophobic or nano-textured coating and dust-resistant seals (e.g., Teflon, fiberglass) offer protection without requiring power (Cannon et al., 2022; Miranda et al., 2023). Yet, over time, these coatings can degrade, and seals may fail under continuous abrasion which makes them insufficient without regular cleaning and maintenance.

Active mitigation includes powered solutions that remove dust once it has settled. Electrodynamic dust shields, vibration modules, pressurized gas, and brushes help keep optics, solar arrays, and mechanical interfaces operational (Miranda et al., 2023). Still, these systems require power, maintenance, and integration with surface systems, making them complementary to but not a substitute for passive barriers and operational controls. Dust-tolerant design ensures critical systems can survive even when exposed to abrasive regolith. This includes the use of wear-resistant materials (e.g., zirconia or stainless steel), contactless magnetic bearing, and sealed or redundant mechanisms (Miranda et al., 2023). While crucial for reliability, tolerance alone does not prevent dust accumulation or system degradation.

Ultimately, no single strategy is sufficient on its own, therefore we propose a novel, integrated approach, combining terrain preparation, resilient hardware, surface coatings, and dust removal systems into a cohesive mitigation architecture. A key part of this vision is our proposed experiment investigating the use of variable-polarity electromagnetic fields to influence lunar regolith particles (See website). If undertaken, this study would track particle motion under controlled conditions to inform the design, sizing, and power requirements for an electromagnetic dust mitigation system capable of complementing electrostatic methods. Insights from such testing, when integrated with established mitigation techniques, could enable a scalable, high-performance framework to keep a lunar spaceport safe and operational over extended missions.

Prospecting and Surveying for Sustainable Spaceport Construction

Surveying for a placement of a lunar spaceport prior to its construction requires a detailed study of the surface conditions and sub-surface geology. Similarly to geotechnical works on Earth, prospecting and surveying techniques serve to minimize operational hazards and utilize available resources. Factors, such as subsurface structures, regolith properties and mitigation of dust and exhaust plumes should be addressed through a geoscience/engineering geology study before an infrastructure development. We are proposing a program of local geological and geophysical surveys that will enable an optimized placement of a launch pad and the surrounding infrastructure. The emphasis is on using in-situ bedrock where it is accessible on the surface (or where it can be excavated under a shallow layer of regolith), compacted layers of regolith itself, and impact geological features, represented by abundant craters of all sizes to position the spaceport facilities. These natural features will be complemented by manufactured construction elements, described further in the following chapters. This approach aims to enable a cost-effective, sustainable design that could be delivered within an established time frame and with realistic technology requirements.

Topography Considerations

This work proposes that a future habitat or a research base would not be in the direct line of sight from the spaceport infrastructure and ideally, it would be shielded by the natural topography and positioned topographically lower. For this study, the minimum distance of the landing pad from the habitat is assumed to be approximately 500 m (Ximenes et al., 2024).

Regolith Properties and Construction Materials

Understanding the sub-surface layering, mechanical aspects, and chemical properties of the local regolith is essential for a sustainable construction. Regolith material could be mechanically sorted by particle size to obtain slightly different mineralogical compositions related to its impact origin and source (Cannon et al., 2023). Sorting could be used to optimize mechanical properties for building material manufacturing. In some cases, the upper porous layer of regolith could be excavated to expose more compact, stable ground, which can then be used directly as a building surface or solidified with engineered binders to form a pad. Such in-situ utilization could reduce the need for transported materials, thus lowering construction costs.

Subsurface Characterization and Geophysical Methods

The lunar near-surface environment is expected to have the complex composition observed on Apollo seismic data due to a scattering effect caused by the shallowest layer of regolith (Blanchette-Guertin et al., 2012). There is already a good track record of geophysical and shallow drilling programs from the Apollo missions. The geophysical experiments conducted on the Moon included passive seismic measurements, heat flow, magnetic, electromagnetic (EM), and gravimetric surveys Bannister, 1973; Chi, n.d.; Latham, et al., 1970; Palmer, et al., 1970; Schubert & Schwartz, 1972). Technology and data analysis have significantly improved since the last geoscience-focused programs from Apollo 17. A more recent analysis of the legacy data demonstrates the value of current processing techniques when applied to existing lunar geophysical datasets (Sollberger et al., 2016).

The geology and shallow subsurface of polar regions are expected to differ substantially from Apollo landing sites due to thick megaregolith (Fig. 1.6, Fig. 1.7) and the absence or distribution of basaltic areas within the LSP's Aitken Basin (Krasilnikov, S. S., 2023). To minimize the extent and cost of launch pad surfacing, a detailed geophysical survey is required to locate compact subsurface layers with favorable geotechnical properties and high-rate regolith compaction. The prospecting methods to measure the thickness and porosity of the regolith are seismic and ground-penetrating radar (GPR) imaging that respond to elastic and electric properties, respectively. They could be complemented by diffusive-field geophysical methods such as EM and electric near-surface sounding that maps the electrical resistivity structure in the overall very resistive lunar environment. Schmelzbach et al (n.d.) propose mini-array geophones combined with an active source and complemented with GPR and EM measurements

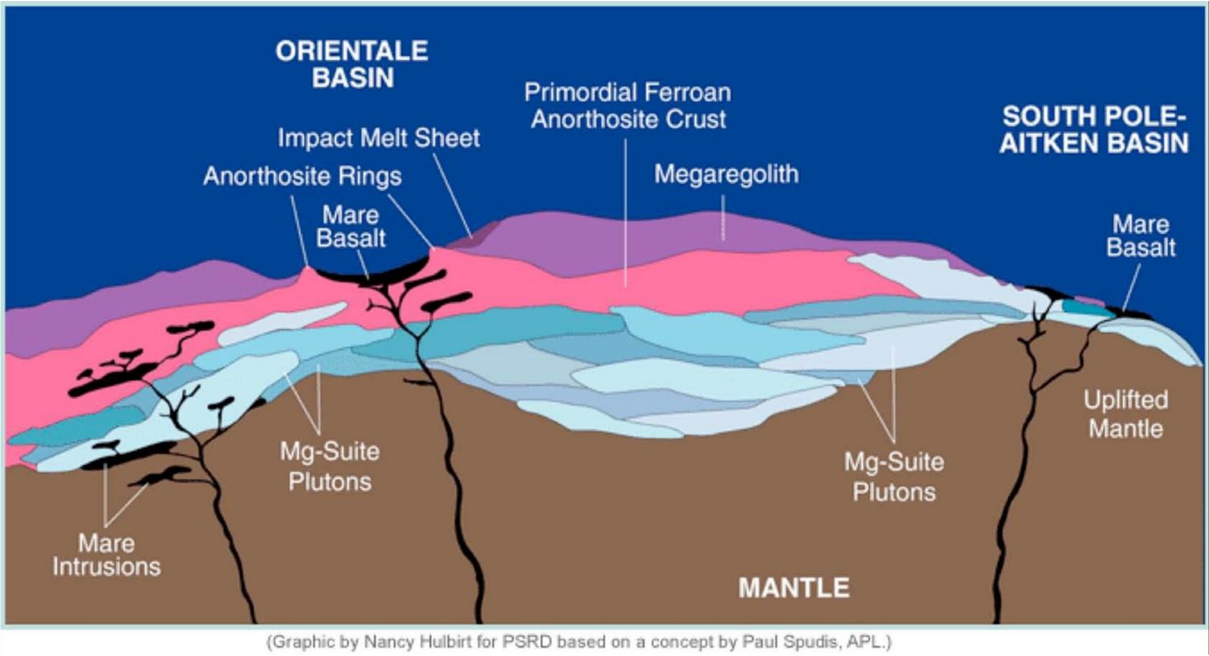

Figure 1.6: Schematic representation of the geological units in the Upper Crust (Anorthosite) and Lower Crust (Mg-suite) in the South Pole region.(Plescia et al., 2008)

to provide high resolution images of the subsurface structure and ground models to calibrate orbital radar measurements.

To further image the depth of bedrock under a thick regolith layer, we are proposing a structured program of 2D seismic-reflectivity profiles robotically deployed as a series of receiver geophones (ideally remotely connected to each other and to the processing unit) and with an active source of the frequency signal deployed as a small mobile vibroseis rover. Vibroseis is a technology used in the form of mobile truck vehicles in onshore seismic acquisition surveys on Earth. More datasets could be acquired through gravimetry, magnetometry, and passive heat flow sensors on the ground which would provide a geotechnical and thermal profile of the landing site.

From site selection to spaceport infrastructure design

After identifying an optimal site for the spaceport and understanding its available resources, a design and construction of an operational infrastructure can begin. The infrastructure of LLP needs to endure mechanical loads, thermal stresses, and dust-plume interactions of each launch and landing. These requirements, along with availability of local construction materials, mitigation of dust hazards, and a required scale of the infrastructure will influence the pad's design and its construction methodology. The following sections explore how these factors shape the technical requirements, material choices, and operational layout for a sustainable LLP.

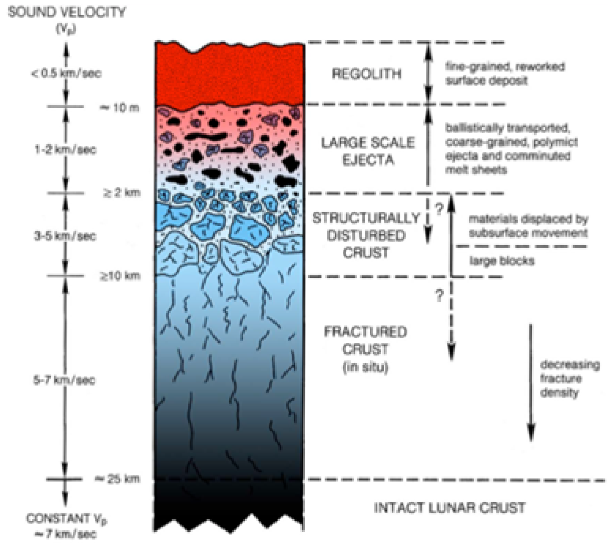

Figure 1.7: A schematic section of the megaregolith profile on the lunar surface. (Plescia et al., 2008)

1.1.3 Lunar Launch and Landing Pad Design and Construction

Context and Justification

The construction of a lunar LLP has been more recently considered as an essential step in the establishment of any longer-term position on the Moon, since landing on unprepared lunar surfaces can excavate tons of regolith, send high-velocity regolith particles transported by plumes (ejecta) that can reach ballistic trajectories greater than 2,000 m/s (Metzger, P. T., et.al., 2011) , and possibly even inject particles into lunar orbit. Therefore, lunar LLPs must have the capability to protect surface and orbital assets from debris damage and to provide solid, impervious surfaces for multiple landings near a permanent lunar facility (Ximenes, S.W., et. al., 2024).

This work presents a two-fold solution: First, deployable and temporary LLPs are considered due to ease of deployment and ability to be relocated, which makes them well-suited for scenarios such as supporting a base in a more accessible lunar region or establishing a hopper station on the Moon's far side. However, in the scope of our case study, the team is considering a scenario and a timeline in which these infrastructures would be implemented at the selected site on the LSP as a precursor to a permanent ISRU-based LLP. The second solution involves preparing a high–bearing-capacity subgrade by lowering the surface to a specified depth, then paving it with regolith bricks to create a durable landing platform (Okonkwo, C., et. el., 2025). This two-fold solution serves to support missions across lunar, cislunar, and beyond-the-Moon domains, and acts as a key factor in the broader architecture of space exploration.

Deployable and Temporary LLPs

While not the main focus of this work, deployable and temporary LLPs plug the gap in development of lunar infrastructure in the very early stages, both in the chosen site location and in other future relevant landing sites anywhere on the surface of the Moon.

The deployable solutions are mainly characterized by their movability, making it possible to reposition them according to the needs derived from the lunar exploration missions. Possible solutions for deployable LLPs identified through our literature study are:

- Using a flexible carbon-fiber blanket that robotic systems, such as rovers, can compactly stow for launch and easily deploy on the lunar surface. Astronauts can also perform the deployment during Extravehicular Activity (EVA) in contingency scenarios. A key requirement is the capability to support both landing and launch operations, demonstrating an inherent reusability across multiple mission phases (Emilie Rusch, n.d.).
- Solutions more closely aligned to traditional style LLPs. Examples of this are the Deployable Launch system (Mantovani et al., 2016) and the Landing–Moving Integrated Gear system (Zhou et al., 2024).

Temporary LLP concepts present simplicity. Some of these solutions are:

- Injection of engineered particles into the rocket plume, creating a hardened landing pad during descent ("instant LLP concept"). This hardened regolith provides superior thermal and ablation resistance, reducing erosion and cratering (Matthew Kuhns, 2020).
- Plume-deployment offers a lightweight solution for dust ejecta mitigation as a temporary alternative to traditional landing pads. As a rocket lands on or launches from the lunar surface, the force of the rocket plume inflates this large toroidal membrane to shield the surrounding base from regolith ejecta, allowing for early base development to proceed unimpeded by environmental hazards (Coffin et al., 2025).

While modular and reusable systems offer scalable and autonomous solutions and enable rapid deployment, there are challenges associated with using them. These include deployment complexity, limited reusability, and strict mass and volume constraints. These systems could lay the groundwork for ISRU-built pads that will leverage local materials to achieve greater scalability and cost efficiency.

Permanent ISRU-built LLP

Lunar regolith and construction techniques

Sustainable human presence on the Moon requires the use of lunar regolith as a primary construction material, rather than transporting large quantities of building materials from Earth. The transportation of construction materials from Earth to the Moon could be cost-prohibitive, making the use of in-situ resources like regolith essential for sustainable construction (Okonkwo, C., et. al., 2025). Planned bases in the LSP region must address multiple engineering challenges, including:

- Protection against radiation and micrometeoroids
- Mitigation of debris hazards from rocket exhaust during landings
- Long-term structural durability in a vacuum and low-gravity environment

Lunar regolith and volatile deposits in the PSRs offer an abundant and versatile feedstock for ISRU, containing oxygen, iron, silicon, aluminum, calcium, magnesium, and titanium (Anand et al., 2012). It must be noted that lunar regolith characteristics can vary highly according to the locations, which can affect what can be made with it and how (the different methods are based on different types of lunar regolith). The main properties that may differ are grain size, particle shape (sphericity), chemical composition, and mineral composition (*Replicating the Lunar Surface*, n.d.).

In developing our spaceport, excavated regolith is transported as bulk raw material to a sorting station for processing, and various grain sizes are prepared for different purposes, such as using the larger grain sizes for gravel production for foundation underlayment and sieving less than 100-micron powdered regolith for brick fabrication. (WUST, 2024). The by-products from the sorting station are stockpiled in a materials yard or stored in a closed and controlled environment for commodity sales to future users and customers requiring bulk-sorted processed feedstock (Ximenes, S.W., et. al., 2024). This feedstock can be utilized for various purposes, including volatile extraction and oxygen beneficiation operations for fuel production or different metal extraction for additional building materials (NASA, n.d.).

The choice for the construction approach falls on lunar regolith brick pavement construction, beginning with excavating and manipulating bulk lunar regolith to prepare the LLP site and provide feedstock for construction materials (NASA, n.d.) that are put in integrated furnace-nozzle for in-situ 3D printing of bricks from molten lunar regolith. This single-step lunar regolith melting, brick forming and placement method doesn't require the use of grouts or mortar for landing pad creation (Ximenes, S.W., et. al., 2024). A cohesive LLP pavement is produced using an interlocking brick shape melded together, and the pavement's melting temperature and heating rate limit LLP pavement ablation during landing and launch (NASA, n.d.).

Material Strength and Durability

ISRU research on lunar construction materials largely focuses on maximizing compressive strength, which is naturally high in regolith-based structures. Compared to compressive strength, tensile strength is lower and less studied, despite its importance for structures exposed to impacts or operational vibrations. This case study explores adapting proven terrestrial reinforcement methods to lunar conditions.

The team proposes two complementary strategies:

- Post-injected molten metal reinforcement: incorporating hollow channels into 3D-printed regolith structures and filling them with molten high-tensile metal, replicating the load-bearing role of rebar.
- Fiber-reinforced regolith composite: mixing high-performance fibers, either imported from Earth or produced from lunar basalt, into the regolith matrix to improve tensile strength and crack resistance.

Both approaches show strong potential but face challenges such as high energy demands for in-situ metal production, limited data on material bonding in lunar conditions, and variability in off-Earth manufacturing. Addressing these gaps require laboratory tests, simulations, and eventual in-situ trials. If successful, these techniques could greatly enhance the durability and reliability of lunar infrastructure, supporting long-term human presence on the Moon.

Initial Operational Configuration (IOC) Site Layout

Designing an IOC is the first step towards establishing an infrastructure plan for a fully developed spaceport. When designing an IOC, considerations must be made for requirements of distances and arrangements of elements and construction timing. Drawing from (Ximenes, S.W., et. al., 2024) some of these would be:

- Power architecture should consider both nuclear and solar sources.
- Required time to reach IOC is three to nine Earth months or around 2,000 operating hours.
- Site layout should take advantage of the site's topology where possible to minimize rover energy requirements.
- The static power system tower and the base station communications tower should be installed at a higher elevation at the top of a nearby small hill.
- LLP location should also be selected based on minimum cut and fill volume and maximum utilization of the excavated regolith.

The IOC should envision the Final Base Operator (FBO) model, which would be analogous to a general terrestrial aviation airport and would offer services including vehicle maintenance, refueling, depot hangar space for refurbishment or materials recycling (Ximenes, S.W., et. al., 2024).

LLP in a Crater-Adapted Landing Infrastructure

One approach to LLP design is adapting naturally occurring lunar features. Small impact craters, particularly those with diameters between 50 and 100 meters, are abundant in the LSP region, as confirmed by LRO imagery (Marco Figuera, R., et. al., 2022). This size range is well-suited to large lunar landers such as SpaceX's Starship, with a base diameter of approximately nine meters (SpaceX, n.d.), because it provides a stand-off distance of five to ten times the vehicle footprint. The concave geometry of these craters naturally contains ejecta, thereby reducing contamination risks to surrounding infrastructure and improving operational safety.

Leveraging the geometry of a small crater for repeated launch and landing operations involves stabilizing its floor and lower slopes to resist erosion from exhaust impingement. The raised rim of a crater provides a natural plume containment berm that can intercept and redirect exhaust flows without the need for entirely artificial structures. Certain sectors of the rim may require reinforcement or reshaping through regolith printing to optimize plume redirection and recirculation.

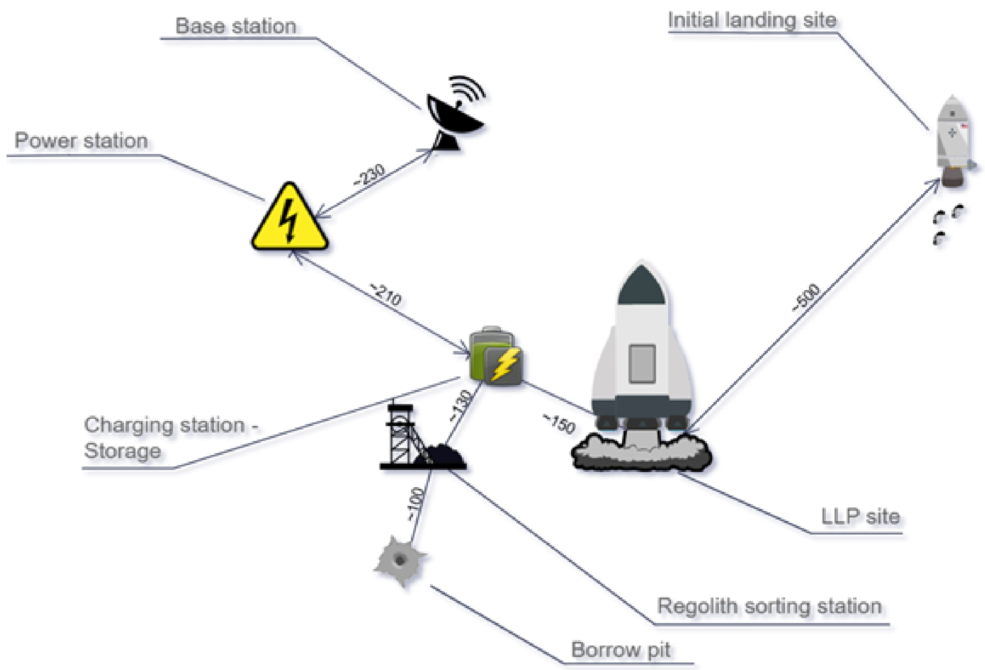

Figure 1.8: Hypothetical IOC Site Layout

The use of small craters as the basis for launch and landing pads offers several interrelated operational benefits. The natural containment geometry mitigates dust dispersion by trapping ejecta within the crater bowl which limits contamination risks to nearby assets. The concave profile also facilitates thermal management because plume gases have space to expand and cool before impacting the crater walls which reduces potential for erosion. From a construction perspective, leveraging existing terrain minimizes the amount of material that must be moved or processed which can shorten construction timelines and reduce energy and resource demands. Furthermore, the approach is consistent with sustainability and ISRU strategies because it relies on locally sourced regolith and enables close integration with resource extraction zones, particularly those near PSRs containing water ice. Although crater-based LLPs offer clear advantages, several critical research challenges remain before the concept can be realized. High-fidelity modeling of plume-geometry interactions is essential to accurately predict gas flow, particle trajectories, and pressure distributions within concave environments at the scale of large lunar landers.

LLP on Engineered Planar Surface with Artificial Berms

Another concept involves positioning the LLP in a planar surface where artificial berms are placed. The proposed LLP is an approximately 100 m wide circular pad, partly enclosed by an internal four wing-shaped berms that would in turn be enclosed by a fully circular berm. The final design called New Era Nexus LLP can be seen in Fig. 1.9.

The main consideration of the New Era Nexus® LLP design solution is to make the interaction of rocket plume and lunar dust minimal. This vortex-generator configuration would contain most of the rocket exhaust plume, while facilitating the dissipation of the kinetic energy of it into heat. The pad is excavated around three meters deep to improve stability

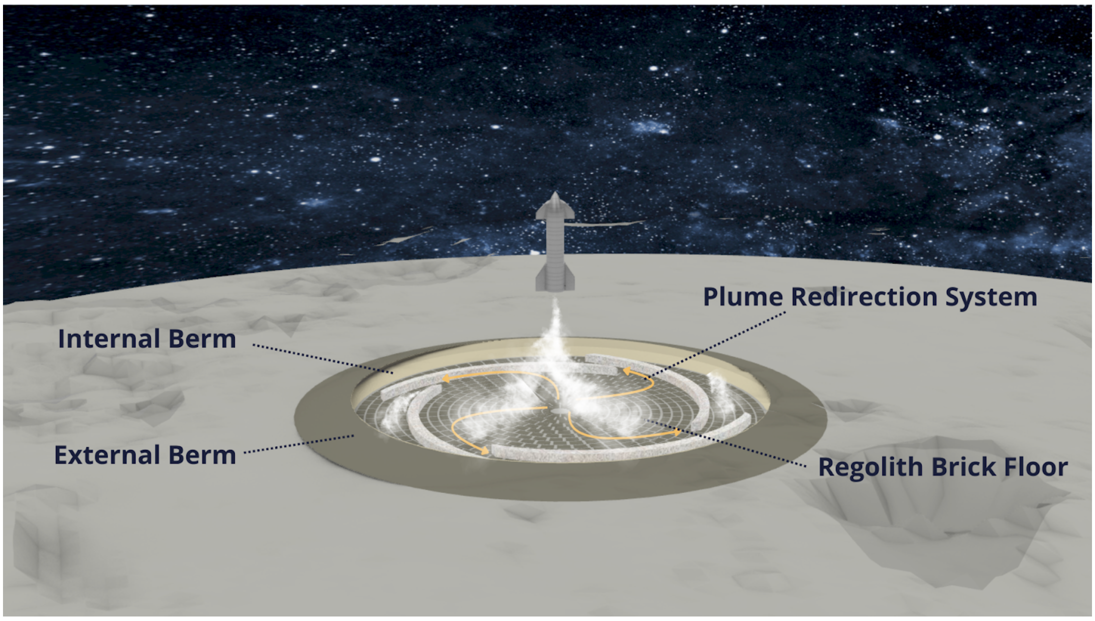

Figure 1.9: New Era Nexus LLP design featuring a 100 m circular pad with internal wing-shaped berms and an enclosing circular berm.

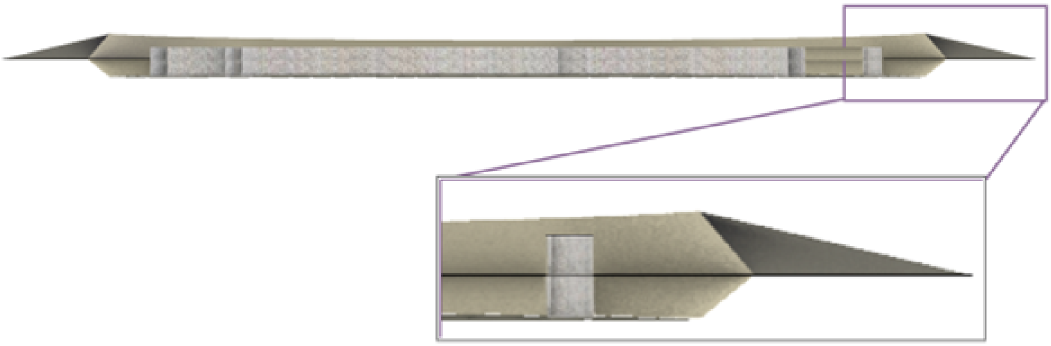

Figure 1.10: Cross section of the New Era Nexus LLP design, with the reinforced artificial berm

using naturally compacted regolith and providing raw material for brick production to pave the surface (Okonkwo, C., et. al., 2025). While dust mitigation techniques would be always applied to the fullest, it should be taken into consideration that particles from pavement ablation will be generated and projected (Ximenes, S.W., et. al., 2024). As illustrated in the image below, the external berm is designed to contain the rocket exhaust so it does not interfere with the environment around it and is not entrapped so it does not cause accumulation of extremely hot gasses that could create large thermal and structural stresses. The berm would be reinforced with the solutions previously proposed.

Radiation Shielding

Space radiation, including Galactic Cosmic Rays (GCRs) and Solar Energetic Particles (SEPs) (NASA, 2011), constitute a critical hazard to the operational longevity of electronic systems, structural materials, and human health in extraterrestrial environments. The risk of radiation is particularly important during the establishment of initial lunar outposts and associated spaceport infrastructure. Earth-derived shielding technologies include aluminum alloys augmented with high-density metals such as tungsten and tantalum; hydrogen-rich polymers such as polyethylene and its composites (PrimeScholars, 2021); boron-infused neutron absorbers; flexible fabrics such as Demron®; and superconducting magnetic systems capable of deflecting charged particles. For sustainable, long-duration operations, cost-effective ISRU approaches are imperative. Among metallic shielding candidates, the 6061 aluminum alloy, particularly in its T6 temper, offers a favorable combination of mechanical strength, corrosion resistance, low mass, and manufacturability (Request PDF, 2021), with the majority of its constituent elements: aluminum, magnesium, silicon, iron, and titanium occurring in significant concentrations in the lunar regolith (ScienceDirect, 2021).

The lunar highlands are particularly rich in aluminum, while magnesium, silicon, and iron are broadly distributed, including in regolith deposits at the LSP (Lasany, et al., 2021). Empirical studies demonstrate that processing regolith into construction-grade material and integrating hydrogenous additives such as polyethylene or water can significantly enhance radiation attenuation, yielding measurable improvements in GCR and SPE shielding efficiency. Further, compaction of regolith to increase bulk density has been shown to augment its protective capacity (MDPI, 2021) which makes it suitable for constructing enclosures or berms around sensitive electronics. The capacity to synthesize 6061 aluminum from locally available resources, in combination with regolith-based composites, has the potential to lower operational costs and enhance the resilience and autonomy of both crewed and robotic systems deployed on the lunar surface (Wired, 2012).

Considerations regarding the transition from IOC to FBO

As lunar missions shift from short-term exploration to long-duration presence, the development of surface-based spaceport infrastructure will support deep-space exploration that leverages the Moon's reduced gravity. When transitioning to an FBO configuration, it is important to account for the architectural and logistical features of lunar spaceports that preserve modularity, maintainability, and scalability.

According to research, there are two conceptual approaches incorporating advanced integrated systems to bridge this gap (Open Lunar Foundation, 2025). One concept relies on Earth-imported materials, supporting active refueling and servicing operations. Although the launch and transport costs of these Earth-imported systems constrain early scalability, such a system can still serve as a template for autonomous, drive-through spaceport operations. The other concept aims for longer-term sustainability, proposing a fully in-situ–constructed spaceport encompassing both landing pads and support infrastructure. This would allow for high scalability, modularity and extended operations.

Infrastructure Design and Architecture

Drawing from the previous assessment, key considerations for FBO infrastructure include:

- Drive-through refueling capability that offers a simpler and more operationally efficient alternative to in-orbit refueling under microgravity conditions

- Maintenance capacity including the usage of modular maintenance bays
- Streamlining of surface operations and reduction of human workload (with consideration to robotic cooperation)
- Roadways and other mobility infrastructure integrated with developed transportation solutions
- Development of vehicle docking facilities that enable the servicing of several launch vehicles simultaneously
- Utilization of rocket exhaust gases for power generation (taking advantage of the vortex generated by the design of the LLP, exhaust gases would lead into a circular tunnel where they would feed a turbine motion for power generation)
- Development of an LLP digital twin for structure health monitoring (e.g., level of pavement ablation, berm degradation, thermal stress, etc.)

1.1.4 Robotics, Transportation and Mobility

To achieve the spaceport concepts previously outlined in an efficient and cost-effective manner, robotic systems need to form the foundation of construction and further expansion, making use of autonomous systems and human interaction. The areas that still require research and value to be added according to NASA's Moon to Mars Architecture Definition Document (ADD) include cargo offloading, transport and mobility, and human-robotic interaction.

Cargo Offloading

A sustainable settlement on the Moon requires cargo delivery to supply the initial resources needed for crewed missions before the longer-term solutions of ISRU are in place. Additionally, many resources are outside the realm of what can be obtained from ISRU and will need to be delivered to the surface, such as rovers, power infrastructure, and laboratory equipment. The Moon to Mars ADD plans describe the need to transport and offload hundreds to thousands of kilograms on the lunar surface (NASA, 2024). The current method for offloading cargo is crew manual labor with some mechanical assistance, however EVAs are physically challenging on the human body. This is not a realistic approach for large scale operation and presents an opportunity for development.

The Autonomous Robotic Networks to Help Modern Societies (ARCHES) mission provides research and experimentation in the area of semi-autonomous interaction of a multi-robot team for planetary exploration (Schuster et al., 2020). Using a team of multiple robots, where each robot can operate independently, reduces mission risk because there is no single-point failure in the mission system. If one robot in the team has issues, the others can still carry out their tasks. The method from the ARCHES mission of using humans-in-the-loop to determine the initial mission planning and send commands to a robot team could be applied to a cargo offloading scenario. Initially, we would expect operations to be conducted from Earth, which would require the advancement of telerobotics, but we would consider planning operations from NASA's Lunar Gateway and the lunar surface in later phases of development.

One study on developing cargo handling devices takes three categories into consideration: technical, operational, and architecture (Gill et al., 2022). The technical category refers to the mass handling capability of the device, the volume taken up by the device in its stowed and deployed configurations, and the design simplicity and maturity of the device. Landers could build in their own payload offloading capability as part of the design, but this adds complexity. The operational category refers to the simplicity and reliability of using the offloading devices, the versatility of the device to handle different payload types, and the level of operational autonomy. The device versatility can be extended to other operations beyond offloading, such as manipulating and transporting the payloads. Developing an approach of a standardized offloading capability is a consideration, but this is challenging when payload sizes and lander vehicles are not standardized themselves. Ultimately, all these categories need to be considered when selecting the cargo offloading method. In some cases, manual methods involving crew may still be more feasible than robotic methods.

There are guidelines defined in the International External Robotic Interoperability Standards document for developing a standardized approach for robotic interfaces, based on learnings from the International Space Station (ISS) (IERIIS, 2019). This document defines standard interfaces and requirements to enable robotic interaction with modules, vehicles, and payloads. Continuing to follow a standardized approach will be essential in large-scale cargo offloading operations. At this time, the document mentions that the mission scenario of a crewed lunar base is something that will need to be addressed in more detail. In general, for the spaceport envisioned, we recommend following the standardized approach and developing modular robotic offloading systems that can be used for variable payload types.

Transport System and Mobility

While we identify the need for cargo offloading systems on the lunar surface, the question persists as to how to get these resources from the point of origin to the point of use. NASA's 2024 ADD white paper flags a critical lunar surface logistics gap: the transport of heavy cargo (NASA, 2024). As a spaceport and settlement grow on the Moon, current demand and mobility capacity are mismatched on the order of 1,000 to 15,000 kilograms per asset for ranges of 50 to 5,000 meters between dispersed sites (NASA, 2024), visualized by Fig. 1.11. Mobility must handle steep slopes, rugged regolith and dust, and operate across tight energy budgets and challenging lighting. Systems should include autonomous operations to prepare for crew arrival and reduce crew burden, as well as to adopt a standard framework for interoperability. Below we compare multiple transport solutions - a lunar railroad, Flexible Levitation on a Track (FLOAT), and propulsive hoppers - highlighting where each contributes without diving into their specific technologies, and proposing a novel hybrid concept that could close the gap. Rovers are excluded from this study under the assumption that the lunar terrain vehicle is well established and can carry an uncrewed mass of up to 800 kg.

Key driving factors of the assessment of these solutions include payload capacity, speed, range, energy cost and flexibility. Northrop Grumman's LunA-10 study for DARPA proposes a lunar rail-based cargo network to move large masses efficiently between surface sites with

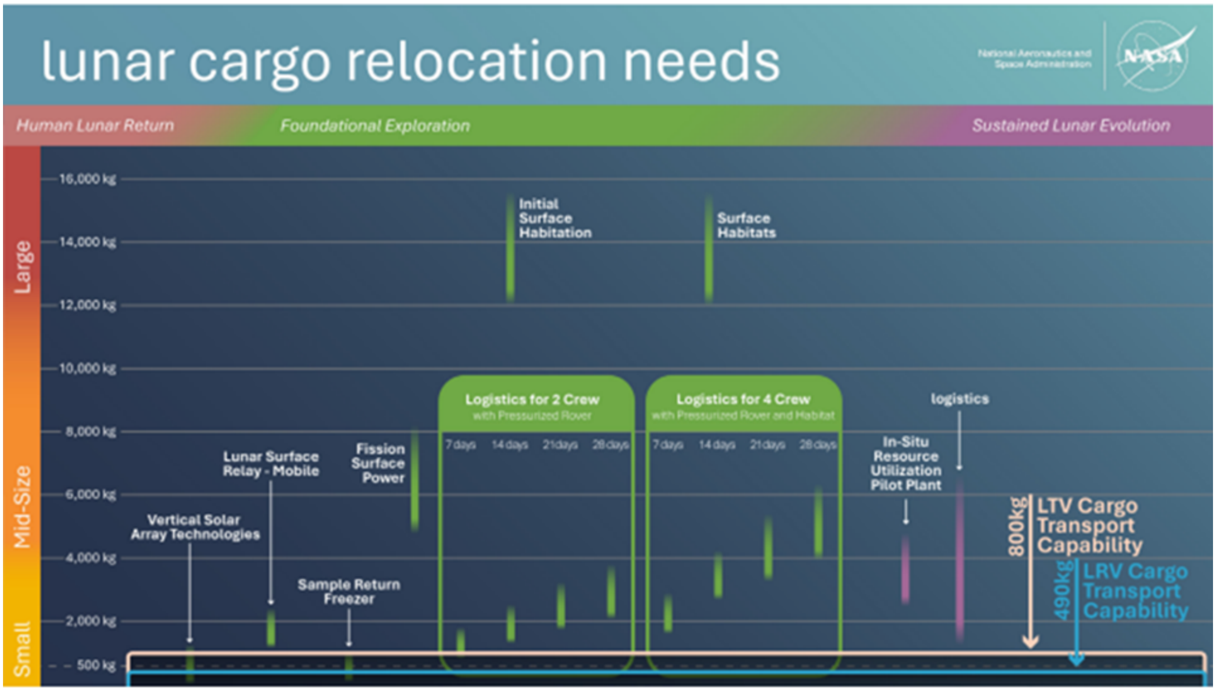

Figure 1.11: Mobility demand forecast ranges compared to Lunar Terrain Vehicle and Lunar Roving Vehicle transport capabilities (NASA)

costs benchmarked against rover logistics. While it presents a familiar system to that of Earth and achieves a high capacity of 100 to 125 tons and 100 km of range, multiple constraints such as reduced gravity, uncertain surface compaction, stress on tracks and high energy costs for regolith sintering and metal production means that the rail system only outperforms rovers once cargo flows exceed roughly 1000 kg-km/min which is shown by Fig. 1.11 (Northrop Grumman, 2024). Hence, it only positions itself as a preferable solution for the longer term where there is sustained and heavy cargo on the Moon.

Alternatively, the FLOAT concept, developed by NASA's Jet Propulsion Laboratory (JPL), targets lunar logistics gaps in durability, mass, throughput, and power. It uses diamagnetic levitation over a flexible, multilayer pyrolytic-graphite track with embedded electromagnetic drive, taking advantage of the Moon's lower gravity pull. The design also includes an optional thin-film solar array for additional power generation. This system is lightweight, dust-tolerant and reconfigurable with little site preparation. Modeling and experiments indicate 10–100× lower energy than wheeled rovers while carrying ∼30 kg/m^2 over slopes $\leq 40^0$ (Hsu et al., 2023). FLOAT is not suited for exploratory, off-route mobility and is also currently limited to speeds ≤2.0 km/hr that would have to be addressed in future research. However, it offers a low-energy backbone for sustained point-to-point cargo transport between landing sites, ISRU plants, and habitats.

The final solution the team explored is the deployable lunar hopper, which uses chemical propulsion in a ballistic or hover fashion to traverse the surface of the Moon, a concept similar to terrestrial drones. Intuitive Machines and NASA have developed MicroNova which can provide access to extreme locations and shadowed regions and has a designed payload mass of up to 5 kg over 20 km. This would offer high flexibility due to being terrain-agnostic, but there

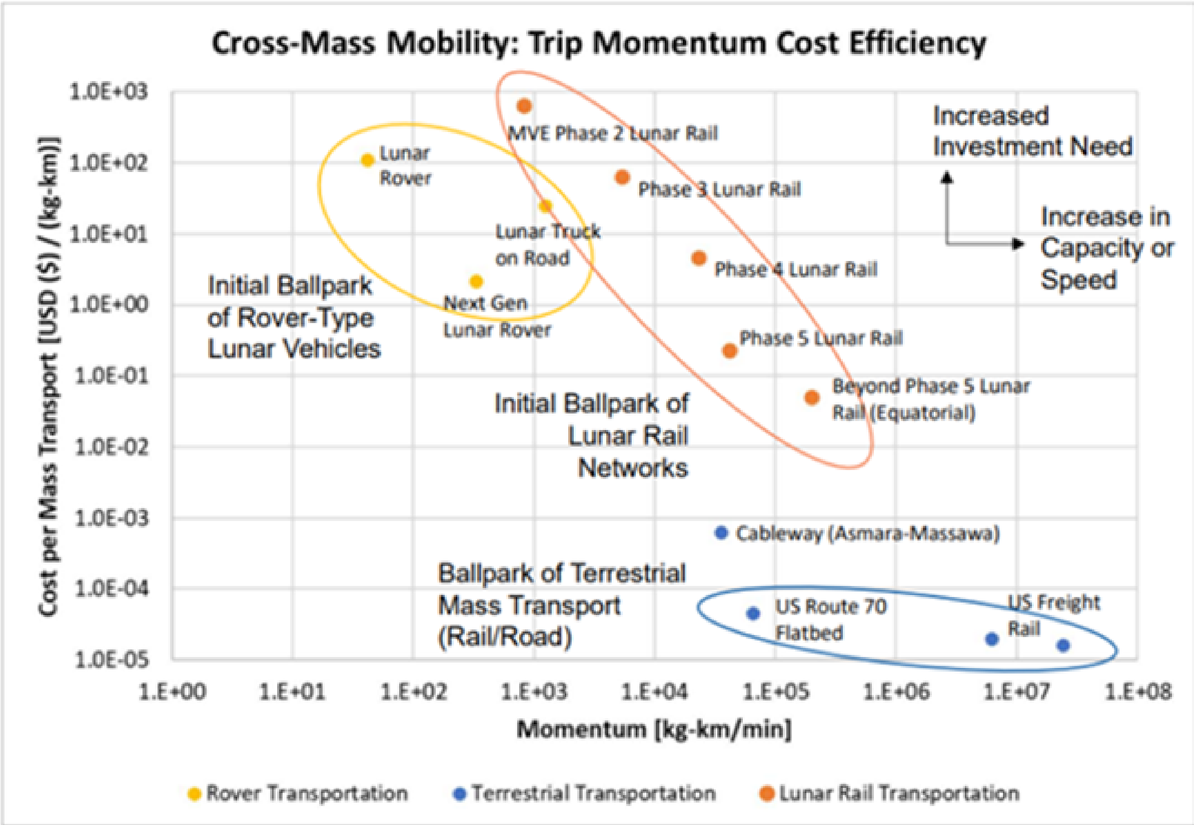

Figure 1.12: Momentum vs Cost per Mass between Rover and Rail

is a high energy cost due to fuel consumption and the need for refueling. It may also need further mitigation for dust concerns, and a balance between size and fuel to develop higher mass capability or range.

We suggest a phased, hybrid transport architecture to best address today's lunar logistics gap - deploying modular, coordinated hoppers for flexible and autonomous point-to-point delivery alongside a FLOAT low-power system that allows fixed, high-cadence shuttling between designated sites. The hoppers could act independently or in unison as a swarm to increase payload capability and allow for freedom of movement across the lunar surface despite different terrains. This system would be even more beneficial once ISRU has developed to create fuels for propulsion, without requiring the proportional mass launched from Earth. Additionally, a FLOAT system would address near-term dust and energy constraints while delivering measurable key performance drivers. This approach would allow for a clear growth path and scalability that allows for upgrades to a railway in the future while retaining hoppers for last-mile and surge capacity. The result is an interoperable logistics network that meets needs and develops into an industrial foundation.

Telerobotics, Soft Robotics and EVA Operations

Finally, the team investigated the application of Human Robotic Interaction (HRI) interfaces to design approaches for lunar surface mobility and sustainable/autonomous operational systems that build upon the previous solutions. Researchers have been inquiring for decades about the paradigm of human-robot interaction and its application in interplanetary exploration. Clynes and Kliene (1960) highlighted that technological advancements such as robots, will take an active part in the evolution of humankind and its dream of settling extraterrestrial terrains. Exploring this vision through the lens of contemporary technological advancements, this section investigates application of HRI interfaces as a proposal for lunar surface mobility and sustainable/autonomous operational systems by looking into two frameworks: the first explores the interface of telerobotics with autonomous systems and the second focuses on soft robotics converging with EVA operations.

The discipline of remote interaction between robots and humans is known as telerobotics, which involves remote human-robot interaction systems, involving spatially separated or temporarily controlled systems (ESA, 2017). Current research indicates significant/evidence-based developments in this interface. One such example is European Space Agency (ESA)'s HRI laboratory, the application of telerobotics in spaceflight context is substantialized through an experiment designed with a haptic feedback loop. In which a rover on simulated Martian terrain was operated through an astronaut positioned at the ISS. Another example of a human-robot autonomous system is the Multi-purpose End-To-end Robotic Operations Network (METERON), a suite designed to address the systems that can be operated through robotic interfaces to be operational on the lunar surface. Such autonomous systems in collaboration with astronauts can conduct scientific experiments and contribute to developmental technologies obtained sharing responsibilities, designing action durations and developing collaborative work strategies (Ye, S. C., & Feigh, K., 2020).

Soft robotics alludes to the intersection of material science and robotic motion capabilities. Developing a bio-inspired system mimicking natural locomotion of organic tissues falls under the domain of soft robotics. This domain aims to develop soft materials to mimic the malleability and mechanical locomotion of biological tissues, further feeding the development of artificial muscles and humanoid robots (Hambuchen, K., 2021). This may allow the machine to adapt and evolve to the environment such as uneven terrains. Matheson & Brooker (2012) proposed an assistive robotic glove based on pneumatic muscle actuators combined with force sensors that can aid and follow the natural hand gesture motion, resulting in less stress on the EVA performing astronaut due to pressurized space suits.

Human-robot interaction interfaces are the future of enabling human operations on the lunar surface. Robotic interfaces can expand human physiological capabilities and aid in experiment operations and construction technologies. Under the extreme conditions of the lunar surface, the interface of HRI with embedded soft robotic material design can assist in sample collection and research experiments and overall mobility over the surface.

1.2 Spaceport Power and Communication

1.2.1 Introduction

This section outlines the critical infrastructure required to maintain our proposed spaceport facility in its early stages, specifically focusing on power generation, communication systems, and positioning, navigation, and timing (PNT) capabilities, which are key drivers to enable its success.

Lunar-based PNT is valuable for spaceports, especially one located in the PSR of the LSP since signals from Earth will only reach that location intermittently. With a functioning PNT network, it becomes easier to operate for necessary communication and landing systems and any potential lunar orbiting systems. Accurately synchronizing pseudolites is integral to the functionality of a highly precise PNT system. Without synchronized timing, the resulting position calculation will not be accurate. Even just three nanoseconds of time error in PNT systems can cause one meter of positional error (Wechsler, 1990). This allows for time synchronization between the lunar system and the spacecraft instead of the spacecraft and the Earth. This communication connection also opens the potential for quicker trajectory calculations (Cheung et al., 2024). Having established PNT is also vital for any semi- or fully autonomous robotics, especially if they must move through unknown terrain.

Due to the many challenges that face lunar infrastructure such as the extreme environment, limited access to external support, and the absence of a pre-existing communication or navigation network, our goal is to define a minimally viable infrastructure setup that enables a cost-effective and scalable spaceport. This includes evaluating the energy generation potential to support essential processes such as water ice hydrolysis that is vital to producing oxygen and fuel. A core assumption is that Earth-based antennas may only connect to the lunar site intermittently, reinforcing the need for autonomous, locally managed systems.

Unlike Earth-based operations, lunar infrastructure must contend with extreme environmental conditions, limited access to external support, and the absence of a pre-existing communications or navigation network. Early missions will rely heavily on human deployment and maintenance, particularly in polar regions where resources like water ice are accessible. These regions offer strategic advantages but also pose unique challenges in terrain and signal coverage.

1.2.2 Expected power, communications, and PNT requirements

We need to determine the spaceport's basic power, communications, and navigation needs to keep it running. These technologies need to be both easy to install with little infrastructure and reliable enough to sustain early missions. Given the worldwide interest and investment in lunar satellite networks, we anticipate the availability of relay satellites in the future. Using a presumed satellite relay will be crucial during times when the lunar settlement is not visible from Earth, depending on the site chosen. Continuous coverage from Earth may be possible for a communications facility on the near side of the Moon, but wherever feasible, our method places a higher priority on independence from these systems. Designing a low-cost, low-dependency system that can operate efficiently even without continuous satellite support is the goal.

There is an assumed connection to the terrestrial network to support the lunar surface network. Although it is unlikely that there will be enough data center infrastructure in the near future to cover all the information processing needs on the Moon, it is reasonable to assume that there will be some satellite communication to the terrestrial portion. One example of a planned relay satellite that could facilitate Earth-to-Moon communication is the Lunar Pathfinder mission, which is scheduled to launch at the end of this year (ESA, 2024a). Additionally, there might be advancements in the creation of an optical communications link that might boost data throughput capacity and facilitate the high data transfer speeds needed for AI applications, which could reach up to 10 gigabits per second (Berenberg & Sambi, 2024). In lower frequency bands, highly reliable communications can be employed to facilitate critical data flows and help with space traffic control and spacecraft arrival coordination. The priority of network traffic will be determined by the necessity of vital operations. Personal communications between residents of Earth and the Moon will be given less priority, and as a result, they can be cut off during periods of high demand.

The absence of a local infrastructure makes communication and navigation on the Moon intrinsically challenging. Current plans, like NASA's LunaNet, call for long-term, fixed or satellite-based systems that will take a lot of time and money to deploy (Israel et al., 2020). Finding short-term, adaptable alternatives that can be swiftly deployed and tailored to mission requirements is our main goal. The framework for investigating such alternatives—such as dual-use technologies and mobile mesh networks—is established in this part and will be covered in more detail in later sections.

1.2.3 Communication and PNT approach

Existing proposals

There are current proposals addressing the issue of navigation and communication on the Moon. As aforementioned, NASA's LunaNet is like an "Internet for the Moon." It is a framework for communication, navigation, and science services. It uses delay/disruption-tolerant networking to send data even when signals are interrupted and provides standard navigation signals. LunaNet is a general design, not a specific system. LunaNet focuses on permanent infrastructure; it does not include AI-based movement or terrain-based repositioning. Another system, the Lunar toCommunications Relay and Navigation System PNT Instrument, lets satellites find their own position and time very accurately (ESA, 2024b). Neither of these systems deliver a moving, surface-level network for short missions.

This project introduces a simpler, cheaper system that uses moving devices – rovers and similar solutions – to make a more flexible communication and navigation network (*See Figure 1.13*). Each node handles both communication and navigation, giving GPS-like location data relative to the base without involving satellites. This system also allows switching between real-time communication and delay/disruption-tolerant networking for storing and sending data in increments, permitting the network to change its shape and coverage in real time based on where explorers are and what they need. The system also can also where coverage will be lost and moves nodes before it happens. It can work on its own or connect with LunaNet to extend its coverage. The system uses existing technology from Earth, does not need constant contact with Earth, and can grow into a more permanent solution over time.

Figure 1.13: Simple visualization of the mobile communication rover and local tower.

Mesh network description

The following is a potential mission architecture that demonstrates this mesh network functionality:

1. The mission team deploys three mobile mesh nodes (MMNs) from the base.
2. AI predicts terrain-induced blind spots and repositions nodes to clear ridges.
3. Mobile and static nodes act as both positioning anchors and network couriers.
4. Astronauts operate confidently knowing communications and navigation coverage will follow them anywhere within the operational radius.

This mobile mesh network removes blind spots and follows mission teams, solving problems that fixed or satellite-only systems cannot. It is especially useful for early missions, scouting, and areas with tricky terrain like the Moon's poles where the relative positioning system keeps explorers in a reliable coordinate frame (See Fig. 1.13). Echoing the goals for this section, each MMN acts as both a communication hub and a navigation point, using proven off-the-shelf Earth technology components to keep MMNs low-cost, quick to deploy, and adaptable for following explorers anywhere.

For communication, MMNs make use of Wi-Fi for short-range, 4G/5G-style links for medium-range, and UHF or S-band radios for long-range, plus optional optical links for high-speed line-of-sight (for static nodes). The system switches automatically based on terrain, signal quality, and data needs. Navigation is provided by a PNT unit. Depending on available hardware, nodes exchange timing signals and either direction of arrival (DoA), angle of arrival (AoA), or both, to build a local coordinate grid anchored to the mission base. These grids are further enhanced by inertial measurement units (IMUs), lidar mapping, and visual sensors. If LunaNet or other satellite navigation is available, it will further improve accuracy.

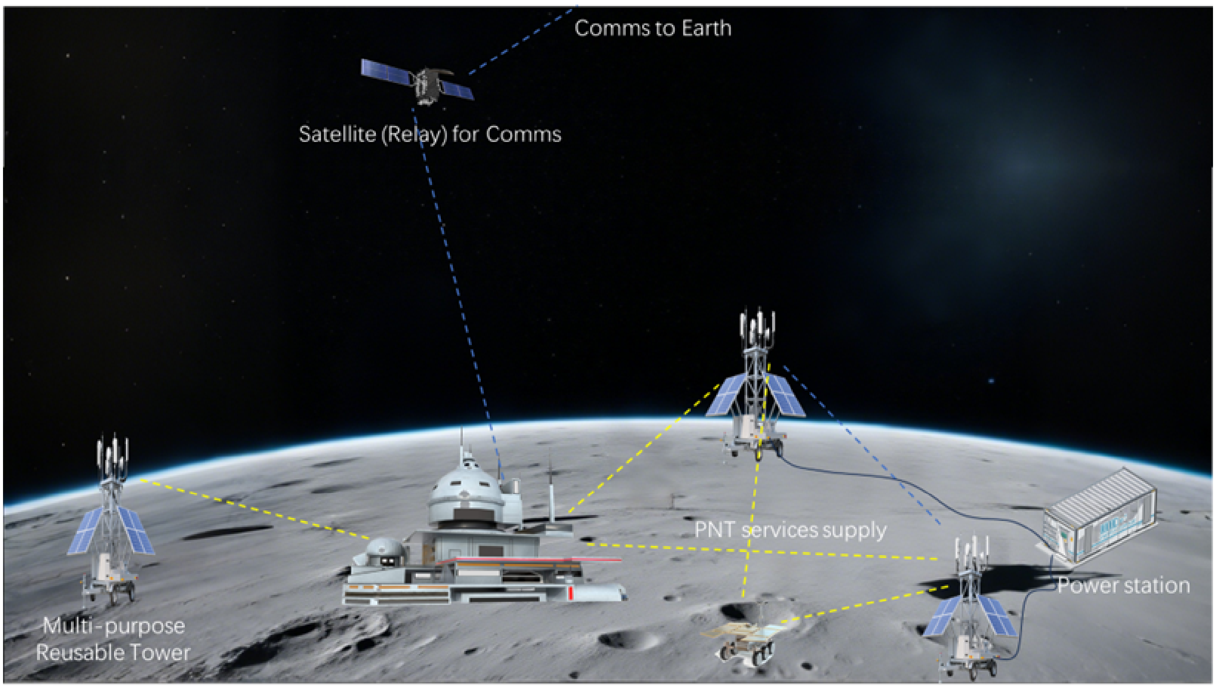

Figure 1.14: Mesh network connections localized around the spaceport (figure is original)

An onboard AI control system predicts potential signal loss and navigation errors in advance by fusing real-time terrain mapping, radio link quality metrics (signal-to-noise ratio, latency, and packet loss), and movement forecasts derived from mission plans. It uses predictive modeling and path planning algorithms to determine optimal repositioning points for rovers, considering power constraints, line-of-sight availability, and multi-node geometry for precise trilateration. This ensures the network not only reacts to issues but also actively adapts to maintain coverage and navigation accuracy as the environment or mission profile changes.

Interfacing with existing plans

To ensure future-forward compatibility, we want to verify that our proposed mesh network is compliant with future LNSS standards. LunaNet is designed like a terrestrial Internet where different service providers work together using shared standards and protocols. This interoperability ensures that users on and around the Moon can access services from both commercial and government providers. LunaNet uses both peer-to-peer navigation (direct communication between a user and a provider) as well as Lunar Augmented Navigation Service (LANS - where multiple provider nodes send navigation signals to multiple users simultaneously). LANS is modelled after the Global Navigation Satellite System (GNSS) and uses a shared signal format called the augmented forward signal (AFS) (Giordano et al., 2023).

To integrate a ground-based mesh network of towers and mobile rovers with LunaNet, we must ensure:

1. Signal Compatibility: Ensure all nodes can transmit and receive AFS signals using the same frequency, polarization, and message structure.
2. Reference Systems: Align with LunaNet's lunar reference frame and time system for

consistent positioning and timing.

3. Interoperability: Design nodes to act as LunaNet service providers, complying with the LunaNet signal-in-space recommended standard and publishing a SISICD.
4. Service Volume Definition: Clearly define the area where each node guarantees signal coverage.

The current protocol description of the AFS communication signal format is clearly defined; the AFS signal includes a carrier frequency of 2492.028 MHz, right-hand circular polarization for signal clarity, and data and pilot channels using specific encoding schemes.

1.2.4 Ground station infrastructure

Permanent Lunar Surface Structure

To maintain minimal dependence on lunar satellites, a permanently environmentally protected structure like the lunar surface system (LSS) as proposed by NASA JPL would be helpful (Cheung et al., 2024). This system would be able to receive intermittent signals from Earth, assuming its placement is on the LSP near the planned landing site. Ideally, the LSS would be equipped with its own electronics equipment to allow cis-lunar navigation (Cheung et al., 2024).

Infrastructure Proposal

To meet the requirements of a multipurpose, minimal infrastructure system, the LSS can be a part of the fixed lunar base. Assuming the base will be placed near the lunar poles and built to protect those inside from the space environment, this would be an ideal place for the LSS, as it will likely also contain highly sensitive equipment such as atomic clocks, which work by measuring the oscillations of specific atoms. The precise timing of these clocks is vital for pseudolites. Changes in temperatures can induce shifts in energy levels, adding to the error produced in these clocks (Safronova et al., n.d.). Thus, it would be ideal if the atomic clocks in the LSS can be placed in the thermally protected astronaut habitat to further reduce necessary infrastructure in the early stages.

The LSS module should also be equipped to receive signals from Earth, even if intermittently, to ensure that lunar orbiting spacecraft and the LSS are time-synchronized and follow a precise globally referenced time. It should also contain transceivers to communicate with the pseudolites stationed around the outpost (LeMaster, 2002).

Communication with the rest of the system

The fixed LSS acts as a known reference point for the other pseudolites, both the tower and the rovers, to calculate their location on the lunar surface. Self-Calibration Pseudolite Arrays (SCPA) use transceiver-based positioning to determine their own location without ever needing to have the area they are in mapped out (LeMaster, 2002). To allow for each transceiver to determine their own position, we recommend that they use bidirectional ranging to calculate the distance between themselves and other transceivers. This method also provides the advantage of not needing the entire mesh network to be in line-of-sight of each other. As long as there is one within line-of-sight, they can effectively form subarrays that can be "stitched together" (LeMaster, 2002). It is important that these transceivers exist within the LSS, but their inclusion narrows potential locations for the placement of the LSS module itself. The use of bidirectional ranging and subarray stitching will also help with scalability, allowing more towers to be placed later without disrupting the existing line of sight. It is important to note that there are still drawbacks to bidirectional ranging, including increased complexity of the system (LeMaster, 2002).

Multi-purpose reusable tower

Part of our proposed solution includes pseudolites in the form of multi-purpose reusable towers (MPRT). These towers will be time-synchronized with the LSS and will be able to determine their own location as part of the Signal-in-Space Interface Control Document. They will also be equipped for solar power generation.

Design of MPRT

The MPRT design constitutes an innovative infrastructure suite of instruments that integrates telecommunications, navigation, and solar power generation within a single, rapidly deployable package. Characterized by full modularity, closed-loop recyclability, and intrinsic mobility, MPRTs offer extensive applicability across future mission scenarios, with particular significance for lunar base architecture (Merila et al., n.d.). As a critical companion to the LSS, MPRTs always maintain strict time synchronization with the LSS.

Based on the existing vertical solar array tower proposal and LunarSaber design from NASA and Honeybee, and tailored to our specific core requirements, we suggest the following MPRT design (Csank & Scott, 2022). MPRTs will be positioned on peaks of near-constant light, seeing over 90% sunlight coverage annually. This consistent power access ensures as much communication uptime as possible. MPRT power reliability will also best support day-time electrolysis for hydrogen production and continuous night-time regenerative fuel cell support for ISRU. MPRT parameters range from 15 m, 10 kW towers to 100 m, 100 kW installations, each integrating optical beaming for PSRs and direct wired output for nearby loads, along with local mesh networking for data and PNT services.

Rooted in a modular design paradigm, each MPRT subsystem is engineered for swift assembly and disassembly, thereby minimizing logistical burden and enabling repeated redeployment at disparate locations (Toyado et al., 2024). The telecommunications subsystem encompasses multi-band transceivers capable of supporting high-throughput data links; the navigation subsystem delivers centimeter-level positioning services to surrounding operational areas. Solar arrays mounted atop the tower convert incident solar irradiance into electrical energy, satisfying on-board power demands while enabling surplus energy storage or distribution to auxiliary equipment.

Fabricated from lightweight, high-strength composite materials, the tower is effectively rated for operation in complex topographies and extreme environments (Tsavdaridis et al., 2020). Within a lunar context, the MPRTs establish a resilient cis-lunar communication backbone, assist in spacecraft landing and surface navigation, and exploit the Moon's abundant solar flux to achieve energy self-sufficiency.

Deployment of MPRT

A multi-purpose signal tower network centered around a spaceport must consider terrain adaptability, communication performance optimization, and navigation coordination requirements. Its design involves the various systems engineering considerations (NASA, n.d).

The lunar surface exhibits significant heterogeneity: densely cratered regions pose risks of line-of-sight obstruction, while flat mare areas are favorable for wide-area coverage (Lordos, G., et. al., 2023). The complex terrain and extreme environment have pronounced topographic variations and unique illumination patterns, directly influencing communication system design and deployment. This has been addressed earlier in the paper with our site selection criteria. Meanwhile, the 14-Earth-day lunar night and extreme cold necessitate hybrid power systems and wide-temperature-range resilience in communication equipment. Based on these characteristics, we recommend a hierarchical topology structure prioritizing backbone nodes and edge extensions.

Core base stations should be located on high-elevation platforms (like the edges of large impact basins), to gain more solar energy and leverage natural elevated terrain to minimize electromagnetic wave depletion. Secondary nodes should be deployed in key mission areas to ensure regional communication and navigation services. Inter-regional connectivity can be achieved through relay links. This non-uniform deployment strategy effectively avoids blind zones caused by craters, while reducing overall construction costs.

For current communication technologies, 4G and 5G may be the preferred options in the short term, but the tower parameters must be configured differently due to the distinct frequency bands. For 4G systems operating in the low-frequency sub-6GHz band – where longer wavelengths enable strong diffraction capabilities – relatively low but densely distributed mast structures can be employed, combined with power control algorithms to achieve deep coverage in localized areas. In contrast, 5G networks dominated by millimeter waves rely on line-of-sight transmission. These require the deployment of tall truss towers exceeding 30 meters in height, equipped with adaptive beamforming antenna arrays to maintain reliable connectivity. Since 6G may be developed in the foreseeable future, it will become possible to establish 6G communications on the lunar surface. 6G utilizes an entirely different frequency band, which could be in the terahertz range. Under this condition, MPRTs might need to be deployed more densely around the base.

Based on the major existing lunar base programs, the deployment and construction of MPRTs can be divided into two phases in the short term: the uncrewed service establishment phase and the semi-permanent base phase.

Uncrewed Survey Phase (Current – 2027)

This phase involves deploying a lightweight MPRT at the pre-selected base site to enable point-to-point communication between lunar rovers. It utilizes an orbiter (e.g., China's Chang'e-7 mission) for wide-area relay, with the ground-based towers serving as enhancement nodes to improve positioning accuracy to the 100-meter level.

Semi-Permanent Base Phase (2028–2030))

This next phase establishes a primary MPRT at the rim of the chosen crater, equipped with an LTE/4G core network (compatible with Artemis standards), providing 5–10 km coverage and supporting concurrent multi-device access. Finally, deployment of secondary base stations in a "triangular grid" configuration, which are interconnected with the main tower via millimeter-wave backhaul links, further mitigates terrain obstruction.

1.2.5 Lunar surface power management

Lunar power management and distribution architecture

It is important to create a lunar surface power architecture that is reliable, flexible, and scalable, and will support a long-term presence on the Moon. The main consumer of power usage in the early stages of surface operations is ISRU facilities. The lunar night, extreme thermal swings, and highly variable solar input in some regions of the LSP present a challenge for power management design. The power management and distribution systems (PMAD) must ensure flexibility and survivability by incorporating autonomy and a use of robotics, not reliant on human oversight. The most efficient means to transfer power is through cabling for short distances, especially to achieve a reduction in losses caused by a high-voltage conversion. However, optical wavelength wireless power transmission (OWPT) could beam power from solar farms to mobile or remote assets (Blue Origin, 2023). This capability is particularly valuable for sustaining energy-intensive operations, such as hydrogen electrolysis and liquefaction in PSRs, without requiring a massive energy storage onboard (Marcinkowski, A., et. al., 2023).

Architectural vision

Early lunar power systems will rely on mobile vertical solar arrays, local DC microgrids, and short wired connections. As infrastructure expands, hybrid AC/DC grids will integrate solar and wireless beaming, with optical towers like the MPRTs serving as both generation and distribution nodes. In the long term, an interconnected lunar grid will support industrial-scale activity that will be powered by diverse sources and backed by a multi-megawatt-hour storage.

Persistent power delivery, particularly via OWPT, will unlock continuous operations in the PSRs, enabling not only science missions but also the hydrogen ISRU processes needed for a sustainable lunar spaceport. Modular, vendor-neutral power electronics will allow rapid reconfiguration in response to failures, mission changes, or load growth.

1.2.6 Power generation for lunar ice hydrolysis

Establishing functional spaceport infrastructure on the Moon depends on developing a reliable system for power generation and hydrogen production through lunar ice hydrolysis. This process enables the creation of liquid hydrogen (LH_2), a sustainable, locally sourced rocket fuel, which is essential for supporting lunar launches, inter-orbital transfers, and deep space missions. Hydrogen's high specific impulse makes it the ideal propellant for chemical rockets, providing the performance needed for an efficient ascent from the lunar surface and travel to Earth's orbit or beyond. Electrolysis of water ice in the PSRs, combined with advanced liquefaction and storage technologies, forms the backbone of this system. Without this capability, rocket launches from the Moon would remain impractically dependent on fuel supplied from Earth. The power infrastructure, ISRU electrolysis, and cryogenic fuel handling are mission-critical factors for enabling a sustainable and scalable lunar spaceport.

Opportunities for hydrogen utilization from lunar polar ice

Among the various proposed methods for extracting hydrogen on the Moon, only one offers the potential for a scalable and feasible implementation: the extraction of water ice from PSRs near the lunar poles, followed by an electrolysis. While hydrogen implanted by solar wind and hydroxyl-bearing minerals are present across the lunar surface, their hydrogen concentrations are extremely low. In contrast, neutron spectroscopy and radar observations from missions such as NASA's LRO have confirmed the presence of water ice in PSRs, with concentrations estimated between 1–10% by weight within the upper meter of the regolith (A. Colaprete et al., 2010). The proposed extraction pathway involves thermal mining of regolith with ice water using microwave or resistive heating, which sublimates ice into a vapor and then condenses it into a liquid water. This water can then be electrolyzed into hydrogen and oxygen. Electrolysis energy requirements are well established. They assume that one kilogram of hydrogen from water requires approximately 4.41 kWh under idealized laboratory conditions (Kornuta, D., 2019). However, practical system efficiencies typically result in an electrical consumption of 50–55 kWh/kg hydrogen when balance-of-plant losses are included. Electrolysis technologies, including proton exchange membrane (PEM) and advanced alkaline electrolyzers, achieve efficiencies of up to 80–82% (NREL, G., & NREL, C. (2004).

Hydrogen cooling for fuel use

Following electrolysis, the produced gaseous hydrogen must be liquefied. Liquefaction is energy intensive due to hydrogen's boiling point at 20.28 K. Real-world liquefaction systems require between 6–13 kWh/kg depending on the process efficiency and heat exchanger design (A. J. Moreno et al., 2023). Advanced Claude- and Brayton-cycle systems operating under ideal conditions can reduce this to $\sim$6 kWh/kg (A. J. Moreno et al., 2023). Thus, the total energy cost for producing 1 kg of LH_2 from lunar water, including electrolysis and liquefaction, ranges from 10.4–17.4 kWh.

Implementing this process on the Moon presents major challenges in energy availability. The lunar night spans approximately 14.75 Earth days, eliminating solar input at most locations. Moreover, PSRs where water ice is abundant receive minimal sunlight year-round. To maintain operational continuity, reliable power systems are necessary. There are many other challenges to building a lunar infrastructure for hydrogen generation and storage, some of which include the measurement of ice distribution, mining in the PSRs, dust contamination, long-term storage of LH_2 and energy infrastructure.

Hydrogen storage is a significant challenge on Earth and poses an equal threat on the lunar surface. LH_2 requires cryogenic containment at $\sim$20 K and is vulnerable to boil-off and hydrogen embrittlement of materials, even with vacuum-insulated tanks. Long-term containment on the lunar surface demands Zero-Boil-Off (ZBO) storage, which integrates multi-layer insulation (MLI) with active cryocoolers. ZBO technologies have been demonstrated on Earth by NASA, using layered insulation and reverse Brayton cryocooling to maintain tank temperatures with minimal losses. Still, the lunar operation must also account for dust contamination, radiation exposure, and microgravity impacts.

Thermoplastic composite tanks offer a promising material solution for cryogenic storage. Compared to aluminum-lithium alloys, these advanced materials can reduce tank mass by up to 30% and manufacturing costs by up to 25% while maintaining structural and thermal integrity under cryogenic cycling. Additionally, fluid management in a reduced gravity, where slosh instability can affect vehicle guidance, must be addressed through internal vanes, sponge structures, or surface energy dampers.

Ammonia as an energy carrier

An alternative to direct LH_2 storage is the chemical synthesis of ammonia (NH_3) as a hydrogen carrier. Ammonia has a hydrogen content of 17.8% by weight and a volumetric hydrogen density of 108 kg/m, significantly higher than LH_2 at 70.8 kg/m^3 (Sun, S., 2023). It remains liquid at -33°C under 1 atm pressure and can be stored under moderate cryogenic or pressurized conditions (8–10 bar), avoiding the need for deep cryogenics (Sun, S., 2023). Industrial infrastructure for ammonia handling is well-developed on Earth and can be adapted for space applications.

At the point of use, ammonia can be decomposed into hydrogen and nitrogen through thermal cracking, using nickel- or ruthenium-based catalysts at 600–900 °C. The process requires 2.3–3.1 kWh per normal cubic meter of recovered H_2 (A. Valera-Medina et al., 2020). This provides a flexible, on-demand hydrogen production near launch sites or fuel cells while maintaining long duration storage stability. Safety considerations also favor ammonia. While toxic, it has a narrower flammability range (17–27% in air) compared to hydrogen (4–75%) and higher ignition energy, reducing the risk of explosive leakage.

Summary and concept

Electrolysis of lunar polar ice is the only technically and economically viable approach for sustainable hydrogen production on the Moon. The process is supported by well-understood technologies and maturing lunar ISRU concepts. The key challenges include energy generation, cryogenic storage, and hydrogen boil-off, which can be mitigated by advanced materials, ZBO tank systems, and alternative storage via ammonia. Hydrogen provides the most efficient rocket propellant known with no carbon emissions. Further, hydrogen fuel cells can be used to power the energy-intensive processes at the lunar spaceport and supply a backup fuel storage and power source for emergencies or long lunar nights. These innovations are essential to production of propellant on the lunar surface and a long-term exploration infrastructure.

1.3 Spaceport Policy and Business

1.3.1 Introduction

This study has so far delved into the technical aspects of establishing a short-term spaceport, covering everything from constructing a launch and landing pad to setting up power generation and communication systems. However, short-term governance and business models must be considered, so that nations, investors, and companies can work together for the development of the first lunar spaceport, After the construction and operation of the first lunar spaceport, as lunar activity becomes more readily available, governance that harmonizes the continued development of infrastructure and resource use is required. For example, the first lunar spaceport would be financed, governed, and operated by government agencies to provide open-access infrastructure, with private manufacturing contracted under common standards. Subsequent operations and ownership would then transition to commercial entities, adopting airport-style governance and diversified revenue streams to achieve long-term profitability. This phased approach leverages public investment to establish early capability and private-sector efficiency to sustain growth. Proposals such as a Lunar Council, a credit system, and Lunar tribunal are all a part of the considerations that have been proposed here.

1.3.2 Jurisdiction

It is assumed that the jurisdiction includes the signatory nations of the *Outer Space Treaty* (OST) and the *Artemis Accords*. However, being a non-signatory nation does not prevent access to the Moon, its land or resources. The Moon and its resources have been, and will continue to be, for all humankind.

Developing governance that promotes equality for all humankind is different from the borders and segregation we have on Earth. This is one important aspect when considering lunar governance. An elegant solution is required to enable commercial operations that apply solely to the Moon, and to incorporate the rights of nations and individuals to promote peaceful, safe, and sustainable operations. Some lunar treaties, UN committees, and national laws are a good starting point, but reform will soon be required as lunar activities increase. For example, the *Artemis Accords* focus on the use of space resources, and the *U.S. Commercial Space Launch Competitiveness Act* introduces ownership and sale of space resources. The purpose of both includes the exploration and development of space and its resources. This is a scope. As activity increases, we must be diligent that the Moon does not become a free-for-all as access to it and its resources becomes readily available. For example, there may be a point in time where governance is required, not just to promote lunar exploration and development, but for protection of the Moon as its resources and activity may become saturated. Currently, we assume that the Moon and its resources are finite, and we must focus on both the long and short term.

The purpose of our short- to- long-term vision is aligned with the current governing laws and treaties, but also to supplement and secure the Moon and its resources long term. The challenge is that we cannot just apply what we currently have on Earth for governance because we have individual and national property rights, with rights varying internationally. Any activity on the Moon must involve shared proprietary rights and reciprocity principles.

As site selection begins for our spaceport, we will follow the *Artemis Accords* using the relevant provisions for *safety zones*. However, we must keep in mind that the Moon's resources are for all humankind, so the application of the non-appropriation and reciprocity provisions from the OST must be considered when infrastructure is constructed. National laws for resource ownership, with their aim and purpose on development, are appropriate for the short term, but we must keep equity and sustainability at the forefront for the long term.

As we transition from basic infrastructure to resource extraction, production, and utilization, and lunar commercialization develops, further oversight and global cooperation is key. To maintain that lunar resources are for all humankind, and not have a free-for-all extraction and mining operation like we have had on Earth in our history, further governance with different aims will be required. A Lunar Council will be selected to develop subsequent and complementary governance for the use of the Moon's land and resources. This is important because we will be using both the property we bring to the Moon, which has attached proprietary rights, and the Moon's land and resources, which do not have global proprietary rights. This creates a challenge where a harmonious balance must be achieved among different nations and in both the public and private sectors.

To balance the principle that the Moon's land and resources are for everyone while providing security through ownership for capital investments on lunar projects, a Lunar Credit system will be established. Article II of the OST prohibits appropriation by means of use, occupation, or any other use. However, keeping lunar development and sustainability in-house, while preventing nations from just buying up all of the Moon, is one way to achieve this harmony. Nations will earn credits if they contribute to the development and well-being of lunar infrastructure, and if these nations use lunar resources they will pay in credits. Having a distinct lunar credit system separate from Earth inherently promotes the Moon and maintains autonomy. A Lunar Credit is something that only can be earned by lunar activity, not bought.

The Lunar Council will be appointed from the various nations that contribute to lunar development. The Lunar Council's purpose will not just be to promote lunar exploration and development but will be overall governance and sustainability. A Lunar Council and Lunar Credit system are important because the aim is to maintain and preserve the Moon and its resources for all humankind. Therefore, a balance must be achieved to allow and promote development with investment protection - a similar system to what we have on Earth in the form of leases for land and property. The Moon's land and resources are for all humankind, but the infrastructure on the land can have separate property rights.

It is important not to contravene existing governance. For example, a nation or company may make a property claim that they brought supplies to the Moon and that they are the only user allowed to benefit from them. As soon as the property is on the Moon, a balance must be achieved because that is shared land. Lunar governance at its core should maintain equity and equality. The reciprocity provision should be interpreted broadly so as not to curtail lunar activity. As an example, constructing infrastructure on the Moon's surface should allow other entities to use the property. Similarly, Article 4 of *The Agreement Governing the Activities of States on the Moon and Other Celestial Bodies*, states that irrespective of a collective or individual degree of development, exploration and use of the Moon and its resources shall be for all humankind - again promoting equity and equality.

Further to a Lunar Council and Lunar Credit system, a Lunar Tribunal will be developed for the long-term sustainability of lunar activity to handle any lunar disputes. This will also be an appointed branch from nations that contribute to lunar development. A tribunal is a fundamental requirement because as infrastructure and utilities are in-place, we will see a larger commercial and tourism industry. Currently, the International Court of Justice and other arbitration and resolution methods are not equipped for speedy, inexpensive dispute resolutions. The Lunar Tribunal will work together with the nations for all claims and disputes. We will also develop a Lunar Safety Organization to oversee safety issues on the Moon. This organization would set safety standards, conduct impartial investigations of accidents and incidents, and promote cooperation among lunar actors to ensure transparency. Occupational hazards and accidents are a large part of everyday construction on Earth; generally accidents occur, and where there is blame, there is a claim. Again, governance at a lunar level is key for a sustainable lunar future.

1.3.3 Liability Framework for Lunar Activities

What kind of liability?

Considering the clear objectives related to the permanent human presence on the Moon - including aspects such as the development of spaceport and the construction of early settlement infrastructure - the core issues of lunar liability should be further addressed. We propose to adopt a hybrid regime that combines the existing legal concepts of strict liability and fault-based liability, applicable to different scenarios, to create a more flexible system for assigning responsibility in future missions. This application of liability is established for both nations and private actors.

Absolute liability

Absolute liability is applied internationally to inherently dangerous activities, including those related to outer space. The *Convention on International Liability for Damage Caused by Space Objects* (the *Liability Convention*) established a strict liability regime for any damage caused by space objects to the Earth's surface or to aircraft in flight. A similar approach should be adopted for activities on the Moon, with strict liability applicable specifically to launch-related operations, which carry a higher degree of risk. This requires an amendment of Article III the *Liability Convention* to include lunar launching, as Article II does not cover space objects on the surface of the Moon or celestial bodies. This amendment would address damage occurring on the lunar surface or to other spacecraft in flight resulting from launches. Limiting strict liability to these scenarios ensures fairness while still addressing the most critical aspects of lunar exploration. Additionally, environmental considerations, such as contamination or disruption of the lunar surface, should be integrated into this liability framework to promote sustainable activities on the Moon.

Fault liability

According to the *Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies* (the OST), the Moon and other celestial bodies are considered part of outer space, thereby forming the basis for applying a liability regime to activities conducted on the Moon. The requirement to prove fault, combined with the lack of specific provisions on fault-based liability, could create challenges in applying the Liability Convention's provisions. In such circumstances, the injured party might seek to pursue legal action against the operator, by relying on alternative legal mechanisms, such as domestic law or general principles of international law. By requiring proof of fault or negligence, this approach ensures that liability is assigned only when a party has failed to comply with established obligations, without disproportionately burdening states or commercial actors.

Damage

According to the Liability Convention, the term "damage" means "loss of life, personal injury or other impairment of health; or loss of or damage to property of States or of persons, natural or juridical, or property of international intergovernmental organizations". It is blatantly clear that the Liability Convention may not address all potential disputes that could be faced by representatives of different nations on the Moon. In such cases, general principles of international law would apply.

Dispute Resolution

To address disputes arising on the Moon, the Lunar Tribunal should be composed of representatives from nations. Such a body would provide a mechanism for resolving conflicts, with jurisdiction over cases submitted by nations involved in lunar activities. The Lunar Council would be tasked with adopting a formal instrument outlining the Tribunal's mandate and relevant regulations for determining both the aspects of damage and liability. For instance, if a nation were to cause damage to the infrastructure of a lunar spaceport, the Tribunal could impose appropriate compensation obligations on the responsible State. Such compensation could be calculated and paid in Lunar Credits, described in Section 3.4.2.

1.3.4 Ownership in Lunar Infrastructure

Current Space Law on Ownership

Under the current international legal framework, there is no recognized basis for sovereign or real property ownership of lunar land or any part of the Moon. Article II of the OST provides 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". Section 10 of the Artemis Accords, reaffirms the OST's non-appropriation principle while advancing the interpretation that the extraction and utilization of space resources does not inherently constitute national appropriation. The Accords also propose the use of "safety zones" to avoid harmful interference through notification and coordination mechanisms, framing these as operational buffers rather than territorial claims.

Virgiliu Pop further describes the current space status as *res communis* doctrine, whereby space is a common belonging to all humanity, but also explores the public trust model, where sovereigns or international bodies act as stewards for the benefit of all (Who Owns the Moon? By Virgiliu Pop, Pg. 2) (37 J. Space L. 405). National legislation has expanded the idea of ownership by recognizing ownership over extracted resources. The United States' *Space Resource Exploration and Utilization Act* of 2015 grants U.S. entities the right to possess, use, sell and even own resources extracted from celestial bodies, while explicitly disclaiming sovereignty over the bodies themselves. Similar legislation in Luxembourg (2017) and the United Arab Emirates (2019) adopts the same approach. These statutes aim to reconcile domestic property rights with the OST by focusing on movable resources and linking ownership to active extraction rather than passive exclusion.

The general consensus is that it is possible to have ownership over resources that an entity has extracted but cannot own anything more. However, there are no binding laws on the abandonment, transfer, or salvage of lunar facilities, let alone owning them, creating potential for disputes analogous to maritime salvage conflicts.

Filling the Gaps

This absence of binding ownership rules illustrates a critical legal gap that must be addressed to ensure sustainable lunar development. To bridge this gap, this paper proposes establishing a Lunar Credit System. As aforementioned, under this framework no legal title would be granted over lunar infrastructure in compliance with Article II of the OST. Instead, contributors who construct, maintain, or improve lunar infrastructure would receive credits proportional to their inputs and contributions. These credits would function as tradable and redeemable rights to buy off prioritized access, operational benefits, or resource usage privileges within the lunar economy. For instance, if a facility lacks the capability to extract resources necessary for expansion or operation, it could use its credit to "hire" another entity with the required capability.

The governance of this credit system would be under the dedicated Lunar Council, responsible for issuing, regulating, and adjudicating usage credits exclusively for lunar infrastructure. Another function of the Lunar Council would be to oversee site selection for lunar infrastructure. Entities seeking to initiate new construction would be required to submit detailed proposals for location approval. These proposals would be evaluated using a *Balancing Test* that weights operational requirements, compatibility with existing infrastructure, environmental protection, and safety considerations. This would mitigate the risk of territorial disputes and overlapping claims, providing more civil and peaceful resolutions.

By decoupling ownership from operational benefits, the lunar credit system creates a legally sound and economically effective way to reward investment without contravening international law. This approach would encourage entities to invest in lunar development by providing clear incentives. Without a clear legal framework that ensures a reliable way to gain benefits, entities will be reluctant to spend the significant money and resources required to build and maintain infrastructure on the Moon.

Application

In practice, a private company that constructs and operates a lunar spaceport would not acquire legal title to the underlying land, consistent with the OST non-appropriation principle. Instead, under the proposed lunar credit system, the company would be allocated credits proportional to its investment, capacity, and operational contributions. These credits could then be traded or redeemed for tangible benefits such as priority docking rights, preferential access to lunar resources, or the ability to contract with other operators for extraction and logistical support. By converting infrastructure investment into transferable operational privileges rather than property rights, this system would incentivize development while adhering to existing space law, reducing the risk of territorial disputes, and creating a structured and cooperative lunar economy under the oversight of a dedicated Lunar Council.

1.3.5 Economics and Viability of the First Lunar Spaceport at the Moon's South Pole

Cost Modeling and Economic Drivers

The final aspect to consider for our spaceport is the costing and feasibility study of the aforementioned proposals. One study by Metzger and Autry examines economic trade-offs in constructing lunar landing pads. The key cost drivers to consider are transportation and program delay, both shaping construction choices.

Transport costs of $1 million/kg (as per the 2020 study) could fall within a decade to $100,000/kg or lower. High transport costs penalize Earth-import-heavy methods (e.g., polymer infusion, paver equipment). As prices drop, material-intensive but faster techniques like polymer infusion become more viable. In this method, imported polymers are used to bind lunar regolith into a solid surface, enabling rapid construction at the expense of higher shipped mass. Additionally, program delays impose economic losses from postponing readiness that are as critical as direct program costs. Delay costs can be modeled as a proportion of total program value, and - even with substantial mitigation - the resulting losses remain significant. Consequently, faster implementation methods, even if they are heavier or more complex, can be justified to reduce delays, enable earlier utilization, and attract private investment.

Hardware and energy costs are smaller factors: $1.684 million/kg and $473,000/MWh respectively, becoming significant only with very low transport costs or high energy demands. The choice of construction method is a primary driver of cost. Figure 15 compares eight candidate landing pad construction technique combinations across three transportation cost regimes (expensive, moderate, and cheap), and three program delay cost assumptions (high, low, none). The results highlight how sensitive total cost is to both method and scenario. Overall, microwave sintering emerges as the most cost-effective option, balancing moderate

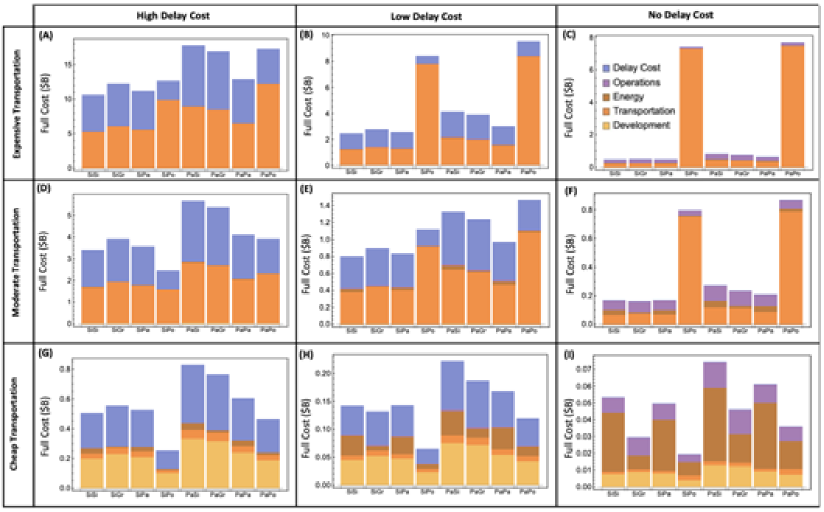

Figure 1.15: Full-cost comparison of eight lunar landing pad construction method combinations under different transportation and program delay cost scenarios. Abbreviations indicate the construction method combinations: SiSi – Sintered/Sintered, SiGr – Sintered/Gravel or Rock, SiPa – Sintered/Pavers, SiPo – Sintered/Polymer, PaSi – Pavers/Sintered, PaGr – Pavers/Gravel or Rock, PaPa – Pavers/Pavers, PaPo – Pavers/Polymer. (source: https://doi.org/10.1089/space.2022.0015)

hardware mass, speed, and operational simplicity.

Despite the potential for delay costs, in this study we have opted for pavers. Pavers, while mechanically complex, are durable, and offer better scalability and easier maintenance by simply replacing damaged units. Scalability is a key factor for the future expansion of the spaceport.

Balancing build speed and shipped mass is essential. Quicker builds cut delay costs but raise shipping costs. For our baseline, given engineering, scalability, and maintainability priorities, pavers remain preferred —even though the chart shows they are generally not the lowest-cost option—as we accept longer build times, the main cost driver, in exchange for modular repairability.

Lunar Spaceport: Costs, Benefits, and Strategic Framework

Spaceport infrastructure could become a long-term economic engine if seed-funded and regulated by a governmental organization while operated efficiently by private enterprise. Strategically, the spaceport would establish sustained and reliable lunar access, facilitating scientific research, commercial operations, resource extraction, and serving as a staging hub for deep-space exploration. Historical precedents like the ISS show that large-scale international cooperation spreads costs, stabilizes political support, and sustains projects across government cycles.

Given the substantial initial capital requirements, early-phase investment analyses highlight the prolonged lead times inherent in developing in-situ resource utilization (ISRU) capabilities and scaling commercial services. Taken together, these factors indicate that achieving a breakeven point within two decades is unlikely without substantial new revenue streams, including high-value resource extraction, lunar tourism, habitat services, in-space manufacturing, deep-space logistics, and large-scale in-space production and transportation.

Experience from terrestrial spaceports reinforces this challenge: Spaceport America, for example, cost $220 million to construct but generates only $7 million annually, with a limited launch cadence, making profitability elusive without high-volume operations. Comparative analyses of multiple U.S. commercial spaceports show that most remain reliant on substantial state subsidies, as launch revenues alone rarely cover operating costs. Given current and projected demand, breakeven generally requires unrealistically high launch revenues.

From State-Led Moon Base to Profitable Public–Private Hub

We assume a multi-agency program in which the state finances and operates the first lunar spaceport while contracting manufacturing to private firms. This structure mirrors state-agency operations at terrestrial sites such as the Mid-Atlantic Regional Spaceport and Spaceport America, which operate under public ownership and management while seeking to expand commercial participation. The government would initially provide open-access infrastructure with fee-based services, transitioning over time to concessions and private investment, following commercialization models seen in terrestrial spaceports and the airport sector."

To diversify income and reduce dependence on a single revenue stream, airports have expanded beyond aeronautical revenues into retail, real estate, logistics, and other non-aeronautical activities—significantly improving profitability. Empirical evidence from U.S. commercial spaceports confirms the need for phased privatization and revenue diversification, as none have become self-supporting on launch revenues alone.

The proposed lunar landing pad, using regolith paving, is estimated at $4 billion, assuming the paver construction method and moderate transportation costs. This $4 billion covers only the first pad and associated early infrastructure, not the entire spaceport build-out. The estimate includes high delay costs, hardware development, energy use, and building operations.

We foresee that funding will come from a 50/50 public-private partnership, primarily from stakeholders with a vested interest in accessing the Moon. On the one hand, space agencies and governments have an interest in reaching the lunar surface to build their base and conduct science. On the other hand, commercial launchers can benefit tremendously from lunar surface access. By opening future access to the Moon for commercial players (e.g., by selling future tickets for lunar tourism) an investment in the launch pad, its future development and future returns, can become feasible. Furthermore, this allows us to secure additional funding for the construction of the first landing pad. Modeled after the Axiom Space-NASA-SpaceX arrangement for ISS tourism and logistics, this plan combines government contribution with commercial investors that have a vested interest in getting access to the Moon as a new market.

Launch and landing fees are ∼20% of mission cost (minimum $20m, e.g., $21.2m for

Blue Moon, \$23.6m for Nova-C, \$20–30m for Starship Human Landing System) plus \$3m per additional pad-week, form the core initial revenue stream. With ∼\$200 m/year Operational Expenditure, driven by largely autonomous systems and ∼\$80 hours/year of high-value astronaut maintenance under NASA partnership, the spaceport must generate ∼\$420 m/year to achieve a 10% ROI (Return on Investment) over 10 years. This equates to ∼20 launches/year at the minimum fee, down to ∼15/year for high-fee missions; extra revenue from pad occupancy further reduces the break-even threshold.

Diversified revenue streams include ISRU propellant / resources sales, cargo handling, and increased tourism. The Lunar Credit system, embedded in governance, locks in multinational demand and long-term customer commitments. For private investors, secured equity stakes tied to recurring fees, multi-year service contracts, and asset-backed bonds on diversified cash flows combine the stability of public co-investment with substantial upside in an expanding lunar economy.

Finally, our business and finance research indicates that the first lunar spaceport is optimally constructed, funded, and operated by a consortium of international partners. In later phases, governance and operation would transition to a public–private partnership model comparable to modern airports. This progression moves the program from high-cost, delay-sensitive construction toward commercially driven, diversified operations. The phased approach supports initial development despite positioning the facility to evolve into a sustainable hub for scientific research, industrial activity, and deep-space exploration.

Conclusion

Our proposed Lunar Council, Lunar Credit system, and Lunar Tribunal aligned with the projected public and private investors, establish a baseline for the short construction and operation of the first lunar spaceport by providing governance and business models that can enable growth, promote equality and sustainability, and safeguard from a lunar free-for-all as technology advances and lunar activity increases.

Worldbuilding

The initial spaceport infrastructure on the Moon is designed to meet immediate mission requirements and pave the way for future settlements. However, its importance extends beyond just the first missions; it serves as the foundation for a long-term vision. Spaceports are the launching pad for the new space economy. However, to secure their future over the long term, spaceport developers must choose the right path today, emphasizing not only the importance of spaceports for future Moon habitation, but also how every step taken today will shape tomorrow's lunar society. Tomorrow's vision should be addressed from a clear perspective, where missions become more than isolated achievements but are the essential stepping stones towards securing humanity's goal of living in space. Keeping in mind the vision of a permanent lunar community, the following section presents an ambitious concept for the future: a spaceport as a centralized transportation hub capable of supporting 10 launches per day to Earth, Mars, or even across the lunar surface while providing a human-Earth-centered approach with the focus on making it sustainable. Long-term sustainability is established by managing cislunar traffic, developing long-term energy solutions, ensuring the welfare of spaceport employees, and exploring the possibility of cislunar tourism and economic development. It is precisely by daring to imagine and acting now that humanity will achieve what today seems unimaginable. As such, a future scenario is envisioned that may become feasible in the coming decades, provided that it is grounded in both technical requirements and the human aspects that must be addressed when that moment arrives.

Long Term Vision

2.1 Communications, Navigation and Transportation

2.1.1 Introduction

Through research and planned deployment, enhanced communication, navigation, transportation, and governance technologies are fast maturing to support a long-term human presence on and around the Moon. Blockchain-secured channels enable predictive, autonomous incident response, while relay constellations, hybrid radio/optical links, and radios driven by Artificial Intelligence (AI) will be used by lunar communication networks to offer continuous, low-latency coverage (NASA, 2021; McGarey, P., 2020; Singh, R., & Bodile, R. M., 2024). To facilitate complicated logistics and traffic deconfliction, navigation has advanced beyond Earth-based GNSS thanks to lunar constellations and quantum inertial sensors that provide centimeter-level accuracy (UNOOSA, 2024; ESA, n.d.). In line with the Artemis Accords goal of safe, sustainable, collaborative exploration, transportation integrates rovers, suborbital rockets, and centrifugal launch systems with orbital depots and fueling stations to form an integrated ecosystem (NASA, 2024; NASA, n.d).

An analogy of traditional air traffic management and its core functions—air traffic services (ATS) for flight monitoring and conflict resolution, airspace management for defining operational zones, and air traffic flow management for balancing demand and capacity—is used in this project to propose a cislunar traffic management (CLTM) framework to support these transformations. Resilience is crucial in the face of political unrest, cybersecurity threats, and deliberate disruptions; key defenses include flexible systems, strong cyber defenses, and open communication. While AI-driven monitoring, real-time data sharing, and tokenized utilities support governance and resource access, future regulations should specify liability and enforcement mechanisms, building on current regulatory structures. To discourage bad actors and promote equity, a combination of practical enforcement and well-balanced international cooperation will be essential. Ultimately, CLTM should provide the operational foundation and governing platform for humanity's expanding space presence, managing traffic with the precision and robustness needed for the next phase of lunar exploration.

2.1.2 Communications

Communications Infrastructure - Assumptions and Evolution

Communication technologies have developed into a robust, multi-layered network that reliably connects spaceports, spacecraft, and Earth in the long-established age of continuous lunar presence (Bhasin, K., et. al., 2006). Constellations of lunar relay satellites orbit the Moon, providing constant, low-latency coverage across the cislunar environment and beyond. To support the high-frequency personnel, cargo, and robotic operations that characterize life in lunar and cislunar space, several constellations from various private and governmental players serve as the foundation for intra-port, surface-to-orbit, and Moon-to-Earth communications.

Satellites that can change orbits will complement independent satellites and constellation grid topologies, increasing the agility and resilience of cislunar communications networks. These satellites can move between low, medium, and high lunar orbits in response to mission requirements. They do this by employing communication techniques established by a regulatory body that functions similarly to the current International Telecommunications Union on Earth. These transfers need less energy than comparable movements around Earth because of the Moon's narrower gravity well, allowing for more frequent repositioning with less fuel. The absence of a dense lunar atmosphere, however, also precludes aerodynamic braking, necessitating meticulous propellant and traffic control for every turn. Overall, if activated, these mobile relays will be capable of supporting high-bandwidth operations in temporary hotspots, serving as ad-hoc relays for long space missions, and bridging coverage gaps brought on by hardware breakdowns. Despite shifting traffic patterns and changing operational requirements, this orbital mobility guarantees that communications stay uninterrupted and efficient. Such resilient networks directly facilitate operations similar to Earth's ATS within the larger framework of CLTM, offering the real-time capacity required for spacecraft separation safety, flight monitoring, and dispute resolution. Without this communication backbone, CLTM could not provide the situational awareness needed to handle increasing amounts of cislunar and lunar traffic.

These sophisticated multi-link designs, which can support simultaneous, high-throughput data exchanges across Earth-based, orbital, and lunar nodes, fuel this established communication ecology. By simultaneously guiding several communication beams, high-gain, multi-beam steerable reflector antennas are autonomously placed and integrated into natural lunar craters. These nodes work in tandem with quantum entanglement-based links and AI-driven software-defined radios (Singh, R., & Bodile, R. M., 2024), which have significantly decreased the effective Moon-Earth delay. A hybrid strategy is used for cislunar connectivity: laser-based optical communications predominate for ultra-high data rate transmissions, intersatellite crosslinks, and science payload returns, while radio frequency systems are still necessary for broad-beam, weather-resilient links and omnidirectional coverage, especially for mobile assets and emergency channels. Whether sending terabytes of imagery from the lunar far side, providing immersive telepresence feeds for distant operators on Earth, or ensuring consistent telemetry for thousands of simultaneous spacecraft movements, the combination allows the network to dynamically adjust to mission requirements.

To provide flexible bandwidth allocation and interference management across congested traffic corridors, the team's network design integrates advanced multiple access techniques, which are methods to share communications resources among multiple users allowing for flexible bandwidth allocation and interference management across dense traffic corridors. For operational command and control, research payloads, real-time navigation, and commercial applications, this framework's sustained gigabit-per-second data rates are essential. As seen in Fig. 2.16, crater-based reflector antennas have evolved into recognizable infrastructure

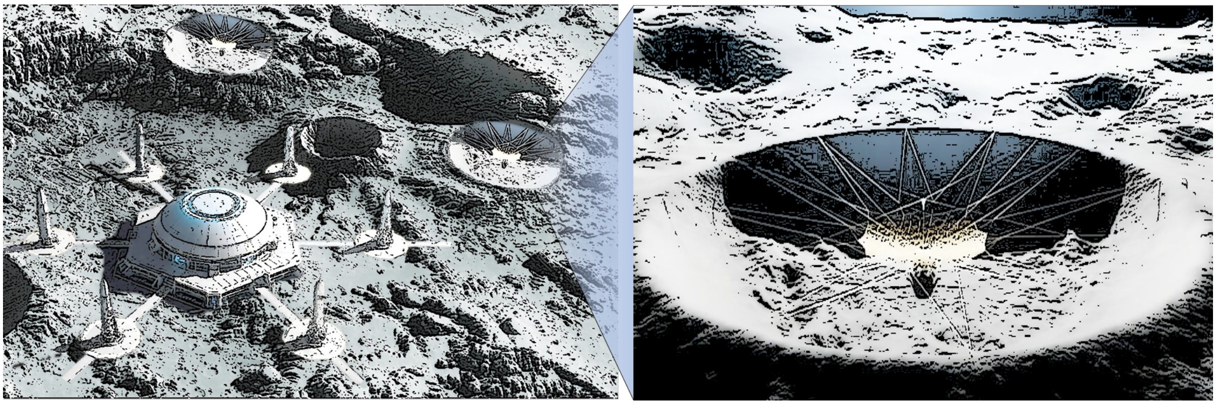

Figure 2.16: Lunar crater-based ultra-high gain reflector type antenna (developed by the authors)

components. They combine scientific research with practical use by acting as both the main communication centers and flexible platforms for radio astronomy. Communication capabilities will be greatly improved by the exceptionally high gain and beam directing capabilities of these antennas with multi-beam functionality.

Incident Response and Autonomy

Conventional Earth-based command-and-control mechanisms are inadequate in the cislunar environment because communication delays of a few seconds are unavoidable. Thus, the first line of defense against operational hazards and emergencies must be strong, low-latency communication networks coupled with autonomous systems. Real-time data exchange throughout the constellation of lunar relay satellites makes possible continuous monitoring of spacecraft positions, environmental risks, and system health. Through the CLTM system, this vital data is continuously sent back to Earth, feeding telemetry and digital twin systems that allow mission control to keep an eye on operations, simulate scenarios, and make well-informed strategic decisions.

Autonomous agents like rovers, drones, and onboard AI systems start fast response protocols without waiting for directives from Earth when such issues as docking abnormalities or environmental risks arise. Resilient communication links enable these self-governing systems to dynamically coordinate in order to prevent collisions, system malfunctions, or security breaches. Secure Communication Channels ensure data traceability and integrity throughout incident resolution, preventing cyber intrusion at critical moments. At the same time, distributed data storage on the lunar surface ensures operational continuity by storing important mission data locally and enabling autonomous agents to function even in the event of partial communications failures. To change incident response from reactive to predictive and adaptive, the team's strategy combines high-fidelity communication with autonomy. This significantly improves safety margins for the thousands of crew and cargo transfers that characterize long-term lunar missions. The self-healing cislunar ecosystem where human and machine collaborators smoothly handle traffic and emergencies is made possible by this architecture's eventual resolution of the intrinsic latency barrier. This is a critical advancement to support humanity's expanding footprint beyond Earth.

2.1.3 Navigation

Operation of a lunar navigation system

A state-of-the-art cislunar navigation system, which is a major improvement over Earth's GNSS or GPS, is required for the establishment of a successful, long-term lunar spaceport. With its ability to provide extremely accurate, real-time position, velocity, and timing services that connect spacecraft, surface habitats, and human explorers around the entire Moon-Earth system, the CisLunar Navigation System (C-LNS) is developing into an essential infrastructure. The safety, scalability, and fluidity of spaceport operations are ensured by this invisible system, which supports every maneuver, landing, and expedition.

The idea for the navigation system was the focus of the brief case study. Although it performs exceptionally well in regional positioning, its unreliability for international expansion raises serious concerns. The successful long-term construction of a lunar spaceport, where reliable and strong navigation systems are essential for operating effectiveness and safety, depends on resolving this constraint. Programs like NASA's LunaNet and ESA's Moonlight established the groundwork in the early decades by putting in place constellations of lunar satellites that offered constant coverage for navigation and communication both on the surface and in lunar orbit (ESA, n.d.). These systems promoted a collaborative lunar economy by facilitating smooth PNT services, high-bandwidth data streams, delay-tolerant networking, and international interoperability.

When experimental methods based on atom interferometry become the foundation of navigation independence, quantum navigation will be the next big step. Without relying on satellite signals, quantum inertial sensors (Gersemann, M., 2025) used in spacecraft and lunar homes offer accuracy down to the centimeter. These satellite-independent, self-calibrating technologies get around signal delays and jamming hazards, allowing autonomous vehicles and humans to navigate the diverse terrain of the Moon and beyond with unparalleled accuracy.

The shift was led by industry leaders like Q-CTRL (Quantum Insider, 2025) and ESA's Navigation Innovation and Support Program, which integrated quantum sensors into navigation architectures to detect small gravitational anomalies and provide continuous, fail-safe guidance in areas where GNSSis not available. By combining quantum inertial units with traditional satellite constellations, the team's suggested hybrid architecture creates a robust, tiered navigation fabric. It enables both tourists and lunar inhabitants to travel safely, carry out research missions, and confidently and fluidly manage intricate logistics.

Despite the enormous distances of cislunar space, the objective is to accomplish perfect synchronization of cargo arrivals, habitat resupply, and emergency responses in almost real-time for the large lunar population. Crewed rovers, drones, and autonomous cars all operated in unison with the help of quantum-augmented telemetry transmitted back to Earth's digital twins. Predictive maintenance and mission optimization are made possible by this technology. The navigation system is now the digital nervous system of humanity's off-world presence, going beyond simple infrastructure. By seamlessly integrating with AI and communication networks, this technology builds a resilient, adaptable lunar environment that is ready to expand humankind's reach to Mars and beyond.

Frequency of operations and traffic deconfliction strategies

At full capacity, the lunar spaceport will handle 10 launches and landings daily, creating a congested cislunar environment that demands a highly advanced, automated Cislunar Space Traffic Control and Monitoring (C-STCM) system. This system will be responsible for preventing collisions through dynamic separation and continuous AI-driven monitoring, maintaining an orderly flow of traffic, optimizing efficiency by minimizing delays and fuel consumption, and managing emergencies in real time.

The Earth-Moon corridor supports various trajectories, including direct transfer, free-return, near-rectilinear halo orbits (NRHO), and cycler orbits (NASA, n.d.). The C-STCM will allocate these trajectories based on mission priorities and commercial needs. The direct transfer trajectory provides the fastest transit time, taking three to five days. However, it requires a high delta-v (Δv) and has low stability, making it most suitable for crewed missions and rapid cargo delivery. In contrast, the low-energy transfer takes weeks to months to complete but requires minimal fuel and offers moderate stability, making it ideal for robotic or cargo missions. Free return trajectories have a moderate Δv and a travel time of four to six days, with safe return paths built in for crewed missions. The NRHO and distant retrograde orbit are designed for long-term operational bases. NRHO offers a balance of moderate Δv and stability, making it suitable for lunar gateway operations, while the distant retrograde orbit provides high stability for cargo staging and observation posts with low Δv. Lagrange point orbits facilitate communications and navigation with low to moderate Δv. Lunar surface rendezvous and hopping allows for short-range mobility on the lunar surface, while cycler orbits that require moderate to high Δv create periodic transport loops between Earth and the Moon.

Central to the system is a hybrid deep learning framework powered by quantum neural networks, which processes extensive real-time data including spacecraft health, traffic density, debris, and regulatory constraints (Beer, 2022). Fault-tolerant quantum computing nodes located in the permanently shadowed regions of the Moon (40–60 K) (Landis et al., 2022) run these algorithms, enabling complex scheduling and optimization beyond classical systems (Quantum Insider, 2025). Strict end-of-life disposal protocols require spacecraft to be moved to heliocentric orbits, lunar impact trajectories, Earth re-entry paths, or designated lunar graveyard orbits. Solar sails provide a low-cost, propellant-free method to manage debris displacement. Collision scenarios, including those in Earth-Moon transfer corridors, lunar orbits, rendezvous operations, and Earth-Moon Lagrange points, are managed through layered fail-safe systems and autonomous interventions. This quantum-enhanced C-STCM infrastructure integrates human and machine intelligence to maintain operational safety and efficiency, promoting a sustainable and scalable human presence around the Moon.

Legal Frameworks for Debris Mitigation, Cleanup, Liability, and Traffic Accidents

In the era of sustained cislunar operations, dedicated and enforceable legal frameworks will be needed to address debris mitigation, liability, and traffic accident management specific to the lunar environment. While foundational treaties like the United Nations (UN) Outer

Space Treaty (OST) and the 1972 Liability Convention will continue to provide broad principles, they will have been amended or supplemented to cover the unique challenges of cislunar commerce and traffic. Key policy tools, including extensions of the UN Long-Term Sustainability Guidelines and Space Debris Mitigation Guidelines from the Inter-Agency Space Debris Coordination Committee, will have been explicitly adapted to cislunar and deep-space operations. Building upon initiatives such as the Artemis Accords, ESA's Space Safety Programme, and emerging orbital "Highway Codes", enforceable cislunar operational norms and protocols will be in place to address both orbital and surface hazards.

Two approaches are presented: amending current laws, and establishing a new multilateral legal framework. Treaty Amendments will define a universally recognized "point zero" marking when spacecraft become classified as debris and embed Cislunar Debris Status Protocols within mission licensing. Protected Cislunar Regions will be formally designated to restrict disposal and transit activities, ensuring preservation of critical lunar zones. Under new multilateral agreements, the Accorded Cislunar Operations Agreement will govern traffic management, designate "no-go" zones, specify tailored end-of-life disposal procedures, and mandate active debris removal supported by shared technical resources. Either approach can be chosen based on a balance among freedom of use, sustainability, and conflict prevention. Operational risk scenarios, such as collisions during Earth-Moon transfers, lunar orbit traffic conflicts, docking incidents, debris fragmentation, and congestion at Lagrange points will be mitigated through autonomous avoidance systems, safe parking orbits, conjunction analysis, and advanced debris capture technologies.

Economic Impact of Safety, Liability Costs, and Insurance Models

By the time sustained cislunar operations are routine, safety performance and risk management will be central drivers of economic viability, shaping insurance models and investment decisions. Insurance frameworks will evolve by blending best practices from terrestrial aviation, maritime, and spaceflight underwriting, tailored for the lunar context. Key features of this future insurance ecosystem will include:

- Dynamic Premium Scaling: Operators deploying certified autonomous navigation and demonstrating compliance with Cislunar Space Traffic Authority standards will benefit from reduced premiums.

- Shared Risk Pools: Collaborative insurance schemes will enable smaller operators to enter the lunar economy affordably while spreading risk.

- Performance Bonds: Financial guarantees will be mandatory for high-risk activities, such as resource extraction in congested zones, ensuring coverage for cleanup and liability

Economic modeling will demonstrate that integration of AI-enabled navigation and robust legal frameworks reduces collision risk by significant margins, driving down asset loss and mission delays. These efficiencies will produce substantial cost savings, fueling ongoing infrastructure development and creating a virtuous cycle where enhanced safety and economic growth reinforce each other.

2.1.4 Transportation

Strategic Lunar Locations and Outposts for Long-Term Habitation

A few strategic sites that are most suited for habitation, resource extraction, and scientific study will be the focal points of a long-term human presence on the Moon. As described in the short-term case study, the LSP, with its near-permanent sunshine and water ice deposits, is predicted to serve as the principal human bases and economic hub. However, in order to access a variety of resource pockets and lower operational risks, mining and water extraction activities will probably be spread across several locations on the Moon. Polar regions, equatorial science stations, and permanently shaded craters for cold storage are examples of secondary outposts. To sustain thriving lunar commerce and exploration, this geographic dispersion necessitates dependable transportation networks linking several towns, resource locations, and landing facilities.

Cargo and Crew Requirements for Lunar Transportation

Transportation needs for passengers and cargo on the Moon will be diverse. Raw lunar materials like water ice and regolith, refined resources like oxygen and hydrogen propellant, infrastructure for habitat expansion, scientific equipment, and life-supporting supplies will all be transported. Astronauts, scientists, maintenance personnel, commercial employees, and tourists will all be among the passengers. Regular supply runs, crew rotations, emergency evacuations, and guest transfers must all be supported by transportation and CLTM systems, which must scale up to handle the expanding population and economic activities of a mature lunar settlement.

Diverse Transportation Technologies for Lunar Mobility

To effectively carry people and products across the lunar surface and into lunar orbit, a variety of transportation techniques will be used:

- Surface Vehicles: While new ideas like lunar trains or maglev technologies facilitate high-volume transportation between important locations, pressurized and cargo rovers are crucial for personnel mobility and freight transporting.
- Suborbital Rockets: Reusable suborbital rockets allow for quick point-to-point transportation for both personnel and cargo, traveling hundreds of kilometers in a matter of minutes by taking advantage of the Moon's low gravity and vacuum environment.
- Centrifugal Launch Systems: By taking advantage of the Moon's gravity and absence of atmosphere, novel mass drivers or centrifugal launchers will enable inexpensive, propellant-free cargo transportation between surface locations or from the surface to orbit.
- Autonomous Hoppers: To increase total operational flexibility, smaller autonomous devices could support maintenance, site scouting, and last-mile delivery over difficult terrain.

Infrastructure Enabling Sustainable Lunar Transportation

The transition from IOC to FBO as discussed in the short-term case study must be taken into account for the advanced infrastructure needed to support this transit network, including:

- Fueling Stations: Landers, shuttles, rovers, and suborbital vehicles need to refuel at strategically positioned propellant depots on the lunar surface, in lunar orbit, and at strategic positions like Lagrange points. Depots at Lagrange points will serve as transfer and storage hubs, allowing for effective fuel distribution and extended mission capabilities, while surface stations will mostly rely on ISRU to manufacture hydrogen, oxygen, and other fuels.

- Orbital Depots: Serving as vital hubs connecting surface activities with Earth and deep space missions, these stations should enable spacecraft refueling, repair, and cargo transfer in lunar orbit.

- Autonomous Servicing Facilities: Robotics and AI-driven maintenance hubs will ensure continuous vehicle readiness, reducing downtime and human labor requirements.

- Integrated Traffic and Fuel Management Systems: To optimize resource use and mission timing, these systems coordinate fuel distribution, vehicle scheduling, and maintenance across the lunar transportation network.

These modes of transportation and the infrastructure they support will work together to create a robust, scalable system that will allow long-term lunar living, research, and business growth. Beyond these limits, additional ambitious developments will be needed to fully realize the potential of lunar transportation and satisfy the increasing needs of long-term human habitation.

Large-scale maglev networks are one example of a breakthrough technology that could allow for quick, high-capacity transit between far-flung lunar colonies, facilitating widespread resource exploitation and cross-surface scientific cooperation. The cost and complexity of transporting people and cargo could be greatly reduced by space elevators, which provide low-energy, practically continuous transportation between the lunar surface and orbit, despite their technical challenges. Beyond the capabilities of solar-powered systems, nuclear-powered surface vehicles could offer dependable, long-range mobility in challenging conditions, allowing for year-round operations. These developments will enable people to establish themselves on the Moon in greater numbers than a few outposts, allowing for extensive building, resource use, and ultimate industrialization. These technologies could turn the Moon from an isolated outpost into a bustling, connected population and economic center by improving transportation speed, affordability, and dependability.

Inter-Lunar Transport: Connecting Spaceport, Landing Pads, and Nearby Settlements

In the short-term case study, the transportation system is designed using coordinated hoppers and a low-power FLOAT system. To ensure long-term sustainability at the lunar spaceport, this transportation method requires reliable technological advancements and enhancements to improve its capability, particularly for covering long distances in a short time. In the operational ecosystem of a mature lunar spaceport, short to mid-range transportation systems form the vital connections linking the core functions of the spaceport together. For the most demanding and high-use transportation solutions, a dedicated swarm of pressurized and unpressurized rovers will manage the continuous flow of crew, cargo, and critical supplies between the main spaceport complex, secondary subsystems, and adjacent landing pads. These rovers, purpose-built for the Moon's low-gravity and high-dust environment, will employ sealed cabins with life-support systems for crew transportation, and advanced suspension to navigate regolith-covered terrain while minimizing vibration and particulate intrusion. Passenger rovers will prioritize rapid embarkation and disembarkation, incorporating docking-compatible airlocks that allow movement without the time-consuming process of donning and removing EVA suits. Cargo variants will feature modular container systems that can be easily swapped with integrated dust mitigation seals, enabling the secure transfer of lunar resources and materials across the surface. Dedicated fragile rover modules will be used to deliver sensitive payloads such as scientific instruments, propellant components, and perishable supplies from landers directly into the controlled environment of the logistics hub.

For larger-scale movements between the spaceport and nearby settlements, expected to range from several kilometers to tens of kilometers, a dual-mode transport system will combine larger high-capacity rovers and maglev trains adapted and built to function seamlessly in lunar conditions. The maglev system, which is supported by regolith-stabilized guideways and powered by a hybrid and sustainable power grid, will enable high-speed transportation with minimal vibration for both personnel and cargo. This will efficiently link the larger and more critical infrastructure nodes with a fast, safe, and reliable mode of transport. Passenger compartments within the trains will incorporate life-support and radiation shielding to ensure comfort and safety, while cargo modules will handle high-mass freight such as refined materials, structural components, refined propellants, and bulk regolith feedstock for processing plants.

For much larger and long-distance travel to destinations both on the lunar surface and in space, launch systems employing reusable landers and orbital transfer vehicles will operate, supported by hardened regolith or sintered-paver pads. Traditional rockets and launching systems will utilize launch and landing pads that are equipped with blast deflectors and dust-suppression infrastructure to minimize the propelled materials generated by the launchers. Complementing the propellant-based launching systems, centrifugal launch systems including mass drivers or electromagnetic catapults will provide a propellant-free initial launch for high-frequency cargo launches to orbit and far inter-lunar sites. These will be positioned at a safe distance from habitation zones and optimized for non-human payloads such as raw regolith, refined metals, or pre-packaged construction elements. Frequent landing zones for these cargo transport systems can be supported by eddy current braking systems, allowing landing and deceleration with minimal power requirements.

Cargo will be loaded into sealed, impact-protected capsules via automated conveyors, where onboard inertial dampening and thermal shielding protect them from the harsh high acceleration environment. Integrated scheduling software will coordinate launch windows with orbital traffic patterns, ensuring efficient handoff to orbital depots or direct rendezvous with transport craft bound for Earth or deep space. Loading systems for these vehicles will be fully enclosed to maintain environmental control and prevent contamination. Cargo loading will leverage pressurized transfer corridors and robotic cranes, moving containerized payloads directly from the logistics hub to the spacecraft's cargo bay without exposing sensitive materials to the external environment. The operational integration of these two launch methods allows the spaceport to balance flexibility and efficiency—traditional rocket systems provide adaptable crew and mixed cargo missions, while centrifugal systems deliver bulk cargo at high cadence and low cost. Together, they form a system capable of supporting both the routine demands of lunar commerce and the surge requirements of large-scale construction or interplanetary mission staging.

In the long term, this layered transport network will form a resilient backbone for the local lunar economy, allowing the spaceport to function not as an isolated facility but instead as the anchor of a connected, multi-settlement ecosystem. These transport modes will operate within the tightly integrated traffic management framework, synchronizing departures and arrivals with spaceport operations to prevent congestion at loading bays, optimize vehicle use, and maintain separation between human and cargo flows where safety dictates. By combining the flexibility of rovers with the efficiency and capacity of maglev rail, the system will sustain both the high-tempo logistics demands of cislunar commerce and the daily mobility needs of a growing lunar population, ensuring that the spaceport remains the primary gateway for movement across the Moon's surface.

Refueling

Traditionally, space missions have been constrained by the amount of propellant launched with the vehicle. Once fuel reserves are depleted, spacecraft operations cease, regardless of the health of other systems. The development of in-space refueling technologies promises to overcome this constraint, providing reusable spacecraft, extended mission lifetimes, and novel operational paradigms. These capabilities are expected to play a critical role in supporting both governmental and commercial space activities, particularly as the focus shifts toward sustained presence in cislunar space and beyond. The existence of the Moon as a fuel source can be the cheapest way to achieve refueling for spacecraft in cis-lunar territory.

Furthermore, the development of on-surface refueling is crucial for extended lunar presence, as it enables rovers and surface transport vehicles to operate continuously and without reliance on driving only during the lunar day when solar energy is available. Surface refueling stations can support a closed-loop operational cycle, reducing logistics costs and increasing mission autonomy. This capability not only allows for sustained crew rotations and expanded exploration ranges but also underpins the construction and maintenance of lunar infrastructure, including habitats, power systems, and scientific installations. Once lunar fuel generation is operational, propellants will dominate cargo traffic both on the surface and into orbit, making it the backbone of cislunar logistics. Efficient transport will require cryogenic thermal protection and optimized transfer routes. As shown in Figure 17, the delta-v costs vary widely across orbital regimes: while escaping Earth's gravity well remains the largest hurdle, transfers between lunar surface, low lunar orbit, NRHO, and Lagrange points are comparatively cheap. This makes the Moon an ideal staging ground for fueling depots.

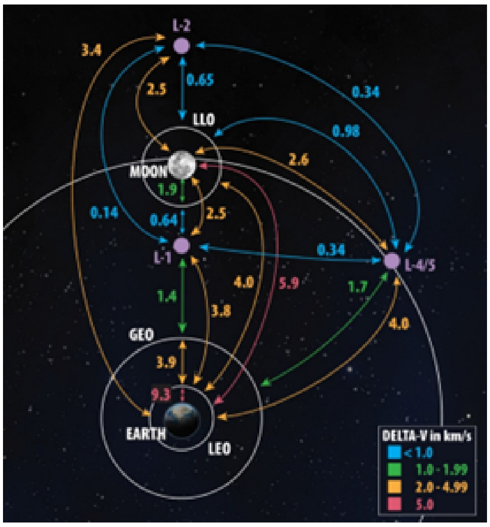

Figure 2.17: Comparative delta-v requirements for Earth-Moon-Lagrange point transfers (source: NASA)

To fully exploit this advantage, a critical layer of the architecture will be small orbit-transfer-capable spacecraft that deliver fuel where it is needed most. These vehicles can move between regimes to resupply satellites, landers, and depots, filling gaps in bulk supply chains. By matching the delta-v requirements of specific missions, these mobile tankers create a flexible, just-in-time distribution network that complements bulk propellant shipments.

Fueling stations on the Moon itself will likely be predominantly electrical fuel based. Most surface mobility - such as rovers, construction equipment, and robotic haulers - can be powered more efficiently by batteries, fuel cells, or direct solar energy than by combustion engines. Electrical "charging depots" can be built using locally available solar power, stored in battery banks or through regenerative fuel cells, avoiding the complexities of cryogenic storage and handling for chemical propellants. This is particularly important given the extreme temperature changes of the Moon, ranging from about +120 °C during the lunar day to -170 °C at night, which make long-term cryogenic storage challenging, since boiling and thermal cycling can rapidly degrade fuel reserves and containment systems.

Lunar surface transportation systems are expected to be largely self-sustaining during the approximately 14-day-long lunar daytime, when solar energy is abundant and can continuously recharge vehicles. However, during the equally long lunar night, when temperatures plummet and solar power is unavailable, these vehicles will require access to fueling or energy stations to replenish power reserves. In these periods, fuel cells or rechargeable energy storage systems supplied by dedicated fueling stations will become critical for maintaining mobility and mission continuity. Consequently, while daytime operations will rely primarily on solar-powered electrical charging, fueling stations designed to support energy needs during the lunar night will play an essential role in round-the-clock surface exploration and transport. For better recharging efficiency, a lunar vehicle battery standard will be used for fast replacement of batteries, rather than recharging the batteries of the vehicles. In this way, "fueling" time will be reduced dramatically, and batteries will be recharged at the fueling station when the fueling station will be sunlit on the lunar day, when it will also be less in use.

2.1.5 Importance of Power Supply for Communications, Navigation, and Transportation

To maintain long-term operations, a fully functional lunar outpost will require the integration of transportation, navigation, and communication systems, as we covered in this section. The tenets of the CLTM architecture will make this possible. While sophisticated navigation networks provide very accurate guidance for cargo haulers, rovers, and landers across difficult terrain, dependable communication links allow for exact coordination between surface vehicles, orbital assets, and Earth-based mission control. The physical framework that transports people, goods, and resources between habitats, orbital gateways, and mining sites are made up of transportation infrastructure. The lunar spaceport is at the center of this network, acting as its operational anchor and main hub.

2.2 Lunar Spaceport Energy Infrastructure

2.2.1 Introduction

Power generation on the lunar surface is one of the most important topics of research for the return to the Moon. Unlike on Earth, on the lunar surface, even basic survival depends on a stable and sufficient energy supply to support and sustain life. While research and planning have been done on the Artemis energy grid, they mostly focus on a lunar base infrastructure in the short-term horizon.

In a long-term view, it is necessary to shift the mindset from a ‘survival’ paradigm to a ‘thriving’ one, in which a permanent human presence on the lunar surface truly becomes part of humanity’s road to become a multi-planetary species. A large-scale spaceport with capability like a terrestrial airport is instrumental to address this topic. One of the biggest challenges facing a spaceport of such size is the energy economy required to sustain such a facility.

Very little research has been done into spaceports in general, so any estimates of the power requirement for a lunar spaceport are difficult. This project creates a chart for assessing the power required by different sectors of a spaceport and then applies the concept to its proposed vision to work out an estimate for the power required. Further, an outline for a power use schedule is presented for a 24-hour working day of the spaceport. It shows how energy demand will fluctuate through the day.

The power requirement for the spaceport is calculated based on the following assumptions:

- The spaceport has 200 employees.
- The 200 employees will be permanent residents of the spaceport.
- A passenger throughput of 30 per day is assumed.
- The spaceport includes five launch pads.

- The spaceport has a maximum capacity of 300 people to accommodate layovers and emergency extra capacity.
- That there will be five landings and five launches per day, four of the rockets being for cargo and one for passengers.
- The spaceport services an external permanent colony of 1000 people.
- The external colony has its own power system. The power system being designed here supports the spaceport, and spaceport alone.

The team evaluates a potential solution to provide the spaceport with sufficient energy generation and storage to ensure stable and redundant operation. To do this, the group assesses potential avenues to generate and store power on the lunar surface, and subsequently ranks them with a matrix for effective comparison. This matrix assists in the decision of the energy mix, as well as for energy storage solutions, depending on their suitability to the application. Finally, this section summarizes and visualizes the proposed grid using a systems diagram, bringing all the systems together in support of the spaceport self-sustainability.

2.2.2 Power Forecast

The presented power forecast focuses on the operating needs of the spaceport rather than on human settlements that might exist on the lunar surface. It is designed to be used as a tool for an approximate estimation of power requirements by using a high-level approach. The major systems needed for a long-term lunar spaceport are:

- Housekeeping / habitation (HAB)
- Mission control and communications (COMM)
- Propellant transfer systems and ground infrastructure (P and GI)
- Maintenance, integration and cargo transfer (MI and CT)
- Pad operations (PadOps)
- Surface mobility (MOB)
- Rocket launch suppression systems (RLSS)

To make educated estimates, we rely on power usages from similar analogues from both space and Earth, such as the International Space Station (ISS) and launch sites. Each major system has its own literature review, system breakdown, and power estimate, sized to the assumptions previously stated. Then the team presents a working day schedule for operation of the spaceport, where major system power usages vary depending on the operation being performed.

Housekeeping / Habitation (HAB)

Housekeeping and Habitation encompasses any subsystems that are essential to a continued human habitation at the launch site, and for people to complete their work. The subsystems include lighting, habitation modules, life support systems, food preparation, and heating. The power requirement data for HAB comes from (Ewert, M. K., 2015), which in turn extracts its values from the life support systems onboard the ISS. The power users from this document used for calculating HAB values are:

- Crew Health Care System (CHeCS)
- Environmental Control and Life Support Systems (ECLSS)
- European Space Agency (ESA)
- Service Module (SM)
- Thermal Control System (TCS)

This gives an accumulated value of 19.82 kW, which is then scaled to accommodate 300 people:

$$Power_{HAB} = Power_{ISS}\frac{300}{7} = 960kW \tag{2.1}$$

Mission Control and Communications (COMM)

COMM covers the systems used to communicate both with the spacecraft and other elements of the spaceport. They also include both active and passive detection systems used for the tracking of approaching and departing spacecraft.

The team adopts power requirement data for mission control and communications from the air traffic control and data segments of Seve Ballesteros-Santander airport. This airport was chosen due to its similar workforce scale to the proposed spaceport. Keeping track of spacecraft and aircraft requires a similar amount of personnel, data capacity, and tracking sensors that a commercial spaceport would employ.

To calculate the power requirement from the Seve Ballesteros-Santander airport, the following power requirements are combined to form the mission control and communications estimate: data center processing, information and communications technology, signaling and information, and radio navigation. The calculation gives an accumulated power value of 144.44 kW, which is then scaled to accommodate the size of our spaceport:

$$Power_{COMM} = Power_{ATC}\frac{300}{288} = 150kW \tag{2.2}$$

Propellant Transfer Systems and Ground Infrastructure (P&GI)

For propellant transfer systems and ground infrastructure the group works under the assumption of just storing liquid oxygen (LOX) and LH_2, which means that the spaceport does not produce it or transport it from the production site to its facilities. Another premise is to store at least the amount of propellant needed for the 10 expected daily launches, and considering the rocket equation, the total amount of fuel required corresponds to 46.2 t of LOX and 7.8 t of LH_2 for a total of 50.4 t.

$$R = e^{\left(\frac{\Delta v}{g_0 \ I_{sp}}\right)} \tag{2.3}$$

$$M_{prop} = (R - 1) \ m_1 \tag{2.4}$$

To convert propellant mass into volume, the team considers typical density values at near-normal boiling point conditions, which are standard cryogenic setpoints for ground storage at approximately one bar. According to National Institute of Standards and Technology and cryogenic safety references, these are:

- Liquid oxygen (LOX): $\sim 1,141 \ kg/m^3$ at $\sim 90K$
- Liquid hydrogen (LH_2): $\sim 70.85 \ kg/m^3$ at $\sim 20.3K$ (Kopetk, P., 2006)

Considering the use of spherical tanks to minimize heat-leak, the minimum area and volume are:

- LH_2: 109.4 m^3 and the sphere area $A = 110.6 \ m^2$
- LOX: 37.3 m^3 and the sphere area $A = 54.0 \ m^2$

Accounting for the passive heat leak of the tanks using multi-layer insulation (MLI), adopt a heat-flux range of 0.085–0.22 Wm^{-2} (Hedayat et al., n.d.) which multiplied by the spherical tank areas gives:

- LH_2 tank ($\sim 20K$): 9.4–24.3 W
- LOX tank ($\sim 90K$): 4.6–11.9 W

To convert heat-in to electrical power using measured cryocooler specific power (input W per W removed):

- 90–100 K RTB(reverse turbo-Brayton-cycle) (LN_2 ZBO(zero boiloff) test): $\approx 17W/Wat\sim$ 93–98K return.
- 20 K RTB (NASA 20 W @ 20 K): 91.6 W/W tested at 285 K reject; 86.3 W/W projected at 270 K.[ref 2]

The final value for electrical power needed to store the fuel under cryogenic conditions is:

- LOX ($\sim 90K$): (4.6–11.9 W) (17 W/W)=0.08–0.20 kW
- LH_2 ($\sim 20K$): (9.4–24.3 W) (86–92 W/W)=0.81–2.24 kW

The total continuous cooling electricity is between 0.9 and 2.4 kW. In view of the amount of energy needed to pump the stored fuel, the group envisions a pump-fed cryogenic propellant transfer system; the CPST baseline LH_2 flow is of 0.0098 kg/s and the total electrical loads are 0.46 kW, which with a 30% design margin is 0.6 kW. Accounting for the need to fill 5.04 t in 15 minutes for each spacecraft, that implies much higher volumetric flow ($\approx$0.016 m^3/s combined for LOX+LH_2). For a mass flow rate of 0.0098 kg/s and a total mass of fuel per rocket of 5.04 t in 15 minutes of fueling time, we have a power requirement of 411.25 kW.

Maintenance, Integration and Cargo Transfer (MIC&T)

Maintenance, integration & cargo transfer (MI&CT) covers the energy requirement of the spaceport's equivalent of the payload integration building, where the payload of rockets is installed onto or removed from a rocket and small-scale routine maintenance is carried out. The source of power requirement data for MI&CT is the usage of the payload integration building at Saxa-Vord Spaceport in the United Kingdom (SaxaVord UK Space Port, 2022), in particular the power output of the generators used to power the integration hangar (IH). The spaceport serves small low earth orbit rockets, which are of similar size to what the spaceport is going to service, which is why it has been chosen for a value donor. This gives a power value of 440 kW for three launchpads, which is then scaled up to the spaceport envisioned with five launchpads:

$$Power_{MI\&CT} = Power_{IH}\frac{5}{3} = 733kW \tag{2.5}$$

PadOps (PAD)

PadOps encompasses any systems both on the launchpad itself and any auxiliary systems required for the operation of the pad. Similarly to MI&CT, the source of the power requirements is Saxa-Vord Spaceport (SaxaVord UK Space Port, 2022). The power requirements to run the launch site processing facilities (LSPF) services is scaled for a five launchpads spaceport:

$$Power_{PAD} = Power_{LSPF}\frac{5}{3} = 933kW \tag{2.6}$$

Surface Mobility (MOB)

MOB refers to the recharging of any roving vehicles that are used in the spaceport to ferry around cargo or crew. Power requirement data per vehicle is 500 W, as stated by NASA's Artemis mission (Sustainable Power for the Lunar Surface). For the spaceport, the team estimates that four rovers will be required per active launchpad, (two for cargo, one for service, and one for crew transport) meaning that a total of 20 active rovers are required, therefore 10 kW of power.

Rocket Launch Suppression Systems (RLSS)

RLSS covers any active measure used to protect the launchpad or launch complex from the blast of a rocket either taking off or landing and is generally only active for the time that the rocket is taking off or landing. Again, the power requirement data for RLSS come from the power usage to run the water deluge system at Saxa-Vord Spaceport. Although it is unlikely that a water deluge system is going to be on the Moon, it serves as a placeholder for any other active suppression system that will be used.

This gives a power value of 800 kW for three launchpads, that scaled up to a spaceport with five launchpads gives:

$$Power_{RLSS} = Power_{DEL}\frac{5}{3} = 1333kW \tag{2.7}$$

Total Major System Power

The results are summarized in Table 2.1 and Fig. 2.18.

Table 2.1: Maximum power requested per subsystem

Power Forecast	Max. Power Request [kW]
Launch suppression System	1333
Hausekeeping & Habitat	960
Mission Control & Communication	159
Propellant & Ground Support Equipment	414
Maintenance & Fab.	733
PadOps	933
Surface Mob. & Logistics	10
Total Max. Power	4543

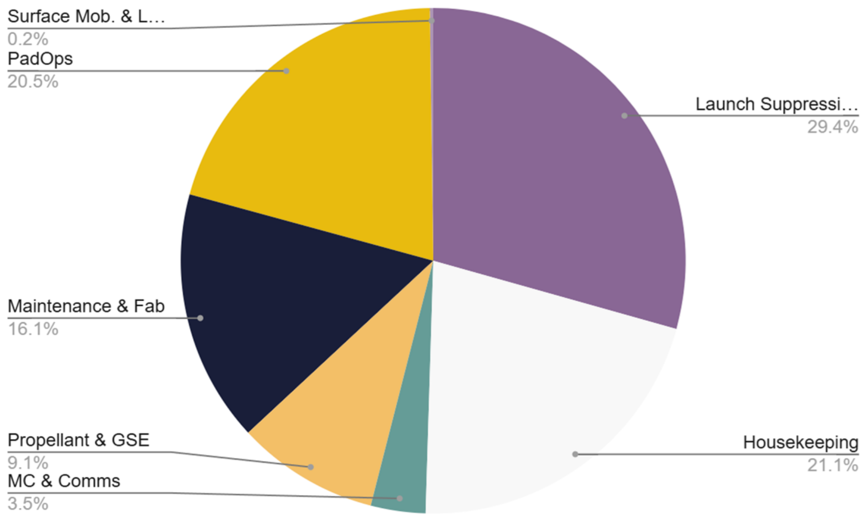

Figure 2.18: Percentage based energy use breakdown per subsystem

Power Use in Practice

To give a better idea of how much power the station will really need, it is important to create a power schedule that mirrors a simulated day of the functioning spaceport. While in theory, the spaceport averages 4.5 MW of power required, in practice that number is much lower as not all systems are running at once.

To simulate this, the team created a timetable of how a theoretical 24-hour day would play out, with a total of five launches and five landings. The group has modeled power use considering when systems would be running at full capacity, and when they would be running at reduced capacities depending on the activities being carried out at the spaceport. The figure 2.19 depicts the power usage throughout the simulated day. By doing this, a much better understanding of the power generation and storage requirements for the spaceport is depicted. Using this information, the required power storage can be sized, and then the power generation, accordingly.

2.2.3 Power Storage

To ensure the continuous operation of a long-term lunar spaceport, a sufficient energy supply system is indispensable. Within the system, the creation of a large-scale energy storage system is of the most importance. The energy storage system plays a key role in ensuring the stability,

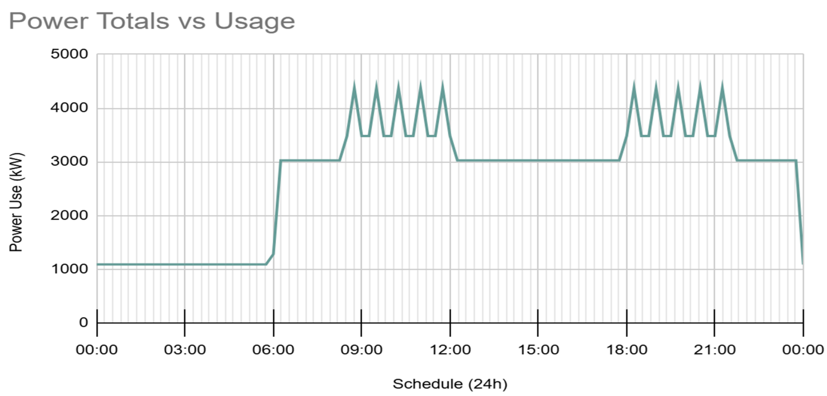

Figure 2.19: Daily usage of power for the spaceport

continuity, and flexibility of the energy supply.

In the existing research, most of the focus is on three types of energy storage. The most common energy storage system is batteries. Their technology has greatly increased since the beginning of space exploration, where they have been used from the start. The second storage system considered is flywheels, a chemical free way of storing and supplying energy when requested. They are mechanical batteries that use an electric motor and a quickly spinning rotor to store the supplied energy in the form of kinetic energy. To provide electricity, the rotational energy is converted back into electrical energy by a generator. Fuel cells are another type of storage systems that stow chemical energy under fuel and oxidizer form. When required, the chemical energy is transformed into electricity through electrochemical reactions between the stored chemicals.

The proposal of this study is to supply the energy required by the entire spaceport via flywheels and batteries. The flywheels are supplying an average and continuous amount of power (about 2,740 kW) based on the energy forecast schedule shown in Figure 2.19. Flywheels mitigate voltage and frequency instability caused by power supply-demand imbalances or grid failures within seconds. They also have rapid response characteristics, high energy conversion efficiency and exceptionally long service life, capable of achieving thousands of charge-discharge cycles. The batteries provide the rest of the energy needed for the spaceport to function. Referring to the schedule created, the batteries are needed for 17.5 h every day, during which the spaceport is operational in some capacity. They also must provide a peak of power of 1,630 kW required during the 10 launches. The team has chosen solid-state lithium batteries for their rechargeable nature, wide operating temperature range, long lifespan, high energy density (400 Wh/kg)(Agrawal, R. C., & Pandey, G. P., 2008) and very promising prospects for future research. The type of battery technology could be changed later to allow for the use of batteries made from the lunar soil. These batteries are currently being researched (Maurel, A., 2023), and their continued development would be a big step in the sustainability of the entire spaceport project. The batteries were sized considering the peak of energy during the launch operations. The estimate is 150 batteries, each of them with a capacity of 237 kWh and a mass of 475 kg. The fuel cells are used as emergency back-up, as they exhibit a rapid load response and are capable of transitioning from minimum power to a required power level very quickly.

They have an extremely long service life, with minimal impact on the environment. There are many fuel cell technologies; however, the design presented in this study uses the regenerative fuel cell energy storage system (RFCESS), where an electrolysis is employed to charge the cell. The produced hydrogen and oxygen are stored until electricity is needed, when the components are combined to chemically react. RFCESS have a wide specific energy range (200 Wh/kg - 1,000 Wh/kg) (Dupont, C., 2022) and can store a large amount of energy. Finally, since water might be available on the Moon, there is a chance to utilize ISRU to lower the need to resupply from Earth.

2.2.4 Power Generation

Generating power is a key factor for a spaceport in the long term. A stable, continuous supply capable of covering both normal operations and peak loads is critical. Based on the forecast from the previous section, the required energy is approximately 5 MWh. To ensure resilience and avoid reliance on a single source, demand should be met through a combination of different power generation technologies.

The five energy generation technologies considered were classical solar panels, space solar power systems (SSPS), thermal solar, radioisotope thermoelectric generators (RTG), and small modular reactors (SMRs). The team compares all technologies in and ranks each aspect from one to five, as shown in table 2.2. The higher the score, the better the technology performs in the category. The overall scores reveal that SSPS is the most optimal solution due to their high specific energy, excellent dust tolerance, and stability. They are followed by SMRs and thermal solar technology, which have a good balance of reliability vs. ISRU compatibility. RTGs are more reliable and stable but lack scalability and are poorly compatible with ISRU. Typical solar panels, although light and affordable, perform poorly in dusty and unstable environments. This evaluation leads to splitting the energy source by percentage according to their score in the matrix, considering only the best three options (See Table 2.19, Fig. 2.20). The power grid architecture is designed to be resilient, even if two out of three power sources are compromised, cutting down on all unnecessary operations and leaving only the vital operations going. This makes this system a "two-failure tolerant" system.

The Artemis program is planning to use solar and small nuclear reactors (SNRs). For both a settlement and spaceport of the assumed size, ground based solar panels do not seem to be a feasible solution due to a dusty environment caused by continuous launches and human activity. Solar panels will also be of low efficiency since direct sunlight will be available only for a fraction of the time in some regions of the Moon. Even in permanently illuminated regions, their size is too small to reach the necessary amount of energy. SNRs exhibit high resilience to lunar dust and can provide continuous, stable power output. However, their specific energy remains comparatively low. According to NASA data, a 10 kWe reactor has an estimated mass of 1500 kg, corresponding to a specific energy of 6.67 W/kg (Gibson, M. A., et. al., 2017). This shows how such systems are insufficient to meet the demands of a large-scale spaceport as a standalone solution. On the other hand, terrestrial SMR designs display specific energy values of around 110 W/Kg (Nuscale, 2025), implying that a 2 MWe unit would require a mass on the order of 18 tons, approximately two times greater than an equivalent SSPS. Nevertheless, with

100 t cargo delivery capabilities projected to become feasible in the near-term, SNRs remain a viable long-term option due to their high operational stability, particularly when deployed in conjunction with complementary power generation technologies.

Table 2.2: Power generation trade-off matrix

	Solar Panels	SSP	Thermal Solar	RTG	SMR
Wh/kg	5	5	4	3	3
Scalability	5	5	4	1	2
Reliability	3	4	3	5	5
ISRU compatibility	4	4	5	1	1
Dust tolerance	1	5	3	5	5
Stability	1	5	1	5	5
Costs	1	2	3	1	2
	22	30	23	21	23

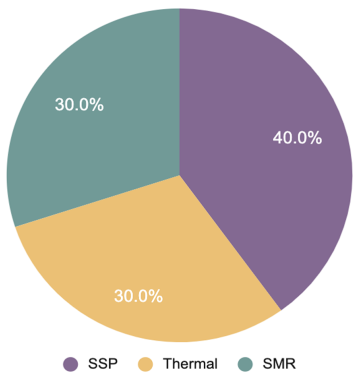

Figure 2.20: Power generation sources percentages

2.2.5 Power Distribution and Management (PMAD)

The power grid (see Fig.2.21) is designed to be resilient, starting by relying on three different energy sources that are connected to the virtual power plant center, where all sources are managed and delivered to the storage site. The center can also operate the bypass switch when needed to deliver the energy directly to the facilities and manage any power generation peaks by switching off part of the generators or slowing down the nuclear reaction to avoid having power surges. The Optical Power Beaming that the team selected for optimal transmission and low costs transmits the energy from the storage site to the Power Management System (PMS). A second delivery system is also in place, relying on an electric cable that cannot deliver all the energy required for all the operations, it can only support vital operations. The PMS splits the energy to the different subsystems on demand. It is also able to deal with any power generation peaks, sending the extra energy to different battery sites in each subsystem.

2.2.6 Energy Report Summary

This study proposes an energy-storage system centered on three options: batteries, flywheels, and fuel cells, each offering different capacity in stability, continuity, and flexibility. The presented design uses flywheels to supply a steady 2,740 kW backbone and smooth transients, solid-state batteries to cover 17.5 h/day and 1,630 kW launch peaks, and regenerative fuel cells

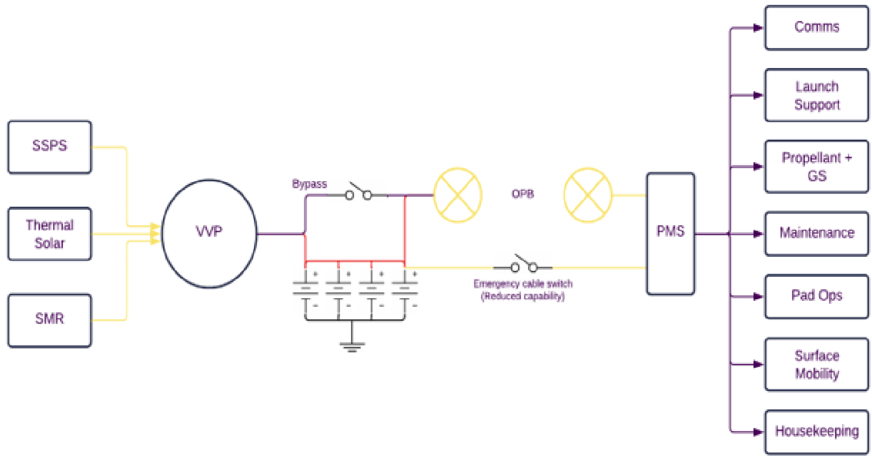

Figure 2.21: Schematic diagram of power management system

as fast-response backup with a future ISRU potential. The team addressed an evaluation of the technology for energy generation comparing five options: conventional solar, SSPS, thermal solar, RTG, and small nuclear. SSPS ranked the highest (due to their specific energy, dust tolerance, and stability), followed by small nuclear reactors and thermal solar, which were the three chosen technologies for the proposed grid. The group also designed the grid to be two-failure resistant by shedding non-essential loads. While Artemis plans for solar and nuclear power, standard panels are currently not viable at the required scale. This proposal is based on the presented energy forecast, where the lunar spaceport drafted considers a permanent staff of 200 people and up to 10 flights/day. The team created the forecast by fixing clear assumptions, such as limiting the scope to the spaceport itself, and breaking the demand into seven major systems. Later the group has scheduled operations over a 24-hour framework to simulate in a more realistic manner the power demand of the spaceport.

One of the largest and most critical uses of power is the habitation modules. Their solutions will be critical to support life at the spaceport. Habitation is a full-time user of power throughout the forecasted day. As such it is critical that its modules are studied and explored in detail and from more than just an energy perspective. The next section explores the spaceport's habitat modules.

2.3 Habitation

2.3.1 Improving the quality of life for spaceport workers

Extended stays in space environments present significant psychological and physiological challenges that can compromise mission success. Research highlights that long-duration missions expose individuals to extreme conditions, including, isolation and confinement, which can lead to emotional instability, cognitive impairments, circadian rhythm disruptions and interpersonal tensions (Arone et al., 2021). Habitability factors, including lighting, noise levels, thermal comfort, odors and air quality, and opportunities for privacy, play a crucial role in shaping both mental health and operational performance. Ensuring wellbeing in such environments demands that it integrates architectural design and neuroscientific insights, fostering a habitat that actively supports psychological resilience and functional efficiency (Ashmore, 1993). Prioritizing worker wellbeing is thus essential, not only for safeguarding individual health but also for ensuring operational efficiency, safety, and mission outcomes in spaceports and other long-term missions. In this context, space design becomes not just a matter of engineering, but of fostering a livable human experience. It understates longstanding humanistic concerns about how the environment shapes identity, meaning, and belonging. In essence, the success of future spaceports may depend as much on how they nurture the soul as how they sustain the body. The proposals within this section are suggestions for mitigating factors which could be implemented during the construction and operation of future spaceports. This work also assumes that basic survival needs are already met but can be optimized and leveraged to turn *surviving* into *thriving*.

2.3.2 Autonomous Digital Twin-Enabled Environmental Control and Life Support Systems (ECLSS) for Lunar Habitation: Integrated CO_2 Regulation and Air Quality Management

Introduction and background

On the ISS, Environmental Control and Life Support Systems (ECLSS) face persistent challenges, including odors and elevated carbon dioxide (CO_2) levels that affect comfort, cognition, and crew health. Optimized ECLSS performance is essential for long-term lunar habitation, as these systems must maintain safe atmospheric composition, pressure, temperature, and air quality while recycling resources and reducing reliance on Earth resupply. This section reviews air-system issues, ISS limitations, and potential solutions for a lunar community of about 230 people.

Research shows that for every one mmHg rise in CO_2, the odds of a headache double: ISS CO_2 levels range between one and nine mmHg. To reduce headache risk to below 1%, the seven-day average must remain under 2.5 mmHg (Law et al., 2014). Odors, often caused by volatile organic compounds (VOCs), may not be toxic but can significantly affect crew morale and cognitive performance over time. Sources include human metabolism, waste handling, material off-gassing, cleaning agents, plastics, and microbial growth. Airborne particulates, including lunar regolith dust, skin flakes, and microbial spores, pose additional hazards. Lunar regolith is chemically reactive and abrasive, risking respiratory health and causing mechanical wear to equipment. The ISS addresses odor and contaminant control with its trace contaminant control subassembly, which uses activated charcoal beds and catalytic oxidizers to remove gaseous pollutants. This system maintains a stable, breathable atmosphere for a small crew by actively filtering air and managing contamination sources, providing a baseline for air-quality control in sealed, microgravity environments.

The Moon's exosphere is extremely tenuous, with an atmospheric pressure of about 3×10^{-15} bar (2.25×10^{-12} mmHg), an extreme vacuum compared with Earth's surface pressure of 1.0132 bar (760 mmHg) at sea level. Lunar surface temperatures range from $+120$°C during the day to -170°C at night. This extreme environment requires fully enclosed, leak-tight habitats with systems capable of regulating internal atmospheric composition, pressure, and temperature to maintain safe, Earth-like conditions.

A permanently habitable lunar spaceport will face amplified air-quality challenges, as odor and particulate sources will be intensified by hundreds of inhabitants and compounded by lunar-specific contaminants such as dust carrying VOCs, industrial byproducts, and emissions from closed-loop agriculture. Odor control must therefore be more robust and scalable than ISS systems, with solutions tailored to lunar conditions. The proposed Lunar Spaceport ECLSS will support an average of 230 people, with a maximum capacity of 300 people. As life-support specialists will not always be present, the system must self-monitor, diagnose issues, and provide clear instructions for non-expert operators.

A digital twin is a dynamic virtual model of the physical system that is updated in real time. It will model atmospheric conditions, track component health, forecast failures, and guide operational adjustments. It can pre-empt unsafe $\mathrm{CO_2}$ levels, optimize scrubbers, coordinate oxygen generation, and regulate pressure, temperature, odor, VOCs, and particulates to maintain Earth-like conditions while keeping contaminants within Spacecraft Maximum Allowable Concentrations (SMACs), NASA's defined safety limits for airborne pollutants in crewed spacecraft. This study focuses on air quality; future work should incorporate water, waste, and emergency systems into a semi-closed-loop ECLSS for long-term habitation. The objective of this research is to address these issues by proposing functional requirements for a digital twin–enabled ECLSS focusing on atmospheric quality: $\mathrm{CO_2}$ regulation for crew physical and psychological health, odor elimination and VOC/particulate control for habitability, and ensuring autonomy and predictive maintenance.

Functional Requirements for Digital-Twin-Enabled ECLSS

We adapted the NASA-STD-3001 ECLSS requirements (for a crew of 6) up for a lunar community of 300, to consider what would need adapting for a larger crew size, lunar environmental constraints, and extended mission durations (NASA Office of the Chief Health & Medical Officer, 2023).

Continuous Atmospheric Monitoring and Trend Analysis

The digital twin should continuously track atmospheric parameters (ppO_2, $ppCO_2$, total pressure, humidity, temperature, and air composition including trace contaminants, VOCs, particulate matter, and odor-related compounds) and provide trend analysis. Partial pressures of oxygen and carbon dioxide (ppO_2, $ppCO_2$) refer to the pressure contributions these gases make in the air relative to the entire mix of gases.

Distributed sensors across habitat zones should meet minimum accuracies

ppO_2 ± 0.1 kPa (normoxic 21.2 kPa), $ppCO_2$ $\pm 3\%$ ($\leq$ 0.333 kPa), total pressure ± 0.5 kPa (22–101.3 kPa), VOCs/trace contaminants at or below SMAC limits, particulate matter $\geq$ $0.3\mu m$, relative humidity $\pm 2\%$ (25–75%), and temperature ± 0.5°C (18–27°C) (Nabity et al., 2022). Trend analysis supports predictive maintenance, as CO_2 and VOC accumulations are gradual; early detection allows intervention before limits are exceeded. Larger lunar habitats increase the risk of localized air-quality hotspots. Current CO_2 sensors typically have $\pm 5\%$

accuracy over 0–5000 ppm (Nabity et al., 2022; Endsley et al., 2020). A $\pm 5\%$ CO_2 sensor is sufficient for rough monitoring but not precise enough for lunar ECLSS control, which will require tighter accuracy ($\sim \pm 1$–2%) to maintain safe crew health margins. Lunar dust guidelines require monitoring respirable particles $< 2.5 \mu m$ at $\leq 1 mg/m^3$, assuming a crew generation rate of 0.006 mg/person-minute (NASA, 2025); sensors rated to $\geq 0.3 \mu m$ coverage ensure safety margins. Accurate, zone-specific CO_2 and O_2 data enable the digital twin to maintain safe breathing conditions and trigger a corrective action, while precise particulate and VOC sensing allows detection and tracking of hazards, such as lunar dust ingress in time for intervention.

Predictive CO_2 Regulation and Control

The digital twin shall predict CO_2 accumulations for each zone based on occupancy, activity level, and ventilation performance, and adjust removal systems to maintain a 7-day average $ppCO_2 \leq 2.5$ mmHg, as higher levels increase headache and cognitive impairment risks (Law et al., 2014). Modeling can use metabolic rate data linked to activity schedules (gym, rest, etc). Predictive load balancing across scrubbers prevents overload and reduces maintenance in a habitat without continuous expert oversight. Bidirectional control interfaces should connect to CO_2 scrubbers for variable load sharing, filtration units for adjustable flow cycles, ventilation systems for fan speed control, and catalytic oxidation units for VOC and trace contaminant removal. By monitoring filter loading, scrubber sorbent saturation, and fan performance, the twin can autonomously respond in real-time, estimate remaining useful life (RUL), and schedule maintenance before a failure.

VOC and Odor Source Detection and Removal

The digital twin shall detect VOCs and odor-related compounds at or below SMAC limits, identify probable sources (e.g., human activity, material off-gassing, contamination events), and adjust filtration or catalytic oxidation rates accordingly. Automated detection and mitigation ensure consistent air quality and reduce reliance on manual intervention.

Particulate and Lunar Dust Management

The digital twin shall monitor particulate matter, including lunar dust, and control air filtration to keep particles $< 10 \mu m$ below a time-weighted average of $0.3 mg/m^3$. It will track a 180-day period, daily, and 7-day averages with warnings and critical thresholds. Given lunar dust's abrasive, chemically reactive, and respiratory hazards amplified in larger habitats, the system must autonomously adjust filtration to protect the crew and equipment. For missions beyond six months, it shall estimate filter differential pressure, mass loading, RUL, and predict dust ingress from landings and EVA schedules.

Zonal Airflow and Ventilation Control

The digital twin will monitor ventilation effectiveness, detect CO_2/heat/VOC pockets, and adjust fans or dampers to achieve uniform air composition across spaceport zones. The system will ensure even gas distribution, i.e., no stagnant zones, as poor mixing can cause dangerous localized gas concentrations. Autonomous zoning monitoring ensures safe air quality.

Alerting and Human Machine Interface (HMI) for Non-Expert Users:

The system must provide clear local and remote alerts when atmospheric parameters exceed safe limits, with step-by-step guidance for corrective actions. Habitats or spaceports may be staffed with non-specialists; therefore, HMI must be clear and accessible to ensure prompt, effective responses to any air quality deviations.

System Block Diagram for Digital-Twin-Enabled ECLSS

The innovation of a scaled-up Digital-Twin-Enabled Lunar ECLSS with predictive autonomy is demonstrated by a basic system's block diagram (See Fig. 2.22); with a CO_2 control, and an odor/VOC elimination as the two major priorities. Future work should explore systems integration with waste management, water management, and emergency systems. Further expansion should include simulation modelling, hardware prototyping, and long-duration analogue habitat testing.

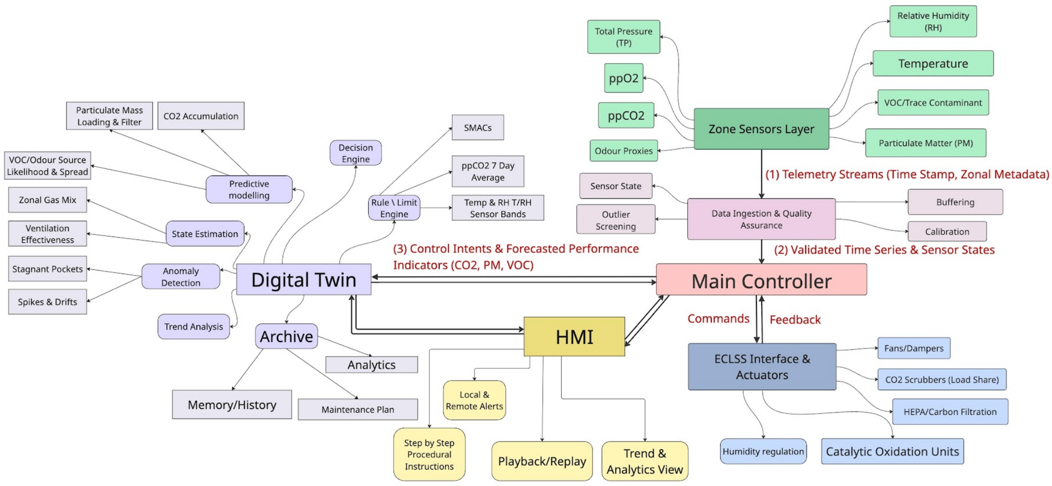

Figure 2.22: A Systems Block Diagram for a Digital-Twin-Enabled ECLSS. This architecture integrates a Zone Sensors Layer (measuring ppO_2, $ppCO_2$, pressure, humidity, temperature, VOCs, particulates), a Main Controller (data validation, quality assurance, command execution), and a Digital Twin (predictive modelling, anomaly detection, trend analysis, and rule/limit decision engines). These feed into ECLSS actuators (scrubbers, filters, fans, catalytic oxidizers) with oversight via the HMI for alerts, procedures, and analytics.

2.3.3 Importance of Psychological Wellbeing in Spaceport Environments

On a lunar spaceport, the workers are an essential element. Without their support, the entire system would grind to a halt. Therefore, it is vital to consider their physical and psychological needs. This section of research will address this aspect of the space port environment and outline any potential issues, challenges associated with the lunar environment, and mitigation strategies that could be implemented to lessen any negative effects.

Expected Psychological Issues

It is difficult to predict issues that future workers may experience in the long-term lunar environment. Assumptions for this study are based on currently available evidence. It comes from scenarios and situations that mirror potential stresses and demands of living and working permanently at a lunar spaceport in future.

To help estimate which psychological issues may be most prevalent, we can analyze the general population. The demands on the spaceport workers are similar to those in modern society. There are similarities with missions on the ISS, but the nature of the residency is different. Any worker living at a lunar spaceport would not be on a mission, instead, they would be living their lives. Consequently, the estimates in this study are supplemented by data about the general population.

A study completed by the World Health Organization found that 15% of working-age adults had a mental health disorder in 2019 (WHO, 2024). The most common mental health disorders were anxiety (301 million) and depression (280 million). In 2021, 2,800 coal miners in the US completed a survey in which 37% reported depression symptoms and 38% reported a significant level of anxiety (Harris, D., 2021). This is significantly higher than in the general population, showing the negative effect of working in high stress environments. Similar findings can be seen in space missions. The conditions of spaceport workers do not directly match these, but the studies offer insights into the effects of stress and isolation. NASA found that 22.8% of male and 85.2 of female astronauts have experienced anxiety symptoms, and 34.8% of males and 43.2% of females have experienced symptoms of depression (Yin, Y., et. al., 2023). These levels show that even highly trained individuals still experience symptoms of mental health at elevated rates. Based on these findings, this project assumes that future spaceport workers would experience similar issues.

Anticipated Psychological Challenges

The anticipation of the challenges faced by future workers is also important. By anticipating the new and unique challenges of long-term lunar missions, potential issues could be better mitigated. It is estimated that high levels of stress and isolation could be the highest contributing factors to psychological issues. High levels of psychological issues would drastically reduce the sustainability and longevity of the lunar spaceport as a society independent of Earth.

The spaceport staff would be working in close proximity to frequent rocket launches, and each one has the potential to cause catastrophic damage in case of a failure. They would also be entirely dependent on their life support systems. These conditions are incubators of high levels of stress. There is also a direct correlation between high stress levels and the development of anxiety disorders (Io Ieong Chan, & Anise M.S. Wu., 2024).

Isolation could also cause and aggravate psychological issues. The spaceport is a dangerous environment and completely isolated from the Earth. It is also further isolated from the permanent lunar community, leaving the workers within the spaceport even further isolated from an already isolated community. Studies have found that social isolation has a direct link to developing depression or depressive symptoms (황민지, & 기명, 2023).

The Impact of Psychological Issues on Worker Overall Wellbeing

Physiological implications

Beyond social consequences, stress also disrupts physiological systems, affecting digestion, the nervous system, immune functions, and regulation of energy storage and expenditure (Pagel et al., 2016a). It is crucial to take initiatives to ensure the worker's physical health by mitigating stress and depression, as it plays a vital role in immune dysregulation (Glaser & Kiecolt-Glaser, 2005). While medical facilities and resources would be available in the long term, an illness or injury in space is inherently more dangerous due to the limitations of caregiving and recovery in the extreme environment. Part of making the spaceport sustainable is to limit the need for a constant resupply of resources from Earth, including medical equipment and medicines. Maintaining a healthy general population is vital to reduce the need for external medical support. Energy balance is also crucial as food supplies may be limited, and conserving energy becomes vital for survival. Chronic stress further alters brain structure and the nervous system by altering the size of brain nuclei and neurotransmitter systems (Cardoner et al., 2024). These changes affect cognitive and emotional functions and alter behavioral responses. This is especially concerning in space operations, where crew members must remain vigilant, logical, and thorough in their actions, as the consequences of poor decisions can be catastrophic.

Psychological and Social Implications

In social species, like humans, isolation is a potent stressor that often elevates cortisol levels (Cacioppo et al., 2009). Any source of stress can threaten survival, if it is not met with sufficient adaptive responses (Selye, 1950). For a sustainable lunar presence, mitigating stress and depressive symptoms is essential, as it profoundly influences workforce well-being. It is crucial to optimize the spaceport environment to reduce further stress on the workers as workers' poor mental healthcare can be just as incapacitating as their physical health. Stress and depression can impair mood and behavior. Their impact then could lead to interpersonal conflicts in the workplace (Pagel et al., 2016a). When considering an active future lunar spaceport, interpersonal relationships within the crew become both the foundation and the vulnerability of operations. The complexity of managing interpersonal relationships in an intensive or isolated work environment can create a socially fragile atmosphere, where even minor conflicts can lead to disruptions in work performance. These challenges are amplified on the Moon, where the high-risk environment, limited resources, and the lack of immediate external support mean that breakdowns in cohesion can jeopardize not only workplace harmony, but also mission success and crew safety. Beyond operational efficiency, attending to the emotional well-being of lunar workers touches on deeper human concerns: how we construct meaning, maintain identity, and foster community in harsh environments. The effort to build a sustainable space culture demands a capacity for empathy, resilience, and collective care in the face of isolation.

2.3.4 Key Design Interventions and structural optimization

The design of spaceports and long-term missions requires integration of functionality, habitability, and structural strength. Structural optimization is not limited to maximizing the use of available volume; it also seeks to ensure safety, psychological comfort, and operational efficiency under extreme conditions. Using NASA's planned Surface Habitat as a current example, its internal configuration is based on a hybrid approach that combines a metal base and an inflatable module, optimizing mass and volume to fulfill the essential functions of life support, radiation protection, and facilities for scientific and basic recreational activities. While this is a very efficient design in the short term, it does not offer complex scalability solutions. Future spaceport structural planning must work with more flexible assumptions, considering everything from lunar dust management to logistical storage and the ergonomic layout of workstations. In parallel, studies of psychological factors have shown that elements such as exterior views, privacy areas, and socializing zones directly influence crew well-being and performance. All of these are factors that will be accounted for in the planning and design of the spaceport habitation and work areas.

Integration of Architecture, Neuroscience

The integration of these disciplines enables the design areas to respond to both physiological requirements and motivational sensory stimuli to improve cognitive performance. Previous studies on confined habitats reveal that the interaction between environmental and social factors is crucial for group cohesion, stress reduction and conflict prevention. Theories such as the biophilia hypothesis emphasize the need to connect with natural stimuli. The Prospect-Refuge Theory states that environments should simultaneously offer visibility and protection. Finally, the Stress Reduction Theory demonstrates that certain spatial and lighting patterns reduce anxiety and improve mood.

Bioengineering provides parameters for adapting space to physical capabilities in a low-gravity environment. NASA's Surface Habitat study proposes standard heights of 2.4 m for most functions, reduced to one meter in areas such as rest or temporary storage of EVA gear, and increased to 2.6 m in areas such as the airlock, where additional space is required for donning/doffing suits. These dimensions are derived from anthropometric data and seek to reduce physical strain and prevent injuries, optimizing mobility in partial gravity.

The integration of bioengineering principles with architectural design and neuroscience is evident in several practical interventions. Dynamic lighting systems that simulate natural circadian rhythms help to regulate sleep patterns and alertness. Ergonomically designed exercise zones address musculoskeletal health, while they also incorporate motivational elements to encourage regular activity. Personal control zones empower astronauts to adjust environmental factors such as lighting, temperature, and sound, fostering a sense of autonomy and comfort. Finally, maintaining visual connections with the external environment, whether through real windows or simulated views, helps to reduce stress and enhances creativity, contributing positively to a psychological wellbeing.

Biophilic Design

Biophilic design principles are powerful aspects of effective human-centric design and must also be considered in the context of human life in space. Biophilic design refers to the incorporation of natural elements and spaces, plant life, and decor to engage all senses and promote a better connection to nature in an area, where it is lacking. On Earth, some examples of biophilic design are city parks, decorative fountains, nature corridors, and the enhancement of indoor spaces through flowerbeds, potted plants, green walls, and natural lighting. The benefits of biophilic design on psychological well-being are robust. Prior research has demonstrated that biophilic environments tangibly decrease anxiety and stress, reduce aggression, increase motivation, and promote concentration and creativity (Dalay, L., 2020; Yin, J., et. al., 2020; Yin, J., 2019). Perhaps even more importantly, physiological effects have also been observed such as decreased heart rate and blood pressure, potentially contributing toward mitigating space-induced health challenges (Dalay, L., 2020; Xiaoxue, S., & X. Huang, 2024). This is further backed up by evidence of enhanced medical recovery for patients in biophilic clinical environments, as opposed to standard clinics where surroundings are usually perceived as uncomfortable or disruptive (Miola, L., et. al., 2025; Babangida Dawus Umar, 2025). Biophilic design is another tool in the toolbox for optimizing human happiness and performance.

The spaceport is 'the face of the Moon' when it comes to lunar culture and aesthetic design. It is the first thing new arrivals will experience, except for the initial glances at the lunar environment. As such, the first impression should invoke as many natural sensory elements from the Earth as possible. This will help to reset expectations and regulate mood after the immediate stresses of rocket travel. The spaceport will prioritize a biophilic immersion in places, where it is sensible to maintain a consistent positive effect on inhabitants. These elements include, for example, copious flowerbeds, artificial skylights, clean-smelling air from filtration (*See Section 3.2.2*), and daytime bird sounds. The spaceport will also provide more complex dedicated green spaces for those who desire deeper experience and reconnection with the Earth. One such green space should be a mini arboretum with a few small trees. Finally, some more experimental ideas might include a scent reaction chamber (*See Section 4.3.4*), synthesizing nature smells using volatile aromatics and other air filtration byproducts, imitation rainstorms, and faux seasonality induced by color temperature gradients in natural lighting fixtures. Inhabitants will ideally feel more relaxed and comfortable through this concerted suite of sensory stimuli options.

Human-Centered Interior Design and Sensory Strategies

Designing interiors for life on the Moon requires a deep understanding of human needs, behaviors, and well-being in environments unlike any on the Earth. The body plays an active role in perception. It is not just a passive receiver of sensory stimuli, but also an active participant that interacts with the environment and develops self-awareness. Through this process, sensory perception mediates the connections between body, mind, cognition, and environment, while social interaction and self-perception play a vital role in integrating multisensory information. Living on the Moon poses a significant challenge since human spatial perception can be distorted and the body will not respond the way it does on Earth. The influence of one sixth Earth gravity affects the way human bodies interact with the surrounding spaces beginning with movement. Higher ceilings and different vertical transitions are the main elements considered. Supporting human performance and factoring in ways to enhance diverse human abilities are essential to delivering an architectural solution that addresses human integration at both the system-wide and individual levels.

Spatial Layouts for Comfort and Social Balance

Different interior distributions and layouts are used traditionally on the Earth depending on the different cultures. Globalization has played a major role in the transformation of these socio-cultural structures. Spatial design has shifted its focus from mere functionality to a comprehensive enhancement of sensory experiences. A space is seen as a multifaceted perceptual system, more than just a physical setting for objects and activities, it also serves as an environment that evokes emotional and cognitive responses.

Off Earth, spaces need to fit different purposes at a time since resources are limited. This converges in flexible and personalized settings. For example, the Office of Google Engineering Hub in Zurich, Switzerland, which is one of the most famous examples of architecture considering people's wellbeing, has individualized workspaces, flexible seating arrangements, and a variety of collaborative zones. The workers there can choose between multiple workspaces based on different topics depending on their preferences which can be jungle, city, arctic, etc. This freedom in selection creates a sense of control and autonomy that boosts motivation and job satisfaction.

Textures and Materials: Balancing Sterility with Warm, Tactile Surfaces

In lunar habitats, material selection must carefully balance the necessary functional sterility to ensure hygiene, microbial control, and durability in a closed life support system with psychological comfort, which is crucial for long-duration missions. Structural materials like metals, polymers and laminates are favored for their cleanability, resistance to lunar dust and compliance with fire, off-gassing and environmental safety standards. Without sensory variation these sterile environments can lead to "sensory underload," negatively impacting mood, cognitive performance, and resilience to stress. Human-centered design research emphasizes that sterile surfaces may accelerate environmental fatigue and contribute to diminished crew well-being over time. To mitigate this, the integration of warm, tactile materials in strategic areas is essential, without compromising safety or cleanliness. Examples include textiles, such as flame-retardant synthetic fabrics, soft to the touch; 3D-printed panels with organic textures or earth-tone finishes; and metamaterials that emulate wood or stone. These not only provide visual and haptic warmth but are also compatible with space-grade requirements. The FLEXHab analog habitat developed by SAGA for ESA's Artemis training missions illustrates this balance well. Its interior incorporates high-performance textiles for a home-like atmosphere, circadian lighting, and even 3D-printed elements using recycled wood, demonstrating how tactile and visual warmth can coexist with operational functionality.

Potential mitigation ideas / different use spatial

Having a well-structured and flexible space distribution on the Moon is key to ensure countermeasures are effective. Differentiated areas such as a canteen or cafe combined with a lounge, botanic garden simulating the outdoors, gym, privacy capsules with sleeping pods, library, workstation, 3D generation room, medical center and more are crucial for a proper cognitive response from the workers.

Other stimuli such as smell, circadian artificial lighting, screens simulating windows, noise canceling and intended sounds generation (such as nature sounds), different texture for touch stimulation, and different temperature areas are crucial elements to implement in the integrative design as part of the "bringing Earth to Space" strategy. Additionally, surface-treated regolith and other materials like mycelium-based composites can contribute to multifunctional furniture solutions that provide comfort while addressing engineering constraints during long-duration missions.

Scent Recreation Capsule

Many mitigation factors have been proposed to increase psychological wellbeing. All of these have merits and address specific challenges, however, most of the techniques are passive methods. The recipient does not actively interact with the system (e.g., specialized lighting). Passive techniques are important as workers have other tasks to complete, but some active measures must also be used. These active measures can be specialized and recipient specific, which is important to consider due to the potential different cultural backgrounds of workers. With such diversity, there are no universal solutions that work for everyone. For example, different foods may evoke different emotions to different people. An active mitigation strategy would be well suited to bridge these gaps and be inclusive for everyone.

The scent recreation capsule (SRC) would be a small room within the spaceport, which could be used by workers to recreate specific smells. These smells could range from a particular favorite flower to a specific dish from their home or childhood. Specific smells could be analyzed on the Earth and the recipe would then be transmitted to the Moon to be recreated in the capsule. This technology would be an important addition to the spaceport, as the link between the smell and memories is powerful. This is because olfactory signals travel directly through the limbic system, engaging the amygdala and hippocampus – the regions related to emotion and memory – making smell much more evocative than the other senses such as touch or sight. The olfactory system was also vital for our ancestors who relied on smells to create maps of their surroundings. Our sense of smell and the connection to memories are engrained within our physiology. This potent link could be used to a great effect in mitigating the effects of isolation. A similar technology has already been explored. It recreates scents by using an AI to analyze the molecular composition and allowing it to be recreated. The technology is currently limited. However, it shows potential for a use in the SRC. The novelty of this technology could also draw interest from potential visitors to the Moon, helping to facilitate lunar tourism.

Lighting, Privacy, and Social Balance

Lighting becomes a critical environmental factor, directly influencing circadian alignment, sleep quality, and cognitive performance in environments where natural light cycles are absent. In such settings, the absence of windows is compensated by high-resolution light-emitting diode (LED) screens that simulate dynamic external views, helping to maintain spatial orientation and psychological comfort. Privacy is ensured through private, enclosed crew pods that serve as multifunctional refuges where astronauts can retreat, decompress, and maintain emotional well-being. These private pods may incorporate scent diffusion using natural oils to evoke familiar and calming environments, such as the scent of rainy grass, and employ projectors to create immersive visual experiences that help mitigate sensory deprivation. Social balance is promoted through communal hubs designed to encourage interaction, strengthen team cohesion, and reduce the effects of social isolation inherent in spaceflight. Functional spatial organization further supports well-being by separating noisy and technical areas, such as engine rooms and computer rooms, from private crew quarters to reduce stress and noise disturbances. Interior materials avoid the use of untreated wood in favor of sustainable, reusable options like textured wall panels inspired by Sasakawa International Center for Space Architecture and mycelium-based furniture and cladding grown in situ. These materials can be thermally treated for reuse, customized in color and texture, serve as a source of fertile soil on the Moon, and even provide edible resources in emergencies.

Adjustable LED Systems Mimicking Natural Light Cycles

In environments devoid of natural light, such as spacecraft or analog habitats, adjustable LED systems that mimic natural daylight cycles are essential for maintaining circadian alignment, improving sleep quality, and supporting cognitive performance. These systems adjust both light intensity and spectral composition, with higher, blue-enriched light during active periods and warmer, dimmer light near bedtime. A 45-day space analog study at NASA's Human Exploration Research Analog demonstrated that dynamic lighting schedules significantly advanced circadian phase compared to static lighting, reduced the incidence of sleep episodes at misaligned circadian times, and improved cognitive performance on reasoning tasks.

Private Pods for Solitude

In a lunar spaceport, private pods for solitude should be conceived as individual crew quarters with high acoustic attenuation and circadian lighting control, located within the Net Habitable Volume (NHV) of the habitat. Recent NASA studies for lunar habitat layouts recommend assigning each crew member a private quarter and, as an acoustic control measure, preventing bunk beds from sharing a common wall. It also notes that the pod volume in partial gravity should clearly separate sleeping and dressing, and ideally incorporate a small desk for private work (although space may be restrictive). These guidelines appear in the internal design study for the Lunar Surface Habitat, which designates two private rooms with sleeping, stretching, and access to a personal desk, and specifies the criterion of not coplanarizing bunks to improve sound isolation. Additionally, NASA's NHV work establishes how to assign and verify the functional habitable volume by activity, which helps justify the minimum square footage for each pod without penalizing the habitat's other functions.

2.4 Economics, Commercialization and Policy

The essential nature of habitation and human-centric design elements extend to every aspect of a sustainable lunar economy and tourism on the Moon. This section addresses economics, law, and policy aspects of a sustainable lunar spaceport and wider society.

2.4.1 Lunar Tourism and Commercial Aspects

Lunar Tourism Offerings in a Mature Lunar Spaceport

In a mature lunar spaceport, a multitude of revenue streams are possible, including logistics, transport, retail, and manufacturing. The focus here, however, is on lunar tourism. At roughly 200 semi-permanent spaceport residents, tourism is organized as an "offerings ladder" with service and product tiers. The section that follows summarizes these tiers, their target markets, and provides a revenue model snapshot. This approach recognizes tourism not as a stand-alone luxury, but as an integrated driver to protect the lunar spaceport's delicate balance and, in doing so, strengthen its long-term sustainability, as well as promoting its financial viability and expansion through investment structures and revenue generation.

Summary of Services Offerings

The service offerings are described in the following paragraphs with additional information in Table 2.3.

S1_Access: S1 includes bookable live virtual reality (VR) "moonwalks" and supervised tele-rover sessions streamed from the spaceport's communications node and guided by mission hosts. This is an ideal revenue model that supports long-term sustainability by adding reach and sponsorship without drawing down habitat or transport capacities.
S2_Transit: S2 includes an orbital sightseeing flight from the lunar spaceport with planned 'Earthrise' and landmark passes. It includes optional live broadcast and photo packages, with limited seats to maintain capacity and operations.
S3_Excursion: S3 presents supervised surface tours that depart from the lunar spaceport, along pre-approved routes, with on-site medical coverage. The excursions will consist of small groups, planned photo and science stops, and defined turnaround windows to keep impact low and safety high.
S4_Residency: S4 gives each participant something they cannot get on Earth. New methods of rehabilitation can be adopted for the low gravity environment. Scientists get dedicated access to instruments, planned surface sessions, and full mission support. This way, a month on the Moon turns into publishable results and reusable datasets. Creators receive exclusive access and scheduled live windows with a co-produced content plan and built-in licensing.
S5_Bespoke: S5 is an ultra-premium offering that includes a private stay in a wellness-focused lunar habitat with bespoke design elements, a panoramic dome window, a garden lounge, personal control zones that tune light, humidity, and air quality, and allows exclusive access to a Scent Recreation Capsule. Guests use EVA suits with couture outfitting, and a two-seat luxury rover for guided outings in approved zones. The experience also offers priority seating on maglev trains for long distance lunar excursions. Chef-led menus pair greenhouse produce with selected provisions from Earth. All activities follow environmental and heritage protection compliance requirements. The offering includes pre-flight training and medical screening, end-to-end logistics, and a reserved launch window.

Table 2.3: Tiered Offerings—Services

	Primary Target Market	Key Enablers	Example Offerings
S1_Access Remote or Virtual Experiences	Global mass market, education sector, brand partners	Communications network, robust rover operations	Subscription-based livestreams, interactive moonwalks, VR events
S2_Transit Lunar Orbitals and Flybys	Upper mass market, premium travel market	Reusable cislunar transport, orbital hospitality modules	Short-duration lunar "cruises"
S3_ Excursion Surface Excursion Day Trips	High Net Worth Individuals (HNI), corporate incentive travel	Short-hop transportation, precision landing, safety protocols	Guided surface tours, heritage site visits
S4_Residency Extended Specialist Residency	Researchers, artists, sponsored athletes	Advanced long duration habitats, ISRU-supported life support systems, edicated work modules	"Scientist in Residence" programs, artistic retreats, low-gravity athletic training
S5_Bespoke Bespoke Luxury and Legacy Experiences	Ultra-High Net Worth Individuals (UHNI), elite brand collaborations	Customized logistics, design-forward habitats, dining offerings, edicated mission crew, exclusive access rights	Bespoke design habitats, lunar attraction tours, heritage site visits, co-branded lunar product creation

Summary of Product Offerings

The product tiers convert spaceport experiences into scalable, low-mass revenue that flows through Earth markets. Early services (S1–S2) generate moments and media that feed P1 merchandise and P5 IP/data; surface offerings (S3–S4) unlock P2 Moon-made artifacts. S5 provides a premium halo that lifts demand across the portfolio. Co-branded luxury fits this model. Recent Axiom collaborations with Prada on the AxEMU spacesuit and Oakley on the AxEMU visor demonstrates a case for brand appetite and unconventional space partnerships. Additional information on these offerings is provided in Table 2.4.

Table 2.4: Tiered Offerings—Products

	Primary Target Market	Key Enablers	Example Offerings
P1_Lunar Merchandise Lunar-Themed Merchandise	Global consumer market, Earth and lunar spaceport commerce	Licensed IP, e-commerce platforms, lunar branding standards	Co-branded apparel, collectibles, luxury watches with lunar spaceport motif
P2_Moon-Made Artifacts Moon-Made or Moon-Touched Artifacts	Affluent collectors, corporate gifting	Limited ISRU, regolith-safe handling, authenticity tracking	Certified regolith inlaid jewelry, small lunar rock samples for display
P3_Luxury Co-branded Luxury Goods	UHNWI, global luxury brands	Partnership contracts, high-value logistics	Limited edition "Moon Made" timepieces and jewelry
P4_Data Packages Scientific and Technical Data Packages	Research institutions, commercial space companies	Proprietary sensors, data processing, licensing frameworks	Lunar terrain maps, ISRU process data, heritage site preservation data sets

Revenue Snapshot

The snapshot in Tables 2.5 and 2.6 illustrates a revenue model using S5_Bespoke as an example. The parameters limit the booking to two participants per stay, with a minimum length of stay at seven days and a maximum of 14 days. The projected number of bookings are estimated to be at eight to ten annually. The proposed price point of $350M benchmarks against known private human spaceflight signals, including $55M-$60M for 14 days on the ISS and a $150M contractual price for circumlunar flights. It also prices in the materially higher costs of a lunar surface stay and aligns with the capital and operating realities of a sustainable lunar spaceport.

Table 2.5: Pricing and Annual Gross Revenue

	Today's USD (per participant)	Future USD (per participant)	Annual Gross (Today) (8-10 participants)	Annual Gross (Future) (8-10 participants)
Price	$350,000,000	$750,000,000	$2.8B-$3.5B	$6B-$7.5B

Table 2.6: Estimated and Proposed Allocation per Booking

	Share	Amount at $350M	Amount at $750M
Costs: Infrastructure and operations	35%	$122,500,000	$262,500,000
Costs: Insurance, legal and compliance	10%	$35,000,000	$75,000,000
Founds allocated for overall spaceport sustainability	5%	$17,500,000	$37,500,000
Reinvestment and returns	50%	$175,000,000	$375,000,000

Summary: Lunar Tourism

Long-term offerings are funded through staged revenue shares, milestone payments, and outcome-based contracts that activate as each S and P tier comes online. Public-private partnerships provide shared infrastructure and standard interfaces, allowing private capital to focus on customer-facing services with clear service-level targets. Partnerships with luxury, media, education, and technology turn authentic spaceport activity into co-brands, product passports, licensed content, and data APIs, expanding demand while keeping the lunar footprint small. Earth-side markets, such as insurance, legal, and logistics, both enable and benefit from this model. Cash flows follow simple rules: a fixed portion goes to lunar spaceport operations, sustainability, and capacity growth, so each tier of offerings helps finance the next. The result is a self-sustaining revenue platform that ties the lunar economy into Earth-lunar value chains and, over time, advances both.

2.4.2 Lunar Society: Turning science-fiction into science-reality using blockchain technology

Future of Space law: Introduction

For our lunar economy, we propose a system that uses the blockchain, which provides continuous monitoring and a permanent record of transactions that is available to everyone. Tokenization, the process of digitally representing rights, resources, or assets on a blockchain, could become the cornerstone of lunar governance and the economy. Every right of use, ownership, access, or intellectual property is embodied in a unique digital token that is exchangeable, divisible, and traceable.

There are some concerns when applying this system, since it creates an environment where everything is tracked, participation depends on holding the right tokens, and exclusion could happen with a single click. This raises the question of whether we are prepared to accept the legal, ethical, and social implications of such a framework. Yet, these challenges do not necessarily disqualify the system; rather, they highlight the importance of designing safeguards, exploring legal checks and balances, and considering alternative governance models. In the following sections, we will examine both the risks and the potential mitigations that could make blockchain governance a viable foundation for a lunar society.

Blockchain Governance: Legal Frameworks for Tomorrow's Lunar Society

Within the blockchain system, we introduce governance tokens which are the keys to political, economic, and social participation in lunar life. This aligns with ongoing international legal discussions on the exploitation and management of space activities. The 1967 Outer Space Treaty highlights a central principle: no state may claim sovereignty over a celestial body. However, it does not discuss the internal governance of a lunar spaceport. Blockchain and tokenization could provide an unprecedented operational framework that ensures transparency and fairness in decision-making, while remaining compliant with international law. For example, a "right-to-petition" token might be required to file a case before a lunar tribunal. If combined with smart contracts, such a process could automate the enforcement of judgments and objectively prioritize cases. This would drastically reduce bureaucratic delays and minimize opportunities for corruption.

Intellectual property could also be centralized on a blockchain-based registry to protect patents, trademarks, and creative works produced on the Moon. Such a framework could limit abuse of dominant positions and foster fair competition between companies and states, which aligns with the principle of "fair competition" already embedded in certain terrestrial trade agreements.

The solution also presents important legal and ethical questions. A governance token system could shape the very foundation of lunar citizenship and participation. Deciding who has the right to hold and transfer these tokens, whether permanent residents, shareholders, founding states, or other actors, will be crucial. If designed inclusively, such a system could foster genuine democratic engagement and ensure that decision-making reflects the voices of all who contribute to lunar society. But if access is restricted or concentrated, it risks creating a digital divide where only the technical or financial elite can meaningfully participate. The challenge is therefore not whether blockchain governance is viable, but how it can be structured to balance openness, fairness, and legal legitimacy. The protection of personal data is another pressing concern. Permanently recording every transaction and vote on a public ledger makes it difficult to respect privacy while being transparent. Without a robust legal framework in place, every action is traceable, analyzed, and can potentially be monetized. The analogy with the British TV show *Black Mirror* (Brooker, 2011) is obvious: technologies built for efficiency and justice can become instruments of control.

Cultural depictions of future societies serve as a warning here. In the movie *Elysium* (Blomkamp, 2013), orbital habitats become exclusive enclaves for the privileged, leaving the majority to struggle in deteriorating conditions below. In the TV show *Westworld* (Nolan Joy, 2016), a highly automated environment collapses under the weight of its own algorithms and corporate manipulations. Even in video games like *Deus Ex: Human Revolution* (Eidos-Montréal, 2011), we see how technological augmentation and digital identity systems create deep divides between those with access to power and those without. The lunar habitat could face these issues if governance tokens are restricted to the wealthy or politically connected. Applied to lunar spaceports or habitats, blockchain-based access systems could streamline life but also lock individuals out of essential services in the event of technical glitches, legal disputes, or malicious interference. Jurisdictional conflicts between Earth-based authorities and lunar governance bodies could further complicate dispute resolution, raising urgent questions about emergency protocols and individual rights in space.

The sustainability of such a governance model will depend on its ability to safeguard fundamental freedoms while maintaining legal stability. Even if blockchain ensures incorruptibility and transparency, it must also incorporate the digital equivalent of constitutional safeguards such as habeas corpus, privacy rights, and anti-discrimination laws. In the end, blockchain-based lunar governance may be the solution for a spacefaring society. The challenge will be to design a system that is incorruptible, adaptable, and transparent enough to inspire trust, but flexible enough to accommodate unforeseen crises. Striking this balance will require embedding strong constitutional protections alongside the technological infrastructure, ensuring that efficiency never comes at the cost of human dignity or equality.

The same technology that could safeguard democratic governance on the Moon could also underpin the fair and sustainable management of its most precious assets. The next section will explore who governs the Moon and how the resources of it can be shared and protected.

Mining the Moon: Utility Tokens as the Backbone of a Lunar Resource Economy

The Moon is a giant reservoir of potential resources that would be capable of sustaining human life and fueling a space-based economy. The issue lies in how those resources are allocated, exchanged, and managed in a system quite different from Earth's economic and legal systems. This is where utility tokens, as part of the blockchain, present a possible model for a successful, open, and equitable lunar resource economy.

Rather than relying on Earth-based bureaucracy to request and authorize resource use, residents will possess a digital wallet with various utility tokens. A water token might provide them with a liter of purified water, an energy token for a kilowatt-hour of community-stored solar power, or a transport token for an hour of rover usage for exploration or travel. These tokens are easily spent using the automated systems: tap your wrist unit at the airlock, and your rover reservation is confirmed; present a water token at the recycling center, and your ration is dispensed. This economy functions with minimal administrative interference, founded on blockchain's ability to document and verify each transaction safely.

The concept of utility tokens has roots in science fiction, albeit not necessarily under that designation. In the series of novels The Expanse (James S.A. Corey, 2011–2021), "Belters" trade water and air on credit-type systems directly tied to life-support consumables, where every liter or breath is billed. In Kim Stanley Robinson's Mars trilogy (1992–1996), settlers track and ration resources through sophisticated allocation systems. The novels point to a truism: in an enclosed system, all resources are valuable, and their allocation should be transparent, accountable, and corruption- and hoarding-proof. Utility tokens are digital tokens input to a blockchain that grant the token holder a right to access goods and services. Unlike governance tokens that are used for voting on system protocols, utility tokens are access rights. For example, withdrawing a water token would involve withdrawing the equivalent amount from the user's account and the colony's stockpiles and updating the ledger to reflect it for all to see. Such transparency would assist in preserving trust in a society where success depends on equal access.

The advantages of such a system are huge. First, blockchain tokens leave an unchangeable record of transactions, making dispute resolution over allocation easier and fraud more difficult. Second, tokens can be exchanged peer-to-peer without a central intermediary. This means individuals can exchange or sell unused allocations. For example, an engineer can trade unused rover hours for more water on a hobby project. Third, programmability of utility tokens allows for dynamic pricing or rationing during periods of shortage to balance demand with an available supply. Decentralized and rule-based, this system can reduce administrative expenses while stimulating an adaptive, resilient economy.

There are still challenges. Technological reliability is required: blockchain systems require robust computing infrastructure, storage, and energy, which are scarce on the Moon. Any breakdown in a system would bring the resource economy to a standstill. There is also the risk of imbalance if token distribution is not properly regulated, which parallels the power imbalance of Earth-based wealth distribution. Furthermore, the blockchain cannot resolve disputes over ownership or the legality of extracting specific resources, which are prevalent issues still not settled under the Outer Space Treaty and other international frameworks. Another challenge is in the user interface. As much as blockchain technology may be familiar to the technologically savvy, others may be unacquainted and unfamiliar with token transactions and digital wallets. Training, interfaces that are intuitive, and fail-safe mechanisms would be important in guaranteeing access on an equal basis. Finally, governance and consent issues must be sorted out with respect to who determines the initial allocation of tokens, the relative values between different resource tokens, and the emergency measures when there are shortages. Without clear rules agreed by the Moon community, the system risks replicating the bureaucratic inefficiencies, which it attempts to overcome.

In conclusion, utility tokens could be the backbone of a lunar resource economy with a secure, open, and flexible way of managing the survival necessities. The tokens will be linked to physical, measurable units of assets with a blockchain technology. Although the concept is borrowed from science fiction, it could eventually revolutionize the process of resource allocation by creating an effective, automated system. If well planned, a lunar utility token economy could help to build the community around spaceport into a fertile, sustainable society. With a tokenized economy such as this, the next step is automation, which depends on smart contracts to manage the terms of exchange and large-scale coordination of lunar activities with minimal human involvement.

Smart Contracts as a Tool for Automating the Long-Term Management of Lunar Operations

Smart contracts are the digital translation of a contractual commitment and operate within a blockchain network. They are self-executing contracts whose terms are written directly into code and use "if...then" logic. When pre-defined or programmed conditions are met, the contract's actions are automatically executed by all the nodes of the blockchain.

On Earth, smart contracts are already used, particularly in the insurance sector. For example, parametric insurance uses blockchain and smart contracts to pay compensation when a specific event occurs. An oracle, which is a programmed monitor acting as a bridge between the real world and the blockchain, detects an event and then transmits the information to a smart contract, triggering a payment. The insurance company Lemonade (Alsdorf, Gina, et al., 2024), implemented this system and was able to compensate farmers through a smart contract linked to an oracle measuring rainfall data, without requiring a claims adjuster or a claims file. This terrestrial example illustrates how smart contracts can be highly effective in automating processes without human intervention.

Implementing a smart contract system to manage lunar activities could be a sustainable solution for several reasons. First, smart contracts enable autonomous execution of operations based on programmed conditions, which reduces bureaucracy and can shorten delays and reduce costs. Delays in communication between the Moon and Earth make automation even more important: actions can be immediately executed on-site, without waiting for instructions from Earth. Instant action is crucial when every minute matters. Furthermore, every operation, transaction, and incident would be recorded, ensuring transparency. Finally, smart contracts could establish a shared framework tailored to an environment where numerous actors from different countries must cooperate without a single central authority. If applied to the management of lunar activities, smart contracts could orchestrate everything from small services, such as oxygen or lighting regulation to more complex operations like managing trade flows or a resource distribution. They could also set shared rules for safety, maintenance, and debris prevention.

Let's take an example of two companies in the space sector: one based in Asia, responsible for extracting water ice at LSP and processing it into hydrogen and oxygen to produce propellant and another, based in Europe, which operates the lunar spaceport and delivers a propellant to spacecrafts heading back to Earth, or to those that are on their way to Mars. In both cases, their commercial commitments could be automatically regulated by a smart contract. Such a contract would be recorded on a blockchain accessible to all parties. It would include all the commercial terms coded onto the blockchain, such as the quantity of propellant to be delivered, the agreed price, the docking slot, delivery deadlines, and any penalties. On the day of the operation, the lunar spaceport's systems and the extraction company's equipment would use physical sensors to automatically capture data, such as cargo weight, volume, and docking time, then it would transmit it via a hardware oracle to the blockchain. If the conditions are met and the cargo is compliant, the payment is automatically transferred. No judicial intervention is necessary because everything is recorded, and all processes are carried out automatically and transparently.

Smart contracts could also make the rules of the Lunar Council directly executable. For example, if the Council sets safety standards or limits for site selection of lunar infrastructure, these rules could be coded into smart contracts that would automatically block unsafe operations or charge extra costs when limits are exceeded. As for the challenges and limitations of smart contracts, oracles remain points of vulnerability. If they fail, provide erroneous data, or are compromised, they could trigger incorrect actions, such as unjustified payments or unauthorized access. Therefore, it is essential to design redundant, auditable, and scalable oracles, with active monitoring mechanisms, particularly in isolated environments, like the Moon. The role of oracles should be strictly defined by a contract, with clear obligations, liability rules, and insurance requirements. It will be important to include safeguards, such as a third-party verification, multi-oracle consensus, backup oracles in case of dispute, or automated oracle-based dispute resolution mechanisms. Implementing such a system raises ethical questions. Entrusting the entirety of lunar operations management and execution to programs and code essentially means delegating a significant share of power to machines. The sustainability of such a system depends on maintaining a balance between automation and human oversight.

Summary

A future is possible where decisions on the Moon are openly recorded on the blockchain. In this lunar society, tokens would act like digital keys, granting political, economic, and social rights. This vision aligns with current space law, which forbids national sovereignty but leaves internal governance undefined. In such a fragile environment, every drop of water, breath of oxygen, and ray of solar energy is precious. Utility tokens could ensure that these resources are tracked and exchanged with full transparency, while smart contracts could streamline operations from docking ships at lunar spaceports to managing disputes. The risks of surveillance, inequality, or over-automation are real, but they are not insurmountable.

History and science fiction both warn us of dystopian turns, but they also remind us that technologies can be steered toward better futures. With strong safeguards for privacy, equality, and rights, blockchain could do more than manage resources: it could set the foundation for the first truly transparent and democratic society beyond Earth.

Conclusion

Humanity's next pioneering chapters on the Moon represent transformative milestones in space exploration, transitioning from brief missions to the establishment of enduring outposts. An indispensable part of this journey is the establishment of a lunar spaceport, a multifunctional hub designed to accommodate frequent landings and launches, and that maintains sustainable cislunar operations with a permanent human presence. This in-depth study is divided into short-term and long-term phases which leverage and build upon developments from NASA's Artemis program and the ILRS. The cases include analysis of the environmental and operational criteria shaping site selection, details of engineering strategies for constructing durable, on-site infrastructure, and examination of how robotic systems contribute to both the deployment and long-term maintenance of the facility.

The first case study is initiated by identifying a location in the LSP as a prime location for a spaceport, due to its rich scientific value, strategic resource potential, and notable environmental benefits. These provide access to rich volatiles in PSRs and to elevated terrain for reliable solar power generation. Nearly every surface on the Moon is covered by lunar regolith, which poses significant challenges due to its abrasive nature, electrostatic charge, and respirable particles that can jeopardize hardware longevity, crew health, and operational reliability. Effective mitigation requires a combination of avoidance strategies, passive and active countermeasures, and dust-resistant designs, such as hardened landing surfaces, protective enclosures, robust mechanisms, advanced coatings, and dust removal systems.

The development of LLPs follows a strategic, phased process, incorporating insights from site selection and regolith studies. This initiative commences with the implementation of deployable and temporary solutions aimed at facilitating early mission operations while effectively mitigating hazards, such as dust ejection and surface erosion. The project incorporates ISRU by excavating regolith to produce interlocking bricks and reinforced composites with high thermal resistance and structural durability. By integrating adaptive terrestrial construction methods with lunar-specific material engineering, this strategy facilitates transitioning from initial landings to a robust and reusable infrastructure that supports a sustained human presence on the lunar surface.

The suggested design for the LLP system progresses from an IOC to an FBO model, reflecting operations at terrestrial airports tailored to the conditions of the lunar environment. Engineered flat surfaces with artificial berms, proposed as New Era Nexus® design, effectively minimize plume and dust interaction through vortex-generator configurations. The move from IOC to FBO highlights crucial aspects of modularity, maintainability, and scalability, supporting early operations reliant on Earth-imported materials while promoting the growth of self-sustaining lunar infrastructure through fully in-situ constructed spaceports.

The areas of robotics, transportation, and mobility systems ensure efficient cargo offloading, autonomous operations, and foster long-term logistical resilience. Mobility solutions address lunar terrain challenges, including slopes, regolith, dust, and energy constraints, while ensuring interoperability for autonomous pre-crew preparation. The proposed phased hybrid transport architecture combines modular hoppers for flexible delivery with FLOAT-based low-power rail systems for high-frequency shuttling, creating a scalable logistics backbone. Advances in human-robot interaction, including telerobotics frameworks like METERON and bio-inspired soft robotics, enhance operational versatility and collaboration between crew members and robotic systems. These systems collectively establish an interoperable, autonomous, and modular lunar logistics network.

Utilizing existing terrestrial technologies like NASA's LunaNet, a dynamic communication and navigation network is proposed. It employs rovers and drones as mobile nodes, featuring adaptive configuration in real-time, anticipated coverage gaps, and proactive repositioning of nodes. To reduce reliance on lunar satellites, the strategy includes an environmentally protected structure similar to NASA's Lunar Surface System. The MPRT design, based on the vertical solar array tower proposal and NASA's LunarSaber design from Honeybee Robotics, will serve as an innovative infrastructure platform integrating telecommunications, navigation, and solar power generation into a deployable asset. The power systems will initially utilize mobile vertical solar arrays, localized DC microgrids, and short wired connections. The project will expand to include hybrid AC/DC grids for integrating solar energy and wireless power beaming through optical towers, establishing both generation and distribution nodes. This case study also presents the short-term governance and business models for sustainable collaboration between nations, investors, and companies for the development of the envisioned lunar spaceport. The establishment of a Lunar Council and its Lunar Credit system provides a governance framework to ensure that lunar development is fair, sustainable, and collaborative. By linking contributions to lunar infrastructure with resource utilization through a transparent credit-based exchange, this system balances public and private interests while protecting the Moon as a shared heritage.

The advancement of sustainable spaceport infrastructure in the long-term presents significant opportunities that necessitate careful planning, comprehensive research, and innovative strategies. The long-term case study investigates the establishment of a permanent human presence and the operational viability of a spaceport on the Moon, with a particular emphasis on the integration of advanced communication, navigation, transportation, life support, and governance systems. While initial developments have been achieved in the short term, the focus now shifts to sustaining and potentially expanding these efforts.

The long-term lunar communication system integrates RF and optical networks, satellite constellations, mobile relays, and iconic crater-based antennas to support sustained cislunar operations. It provides continuous, low-latency, and high-throughput links between lunar assets, orbital platforms, and Earth, supporting mission-critical data exchange and CLTM functions. When combined with autonomous operations, blockchain-secured channels, and digital twin integration, this multi-layered architecture provides operational resilience, quick flexibility, and uncompromised data integrity, establishing the groundwork for safe, efficient, and scalable lunar exploration and trade.

Successful operation of the spaceport also calls for the C-LNS, which combines legacy satellite constellations with cutting-edge quantum inertial sensing for reliable location, navigation, and timing in the lunar environment. This hybrid architecture combines centimeter-level precision, gravitational anomaly detection, and worldwide interoperability to coordinate cargo delivery, habitat restocking, emergency response, and autonomous vehicle operations, even in non-GNSS zones. Coupled with high-bandwidth data links, delay-tolerant networking, and real-time integration with Earth-based digital twins, the C-LNS establishes a resilient, adaptive, and cooperative navigation fabric.

The C-STCM system is also proposed, an automated, AI- and quantum-enabled framework ensuring safe, efficient, and sustainable operations in the Earth-Moon corridor. It combines real-time health monitoring of spacecraft, dynamic separation, and mission-priority based trajectory management. Quantum neural networks and fault-tolerant lunar-based computing deliver advanced scheduling and optimization, while strict disposal protocols for solar sail-assisted debris relocation maintain long-term orbital safety. A specific legal framework for treaty revisions, as well as a new Accorded Cislunar Operations Agreement, are also established to specify debris categorization, govern "no-go" zones, and impose disposal and removal processes.

The envisioned lunar spaceport will serve as the core of a multi-layered, high-capacity transportation network. Supported by advanced infrastructure like orbital depots, fueling stations, AI-driven servicing facilities, and integrated traffic management, this system combines surface vehicles, maglev trains, reusable landers, and propellant-free launch technologies to sustain both routine operations and emergency needs.

To support energy needs, an integration of energy storage sources, such as flywheels, solid-state batteries, and regenerative fuel cells is proposed, for a reliable, two-failure-tolerant grid, supported by a hybrid generation mix of SSPS, small nuclear reactors, and thermal solar systems. Designed to meet the demands of a permanent 200-person crew and up to 10 daily flights, the system balances steady backbone supply, peak load handling, and rapid-response backup while maintaining operational stability.

Ensuring a healthy and habitable environment within a permanent lunar spaceport is another critical consideration, requiring advanced systems to mitigate both psychological and physiological stressors. An autonomous digital twin enabled ECLSS will provide real-time atmospheric monitoring, predictive maintenance, and autonomous regulation of atmospheric constituents, maintaining conditions within safe parameters. This system protects crew health, maintains operational performance, and facilitates long-term residence for over 200 inhabitants by combining distributed sensors, predictive controls, and user-friendly interfaces.

Psychological well-being is an important predictor of operational performance and sustainability. High stress, solitude, and the inherent hazards of frequent rocket operations can cause anxiety, depression, and physiological changes, while interpersonal conflicts among crew members can further impair performance. Ensuring robust mental health support, stress mitigation strategies, and social cohesion is therefore suggested to maintain vigilance, decision-making capacity, and long-term resilience of a self-sustaining lunar society.

Design interventions and structural optimization are essential aspects under harsh conditions. By integrating architecture, neuroscience, and bioengineering principles, features such as dynamic lighting, ergonomic exercise zones, personal control areas, and immersive biophilic elements including natural sights, sounds, and scents, enhance cognitive function, reduce stress, and promote motivation and creativity.

Human-centered interior design and sensory strategies are essential to support crew well-being, comfort, and social cohesion. Flexible spatial layouts, tactile and visually calming materials, and innovative sensory interventions, such as innovative scent recreation capsules and simulated natural lighting, help mitigate isolation, fatigue, and stress. These tactics, when combined with private pods, social gathering places, and well-planned functional areas, promote cognitive function, circadian synchronization, and teamwork, establishing a habitat that promotes psychological fortitude and operational effectiveness in the harsh lunar environment.

Finally, to facilitate sustainable governance, resource management, and tourism, the establishment of a lunar spaceport economy necessitates the integration of legal, commercial, and technological frameworks. The future of space law leverages blockchain technology, proposes utility tokens for transparent resource tracking, transaction regulation, and rights allocation in line with international treaties. Smart contracts further streamline operations from docking to dispute resolution. Complemented by carefully managed lunar tourism, which includes VR experiences, tele-rover sessions, and supervised surface tours. These strategies support economic activity, protect operational balance, and foster a resilient, self-sustaining lunar spaceport ecosystem.

This case study presents a comprehensive exploration of the essential elements necessary for establishing a sustainable human presence at a lunar spaceport. It intricately examines diverse fields such as science, biology, engineering, economics, and policy, underscoring their crucial interconnections. The vision is powerfully encapsulated in the words of Les Brown, inspiring us to reach for the Moon and transform our aspirations into reality:

"Shoot for the Moon. Even if you miss it you will land among the stars."

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