

A Feasibility Study on Space-Based Solar Power for Lunar Economy

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Energy solutions are essential for the exploration and establishment of long-term lunar activities. Re-energized rush for lunar adventures in the near term and future, alongside investigation of lunar bases in the upcoming years. Most of the current mission functions for a relatively short lifetime of research activities, and they include continual testing with landers to test the survivability of stringent temperatures on the lunar with varying levels of autonomy, resulting in new insights, and requirements for future settlements over the Moon ultimately paving step towards Mars colonization. Current suggested or planned power sources have Batteries, Fission Surface Power, and Vertical Solar Array Technology (VSAT) may encounter hurdles in terms of efficacy, scalability, significant system failures over time due to harsh space weather and lunar environment, and especially during the long prolonged lunar nights. To overcome the obstacles posed in the lunar environment, an innovative technique called Space-Based Solar Power (SBSP) is a prospective option to support lunar explorations, and infrastructure. A systems engineering breakdown approach is employed to explore the feasibility study of the proposed technology. That led to the breakdown of each step as a requirement to address the needs. The whole architecture is partitioned into data set formation of current, future, and past missions, where this information leads to developing hypothesis and approximation for the lunar operational needs, and lunar power demand analysis is driven by utilizing the data set. The above steps are defined to evolve a qualitative study for formulating different concepts and a thorough trade-off analysis addressed to select a concept. The above steps lead to the development of mathematical frameworks to fulfill the expected power demand. The study indicates that SBSP systems are a realistic and scalable alternative for satisfying the lunar economy's energy demands, overcoming hurdles such as long lunar nights and harsh climatic conditions. Simulations and trade-off evaluations show that SBSP systems based on Microwave electricity Transmission (MPT) can offer continuous and dependable electricity. Economic budget estimates provide vital insights into the overall profitability and sustainability of the determined architectural concept. The findings show SBSP systems' flexibility in dealing with lunar circumstances, integration possibilities with future infrastructure, and long-term cost advantages over alternative energy methods. While hurdles remain notably in lunar dust mitigation, SBSP promises a game-changing method to power long-term lunar operations, facilitating industrial growth and supporting human and robotic activities.

Keywords: Space-Based Solar Power (SBSP); Microwave Power Transmission; Laser Power Transmission; Solar Reflectors; Lunar Surface Technology Research (LuSTR); Lunar Infrastructure; Lunar Exploration.

I. Nomenclature

<i>FSP</i>	=	Fission Surface Power
<i>LCOE</i>	=	Levelized Cost of Energy
<i>LPT</i>	=	Laser Power Transmission
<i>MPT</i>	=	Microwave Power Transmission
<i>SBSP</i>	=	Space-Based Solar Power

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SD = Standard Deviation
SH = Surface Habitat
VSAT = Vertical Solar Array Technology
WBS = work breakdown structure

II. Introduction

A. General Background

Renewed attention to lunar activities and the possibility of building permanent lunar habitual outposts, which could open pathways for future colonization and industrialization. Over the years, several lunar missions have contributed significant breakthroughs to our knowledge of the lunar surface and its environment. NASA, ESA, ISRO, JAXA, and other agencies coordinate a variety of missions towards exploring the lunar water bodies, scientific research for advancing technology developments for communications, advancing electronics, and space life support technologies identification and development. In the future, these joint endeavors will not just advance the lunar infrastructure but may also lead humanity's journey from the Moon to Mars, bringing us closer to our objective of interplanetary colonization. The future of lunar exploration is ambitious, with over 250 projects by public and commercial groups wanting to establish a long-term presence on the Moon.

NASA's Artemis program lays the framework for long-term exploration, whilst ESA's Moonlight project focuses on communication and navigation infrastructure development, Nokia's 4G communication technology exploration, In-Situ Resource Utilization, autonomous or human-operated lunar rover, microgravity manufacturing, lunar mineral mining and exploration, and far-side activities for solar system exploration, about almost all of the missions planned near the Shackleton Crater region near the Moon's south pole due to the discovery of water molecules in this region and Crater's favorable conditions. The anticipated Lunar Gateway mission connects the Moon and Earth, providing uninterrupted connectivity for lunar expeditions and Deep Space Communications. This system converges many responsibilities, including Artemis missions, from the deployment stage to 2033 and beyond. The Lunar Gateway will provide early lunar surface habitation trials and build the groundwork for long-term human settlement [1, 2].

Due to the constraints and harsh environmental conditions of the lunar surface regions, numerous scientific research missions face limitations to battery health and their solar recharging capability based on the location and lunar orbital period. Recent missions have tested the battery's survivability during the lunar night phase. Current research missions have significant financial influences for a very short period of operational time. NASA is collaborating with commercial enterprises under Lunar Surface Technology Research (LuSTR) to investigate technological options for future long-term and habitat module experiments, including Vertical Solar Array Technology (VSAT) and Nuclear Fission Surface Power. Having a reliable and adequate power source is one such system that is crucial for any expedition. Meeting power demands is essential for the success of individual missions and the long-term feasibility of human presence on the Moon. The following Tab 1 represents the ongoing research or current trends in the lunar power sources.

Space-Based Solar Power (SBSP) is a sophisticated technology that can meet energy demand while being a sustainable, reliable, and scalable solution. With recent developments and advancements, it can be a potential option. Building and launching satellites, creating ground support infrastructure, and ensuring interoperability among international and commercial partners require significant time and money. These Expenses should be evaluated against the advantages, which include improved mission performance, higher research output, and the construction of a viable and sustainable lunar economy.

B. Problem Statement

In 2025 alone, six missions have been launched towards lunar explorations as of last week in February. It illustrates how we are evolving towards lunar growth. In the near-term plan, various organizations planned different types of missions using Pathfinders, Rovers, and Lunar Landers for various research missions. Each mission spends extensive budgets on developing its onboard power generation system using batteries and solar arrays for a short period of operations. Therefore, the total mission costs several millions of dollars, and with high variation in temperatures during lunar night and day phases, these systems are struggling to get back online after lunar night. That describes significant investments not being utilized to their utmost potential.

There is currently no prior infrastructure to support lunar operations around the clock in terms of power demand. Lunar-based power infrastructure is crucial for long-term mission success, habitat module support, safety, and scientific

Table 1 Comparison of Lunar Power Sources

Source	Safety	Technology Availability	Sustainability	Reliability	Remarks
Batteries	Yes	Yes	No	Limited	Mission-specific, not scalable due to mass for long missions, increasing launch and system cost.
Nuclear Fission Surface Power	Yes	Yes	No	Limited	Not sustainable due to nuclear waste. Scalable regionally. Under development for operational evaluation.
Vertical Solar Array Technology	Yes	Yes	Yes	Limited	Highly sustainable. Regionally scalable. Currently under study for lunar application.
Space-Based Solar Power System	Yes	Yes	Yes	Yes	Sustainable and scalable for entire lunar surface. Currently in feasibility study phase.

returns.

Hence, the objective is as follows:

- Defining a Lunar Power Demand Model.
- Analysis of the SBSP system architecture for a focused lunar regional support and global energy infrastructure capable system to meet the expected power demand, determining technologies, and understanding key elements within that infrastructure.
- Economic budget estimations of the system.

This article is structured as follows. Section III explains the detailed methods and techniques used throughout the system development. Section IV provides a brief analysis, including lunar economic estimates for the system. Section V summarizes the system development outcomes along with future work.

III. Methodology

This section explores the system engineering approaches to determining the power demand model and the qualitative analysis strategies alongside MATLAB simulation models to support lunar operations and budget estimations.

A. SBSP Architecture Development Using Systems Engineering Process

The systems engineering technique divides this system into high-level phases. This approach underpins the breakdown of system development by establishing specific requirements for fulfilling the objectives. The illustration depicts the system design and development procedure refer Fig. 1.

This analysis focuses on phases A and B of the system formulation, which includes establishing functional baseline ground rules and assumptions, followed by the development of power demand analysis. It then moves on to using the Morphological Matrix, trade-space analysis under the qualitative analysis procedure for concept identification, and mathematical model calculations to determine the system's feasibility in the lunar economy. However, the high-level system engineering technique has three stages: formulation, authorization, and implementation. Whereas the following mainly focused on the formulation of the system.

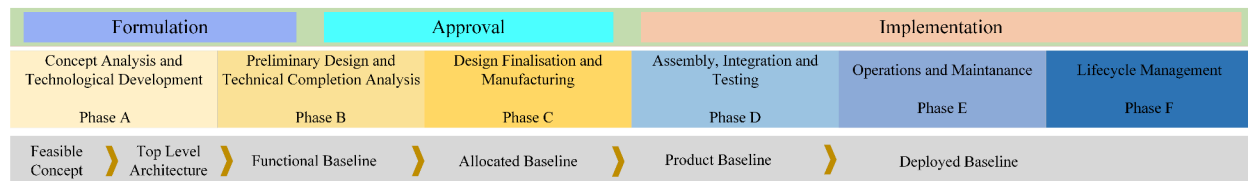


Fig. 1 Systems Engineering Procedure for SBSP Architecture Development

To evaluate the system's feasibility for lunar applications, one must consider lunar factors, goals, possible benefits, and drawbacks of implementation in this fierce lunar environment. The system must be consistent with the lunar economy's future developments, and technological needs. Concepts, data analysis, mathematical model simulations, and trade study definitions are all typical outcomes.

B. Baseline Functional Hypothesis and Assumptions - Lunar

The following outlines an overview of what will likely occur throughout the lunar's expected initial exploration phase. These act as ground rules for the following system developments and analysis.

- According to the Lunar Renaissance statistics, lunar rover and crewed excursions are expected to increase by 50 % per year.
- NASA is examining lunar habitat concepts for 30-day voyages for two people. The concept is supposed to allow for a four-person crew turnover for up to seven days during crew transition periods. Annual excursions are envisaged during the early stages of lunar exploration [3].
- NASA plans to expand the habitat module to accommodate four astronauts for 60 days. The module's expected lifespan is 15 years, with a 10-year operating period [4].
- The ESA lunar habitat is designed to support four astronauts for 300 days. The habitation module intends to last 10 years and support numerous trips [5].
- Assume that the lunar surface dwelling demonstration phase begins around 2030. Artemis' plan extends until 2032. It indicates that ongoing missions will continue beyond 2032 [6].
- Currently, the typical launch delay is two to three years. Despite hurdles, the development of habitation modules and other component innovations will continue towards lunar infrastructure. The objectives of crewed and un-crewed missions ranging from 2035 to 2050 are assumed to be continuous and beyond along with autonomous missions.
- Assuming Habitat module excursions continue, lunar surface colonies might occur after 2050. Astronauts will explore the lunar surface using a pressurized rover alongside autonomous rovers.

The lunar surface missions offer unique opportunities for scientific research fields like biology, physics, and cosmology. Scientific expeditions include astronomy, biological and physical sciences, planetary science, and heliophysics. NASA forecasts probable scientific payloads for the Artemis missions based on historical data, including Constellation Program information. However, specific scientific pursuits are yet to be specified. The assumed packages will support human astronauts' scientific operations on the lunar surface, including labs for geology, biology, physics, and human sciences [7].

C. Lunar Power Demand Forecasting Strategy

To comprehend the power demand in the lunar economy, a data collection was formed by exploiting previous and future mission data alongside the lunar hypothesis and assumptions. Based on available data, statistics predict a 25% growth in lunar rover missions year on year, with total future missions expected to climb at a 50% rate annually by including crewed missions. Michael Inter-Bartolo [7] presents information on the power budgets for the Lunar Transport Vehicle (LTV) and Lunar Surface Habitat (SH) Module, including operation-wise separation usage of power.

Operational timelines shaped by data from various missions represent quarterly increments, with missing data shown in similarly approximate intervals. Based on this, a power budget estimation model can be derived, using the outlined procedure.

The statistical evaluation is performed on the built data sets using the given data. Additional statistical analysis involves checking data using the standard deviation (SD) technique. The SD measures the variability of findings around the mean in a group of computations.

D. Qualitative Analysis Approach

Qualitative analysis is the methodical investigation of non-numerical data to uncover patterns, themes, and insights. Morphological Analysis and the Pugh Matrix are part of organized decision-making methods that explore many design options and evaluate choices based on subjective criteria. These techniques assist in producing unique ideas and making informed judgments during complex circumstances.

1. Determination of Concepts using Morphological Matrix

It is a method for scaling down complex issues into manageable chunks. The table categorizes components based on hypotheses and assumptions to attain objectives. The parameters are as follows: the decision variable is d , column choice for defining or identifying alternatives, where identifying alternatives stands as x_i^d , and A is a set of architectures that may include many architectural concepts [8].

It is furnished in a table configuration to illustrate possible outcomes depending on the criteria and aims. The Morphological Matrix can develop diverse concepts using MATLAB modeling, Python-based simulations, or matrix-based brainstorming.

2. Pugh Matrix Usage for the selection of Concept

This decision-making tool compares many concepts developed by morphological methodologies. It employs weight-age criteria on a scale of 1 to 9 for all the concepts determined using the Morphological Matrix and Trade-off analysis matrix. In comparison, depending on the complexity of engineering design and manufacture [9], where 9 reflects more significance and 1 implies substantially less priority. The overall weighted average score ranges from 0 to 100% across all categories, creating an optimal evaluation framework to identify a well-informed concept.

Trade-Off Parameters Involved in the Overall System Optimization

- **Simplicity:** Refers to the ease of designing, commissioning, and operations. The system's outstanding simplicity makes it simple to implement and maintain, making it an excellent choice for first-time or small-scale activities.
- **Scalability:** Refers to the system's capability to extend and adjust to varying power necessities. Long-term lunar operations necessitate excellent scalability, where the system usually supports its increasing number of activities and locations.
- **Reliability:** The system's ability to consistently deliver power without fail. Systems with elevated steadfastness deliver a consistent power supply, which is necessary for crucial operations.
- **Cost** is the overall financial commitment required for development, implementation, and maintenance. Although Low-cost systems are accessible, they may hold slightly less cutting-edge features. High-cost systems often provide more scalability, durability, and flexibility.
- **Technological Complexity** refers to the state-of-the-art technology and engineering demands to operate the system. High-complexity designs offer advanced characteristics like precision and efficiency but are more challenging to implement and maintain.
- **Precision** refers to the accuracy with which a power source supplies power to precise areas. High accuracy reduces energy loss while being efficient, which is critical for long-distance power transmission.
- **Flexibility:** the ability to transmit power to several locations while adjusting to changing demand. High flexibility is favorable for missions that require dynamic power across numerous lunar sites.
- **Deployment Challenges** are connected with installing and operating the equipment, notably in harsh or remote environments such as the lunar surface. Increased deployment issues raise the resources, stretch, and sophistication needed for installation.

To calculate the weighted score, employ the following equation for each concept:

$$Total\ Score = (C * WC) + (R * WR) + (S * WS) + (T * WT) + (D * WD) \quad (1)$$

Where:

- C = Cost score
- R = Reliability score
- S = Scalability score
- T = Technological Feasibility score
- D = Deployment Complexity score
- WC, WR, WS, WT, WD = Weights for each criterion

The total score reflects concept exploration and selection for final calculations and analysis.

E. Mathematical Computations

A multi-manipulative formulation was employed to analyze Microwave Power Transmission (MPT), Laser Power Transmission (LPT), and Solar Reflector model computations and establish essential constants. It offers a model experimentation with different inputs and outputs based on specific data inputs and constants, which are considered based on the current SBSP literature. This methodology relies on assumptions for computations and is very manipulative

when extrapolating data. These formulas originate from the transmitter and receiver, which are placed at a distance. Identifying and defining variables like Distance, Solar Flux, Rectenna efficiency, Power Density at the Receiver, Estimated Power Demand, Solar Array, and Operating Frequency.

Understanding the needed power at the receiver side is critical to fulfilling the projected power requirement. Since energy conversion involves converting one state (radio or optical) into another valuable state, it is known as conversion efficiency. As a result, the power required at the receiver before conversion gets calculated using the following equation.

$$\text{Power Required at Receiver } (P_{rx}) = \frac{\text{Power Demand at Receiver}}{\text{Conversion Efficiency}} \text{ W} \quad (2)$$

Where P_{rx} is the Power Required at Receiver.

1. SBSP - MPT - Formulation

Area of Receiver and diameter calculation (assuming it is a circular antenna).

$$A_{rx} = \pi r_{rx}^2 \quad (3)$$

where r_{rx} is the Radius of the Receiver, A_{rx} is the Area of the Receiver.

$$A_{rx} = \frac{P_{rx}}{\text{Power Density at Receiver}} \text{ m}^2 \quad (4)$$

$$r_{rx} = \sqrt{\frac{A_{rx}}{\pi}} \text{ m} \quad (5)$$

$$D_{rx} = \frac{2 \times r_{rx}}{1000} \text{ km} \quad (6)$$

where D_{rx} is the Diameter of the Receiver. The distance between the transmitter and the receiver determines theta (Apex angle), which is simply the divergence of the beam from the transmitter to the receiver.

$$\Theta = \arctan\left(\frac{r_{rx}}{\text{distance}}\right) \text{ rad} \quad (7)$$

Using directivity equations, the effective area of the transmitter is estimated.

$$D = A_{e_{tx}} \frac{4\pi}{\lambda^2} \quad (8)$$

Where $A_{e_{tx}}$ is the Effective Area of the Transmitter. Consider the link between directivity and beam width to reflect the following. .

$$D = \frac{4\pi}{\Omega_A} \quad (9)$$

where Ω_A is Solid Angle, apex angle relationship with the conic section helps to obtain the solid angle.

$$\Omega_A = 4 \times \pi \sin^2\left(\frac{\theta}{2}\right) \quad (10)$$

By rewriting the Eq. 9, following is derived.

$$\Omega_A = \frac{4\pi}{D} \quad (11)$$

By equating Eq. 10 and Eq. 11, following is derived.

$$D = \frac{1}{\sin^2\left(\frac{\theta}{2}\right)} \quad (12)$$

$$A_{e_{tx}} = \frac{\lambda^2}{\sin^2\left(\frac{\theta}{2}\right) \times 4 \times \pi} \quad (13)$$

Antennas in physical apertures are typically parabolic or horn-shaped, with errors ranging from 0.35 to 0.7 due to shadowing or other losses.

$$A_{tx} = \frac{A_{e_{tx}}}{\text{Aperture efficiency}} \text{ m}^2 \quad (14)$$

$$D_{tx} = \frac{2\sqrt{\frac{A_{tx}}{\pi}}}{1000} \text{ km} \quad (15)$$

Where A_{tx} is the Physical Area of the Transmitter, D_{tx} is the Diameter of the Transmitter.

2. SBSP - LPT - Formulation

Area of the receiver and diameter (assuming it is a circular type).

$$A_{rx} = \pi r_{rx}^2 \quad (16)$$

where r_{rx} is the Radius of the Receiver, A_{rx} is the Area of the Receiver.

$$A_{rx} = \frac{P_{rx}}{\text{Power Density at Receiver}} \text{ m}^2 \quad (17)$$

$$r_{rx} = \sqrt{\frac{A_{rx}}{\pi}} \text{ m} \quad (18)$$

$$D_{rx} = 2 \times r_{rx} \text{ m} \quad (19)$$

where D_{rx} is the Diameter of the Receiver. Calculate angle theta.

$$\Theta = \arctan\left(\frac{R_{rx}}{\text{distance}}\right) \text{ rad} \quad (20)$$

Calculate transmitter area and diameter.

$$A_{e_{tx}} = \frac{\lambda^2}{4\pi \sin^2\left(\frac{\Theta}{2}\right)} \text{ m}^2 \quad (21)$$

$$A_{tx} = \frac{A_{e_{tx}}}{\text{LPT - Efficiency}} \text{ m}^2 \quad (22)$$

$$D_{tx} = 2\sqrt{\frac{A_{tx}}{\pi}} \text{ m} \quad (23)$$

$$\text{Power at the Transmitter } (P_{tx}) = \frac{P_{rx} \times (\text{distance}^2) \times (\lambda^2)}{A_{rx} \times A_{tx}} \quad (24)$$

3. SBSP - Solar Reflector - Formulation

Solar Rays and a Parabolic Reflector Converge at the Focal Point. The following is the equation for a parabola with a focal length f .

$$z = \frac{y^2}{4f} \quad (25)$$

Where:

- z represents the height of a parabola at a given horizontal location y .
- f is the focal length of the parabola.

The direction vectors of rays reflected off the parabolic surface are computed and extended toward the focal point, as given by the equation below. After that, the rays are diverged toward the focal point via the parabolic surface.

$$\text{Direction Vector} = \frac{\text{focal point} - [y_{\text{current}}, z_{\text{current}}]}{\| \text{focal point} - [y_{\text{current}}, z_{\text{current}}] \|} \quad (26)$$

By following the above equations power required at the transmitter is defined. Implementing EOL power calculations, total solar array area was defined in each case. As previously stated, this formulation is predominantly manipulative in its technological study in the view of taken or set constraints. Additionally, modifying the power density in the reception and transmitter areas has profound implications on every technical condition.

F. Cost Estimations

One of the influential aspects of any architecture or proposed system is cost, as it decides its viability compared to other systems or solutions throughout the operational period. Concerning energy solutions, the Levelized Cost of Energy (LCOE) is used to determine the economic analysis. LCOE provides cost analysis based on the lifetime aspects of the system or architecture used by involving the outputs, management costs, manufacturing costs, and other variables to manage the system. Nonetheless, this relies on how the mission is planned and operated over its lifetime. The following simplified LCOE equation is applied to calculate cost forecasts for the chosen idea. It helps to compare with other energy or power solutions in the respective environments.

$$\text{LCOE} = \frac{\text{Total Life Cycle Cost}}{\text{Total Lifetime Energy Produced}} \quad \$/\text{kWh} \quad (27)$$

IV. Analysis and Outcomes

A. Power Demand Analysis - Lunar Economy

According to the future planned missions, the Artemis program consists of a blend of habitat demonstrations that might potentially occur around 2035 or thereafter. A data cluster is constructed around the prior and future missions, considering baseline functional requirements or assumptions refer Sec III.B. However, most missions indicate concentration in the Shackleton crater region due to its operational feasibility, and the evidence of water molecules in the lunar's south pole region, a potential source in the lunar exploration and surrounding locations focused on expected mineral mining and other investigations.

The data review outlines a detailed power budget for each daily procedure, considering mission-specific requirements and operational duration. However, Lunar SH data depicts the task usage in the power allocation and the estimated power allotment. AS Crew Systems, Internal Power Modules, Thermal Systems, and Robotic Systems are among the most power-intensive tasks. Similarly, LTV will help astronauts and present a similar power budget based on usage-specific conditions [2].

Using data manipulation based on the assumptions alongside the existing data helps to extrapolate power budget estimation over the years, and the SD approach renders a graph that portrays power demand in the specified period. A momentary leap in the illustration denotes employing cutting-edge technology for demonstration or investigation. Consistent growth means that power demand in the environment will remain high. After performing maximum and minimum calculations on the data, a mean value is calculated and allocated to reflect the whole dataset, producing a balanced and trustworthy estimate based on factual criteria.

By 2050, the lunar economy power demand model anticipates requiring around 141 kWh of power to support its operations, critical infrastructure, technological advancements, and resource use in the extraterrestrial environment. NASA and others are exploring several approaches to address this issue. However, due to the unpredictable nature of lunar activity, it is necessary to maintain mean power consumption, which can support high power because of operational needs. SBSP is a significant approach for handling the lunar economy's projected power budget. Figures 7 and 2 corroborate the 141 kWh projection.

B. Concepts Shaping and Identification

By integrating the procedures involved in the Sec III.B and III.D, the following Tab 2 provides prominent factors involved in the SBSP system development for the lunar economy, describing critical elements, technological considerations, and operational methods required for effective energy generation and usage on the Moon.

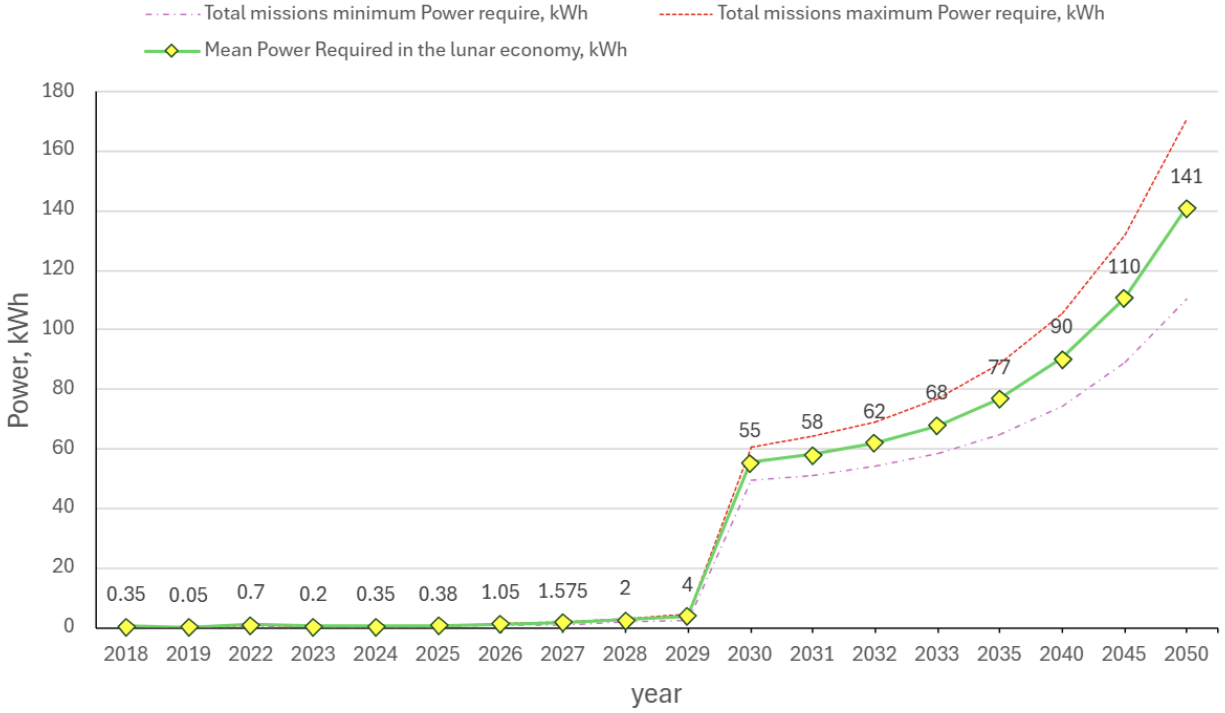


Fig. 2 The projected Lunar Power Demand.

Table 2 Key Parameters Involved for Distinctive Lunar SBSP Concepts Shaping

Parameters	Option 1	Option 2	Option 3
Power Transmission Technology	MPT	LPT	Solar Reflector
System Size	Single large space segment	Multiple large segments	Constellation of satellites
Receiver Location	Single Location (Shackleton Crater)	Multiple Locations (Shackleton Crater and others)	Distributed Across Lunar Surface
Redundancy	No Redundancy	Multi-Transmitters	Multi-Transmitters and Multi-Receivers
Scalability	Low	Medium	High
Flexibility in Power Distribution	Focused Power Delivery	Flexible Power Distribution	Wide-Area Power Distribution
Deployment Complexity	Low	Medium	High
Operational Phase	Initial Deployment (Phase 1)	Operational Expansion (Phase 2)	Sustained Operations & Settlements (Phase 3)

To shape and formulate various concepts that are likely to support the projected 141 kWh power demand was brainstormed based on the Tab 2. Scalability, reliability, redundancy, cost, and deployability are key aspects that indicate their importance in supporting the lunar economy at higher and lower levels. Each concept has benefits and drawbacks

for satisfying electricity demand in the lunar economy refer Tab 3. These high-level concepts demonstrate how rapidly we can get the system up and operating with current technology added to future developments, particularly in SBSP technology advancements.

Table 3 Summary of Distinctive Lunar SBSP Concepts

Concept Name	Tech	Architecture	Advantages	Disadvantages
Simple Large SBSP System (MPT)	MPT	Single transmitter, single receiver	Easy to build, deploy, focused power delivery	Single point of failure, low scalability
Simple Large SBSP System (LPT)	LPT	Single transmitter, single receiver	High precision and efficiency	High tech complexity, requires precise alignment
Large SBSP - Multi-Transmitters (MPT)	MPT	Multiple transmitters, single receiver	Redundancy, higher output	Complex integration, high cost, interference risk
Large SBSP - Multi-Transmitters and Receivers (MPT)	MPT	Multiple transmitters and receivers	Redundant, flexible power delivery	High complexity and cost, deployment challenges
Large SBSP - Multi-LPTs and PV Receivers	LPT	Multiple LPTs and PV receivers	High efficiency, enhanced redundancy	High tech complexity, requires precise alignment
SBSP Constellation - Transmitter and Multi-Point Receivers (LPT)	LPT	Distributed constellation, many receivers	Scalable; wide-area power coverage	Very costly; coordination needed
SBSP Constellation - Transmitter and Multi-Point Receivers (MPT)	MPT	Distributed constellation, many receivers	Reliable and scalable	High cost, potential interference
Reflector Satellite Constellation - Ground-Based Solar Array Receiver	Solar Reflector	Distributed constellation, many receivers	Provides power around the time, less storage needed	Complex control, energy loss due to reflection

Using the Pugh Matrix technique refer to Sec. III.D.2, the most optimal solutions for producing 141 kWh of power demand are carefully studied and selected based on comparative analysis, ensuring efficiency and practicality in decision-making. Nonetheless, weighted choice matrix data is probed against considerable industry knowledge, historical precedent, and logical reasoning to determine the essence of each SBSP proposal. These criteria rank each thought, and each component is weighted based on significance. The architecture that scored the highest overall was selected. This technique allows for objective selection through a qualitative approach [2].

The *SBSP Constellation - Transmitter and Multi-Point Receivers (MPT)* idea received the highest overall score, suggesting that it efficiently balances cost, reliability, scalability, technological feasibility, and deployment complexity for the 141 kWh power requirement in the projected lunar economy by 2050. It has an overall score of 7.75, suggesting it is the most balanced choice for generating 141 kW of power by retaining key parameters. Despite its high cost and complexity, this technology offers a future-proof solution to meet the changing power demands of a lunar economy throughout the lunar exploration period.

C. MATLAB Model Simulated Analysis

Based on qualitative research, *SBSP Constellation - Transmitter and Multi-Point Receivers (MPT)* is the most suited to support the power demand in the lunar economy. This model is analyzed using the formulation mentioned Sec. III.E.1 for the required power transmission and solar array area to meet power consumption in the lunar economy by 2050. The

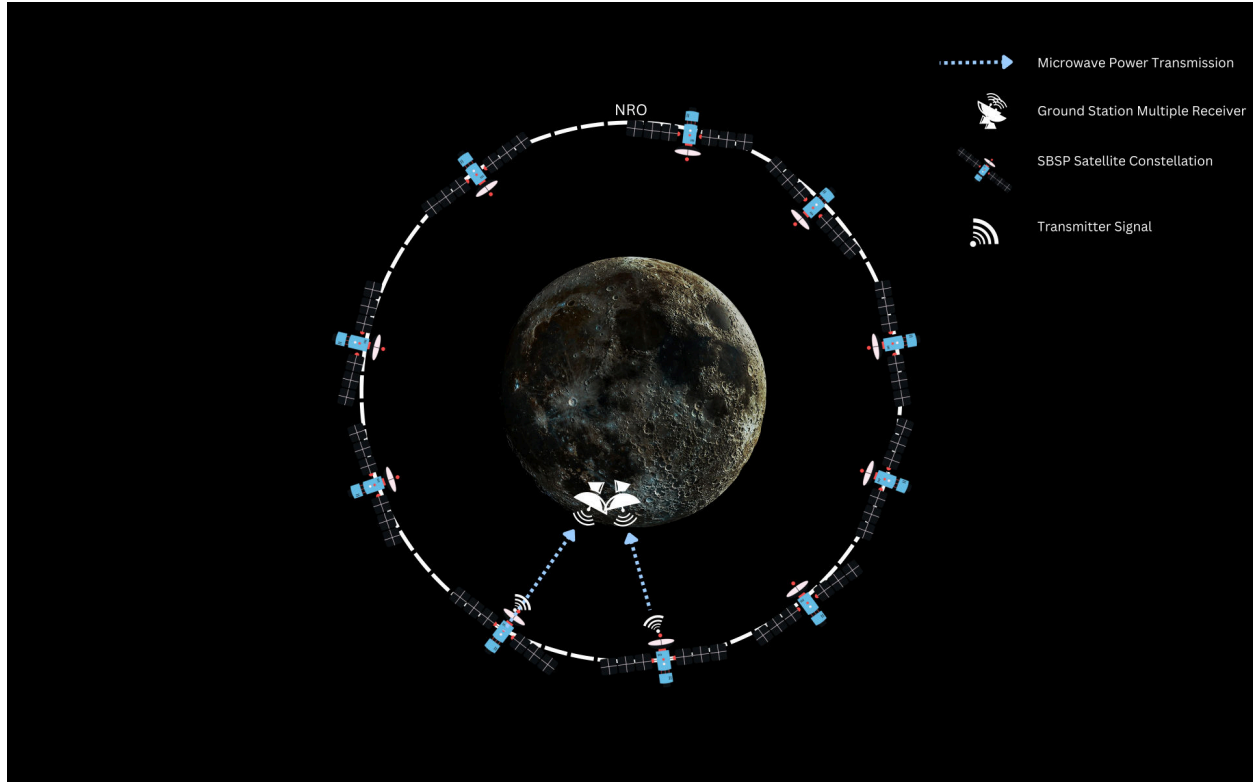


Fig. 3 Illustration of SBSP Constellation - Transmitter and Multi-Point Receivers (MPT)

model takes into account the following limitations.

- Space Heritage Antenna is chosen with an 18 m diameter.
- The solar cell array infrastructure has a 30% energy conversion efficiency.
- The SBSP constellation seeks to generate 141 kW over 10 SBSP satellites and to account for redundancy, added 20% to the total power consumption, equating to 168 kW.
- The data was evaluated in vivid orbits [65] over several distances. The ideal distance of 70,000 kilometers is marked to avoid occultation (considering it as the Near Rectilinear Orbit (NRO) type).

These factors will be used to simulate the amount of power demand that is maintained and the size of the solar arrays required to sustain the lunar economy operational by 2050.

Fig 4 depicts the 18 m transmitter diameter vs the reception diameter, which varies with frequency and distance. The highlighted dots indicate the selected orbit distance. The highlighted dots indicate the selected orbit altitude from the lunar surface.

Fig 5 depicts the receiver diameter across distances. It exposes how the receiver diameter varies depending on the frequency and distance. The highlighted regions represent the given orbit distance and correspond to other locations. The simulation also offers statistics on the solar array area vs overall mass. It reveals a linear trend due to the association between area, mass, and density. Each SBSP satellite orbit segment will produce 84 kW, which transmits power. Ten satellites are sent over the receiver to supply the lunar economy's electricity requirement. The study furthermore demonstrates how much power is generated on the space segment transmitter side to match the power requirement from the receiver. The simulated model provides information on solar array area estimations, which stand at 400.5 m^2 .

D. Lunar SBSP: SBSP Constellation - Transmitter and Multi-Point Receivers (MPT) - Economic Analysis

This economic investigation was conceived to understand the long-term feasibility and better solution towards current lunar power sources Tab 1. Due to the limitation for accurate financial analysis of the system or architecture in the lunar regional-based SBSP, a similar SBSP study over Earth operational systems is being considered to have a perspective on cost analysis.

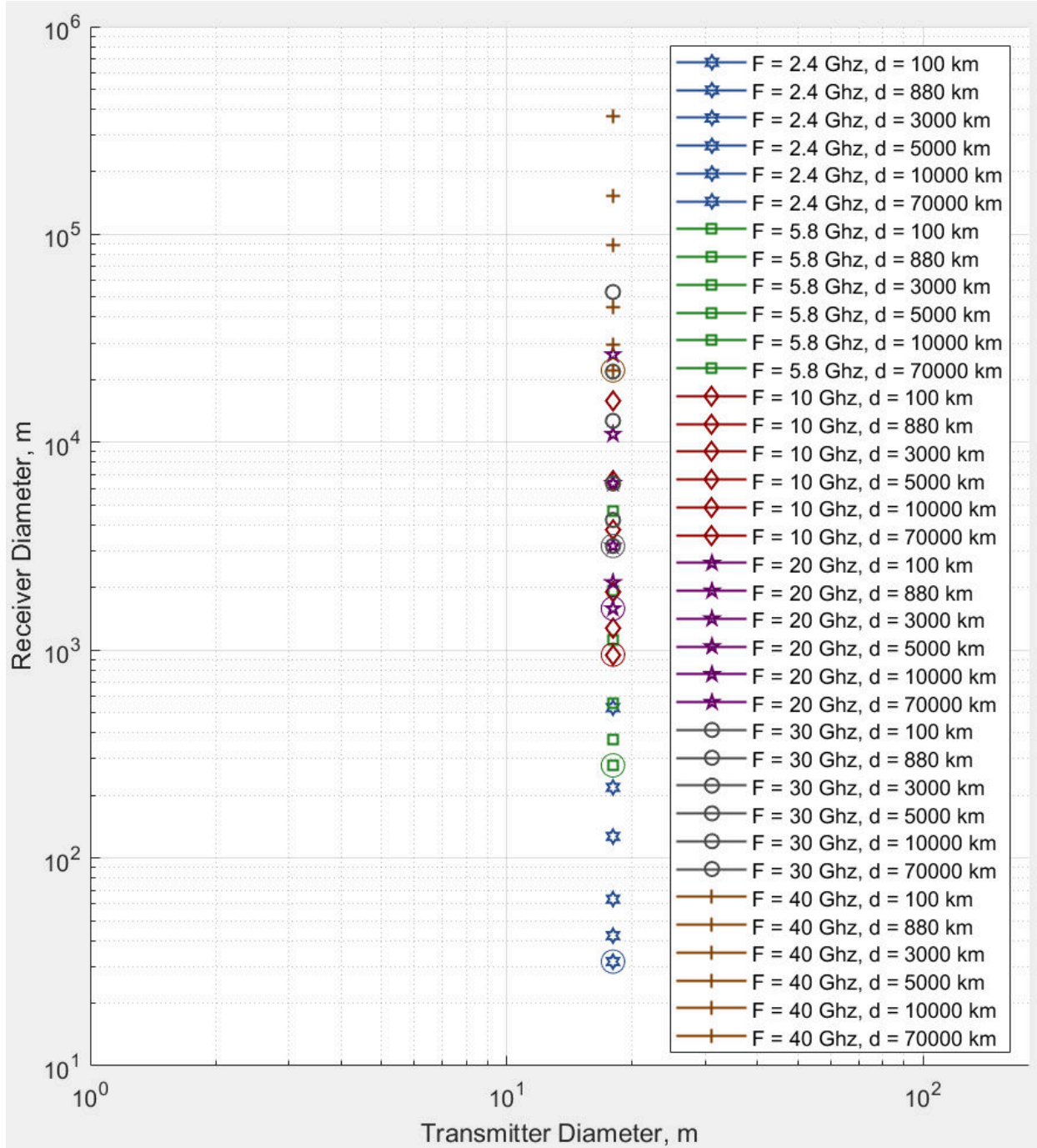


Fig. 4 The Transmitter vs Receiver Diameter with Highlight at 70,000 km, for the Selected Concept

Mature Planar Array Concept is a constellation of satellites that aims to provide 2 GW of power over Earth's operational environments. Similarly, the presented SBSP architecture for the Lunar Economy has a constellation of 10 satellites for which power demand is 141 kWh over the lunar surface by 2050. The characteristics of optimization, scalability, reliability, and launch feasibility conditions are some constraints [10].

The present intended architecture splits into several steps: These steps provide an overview of the proposed architecture's work breakdown structure (WBS).

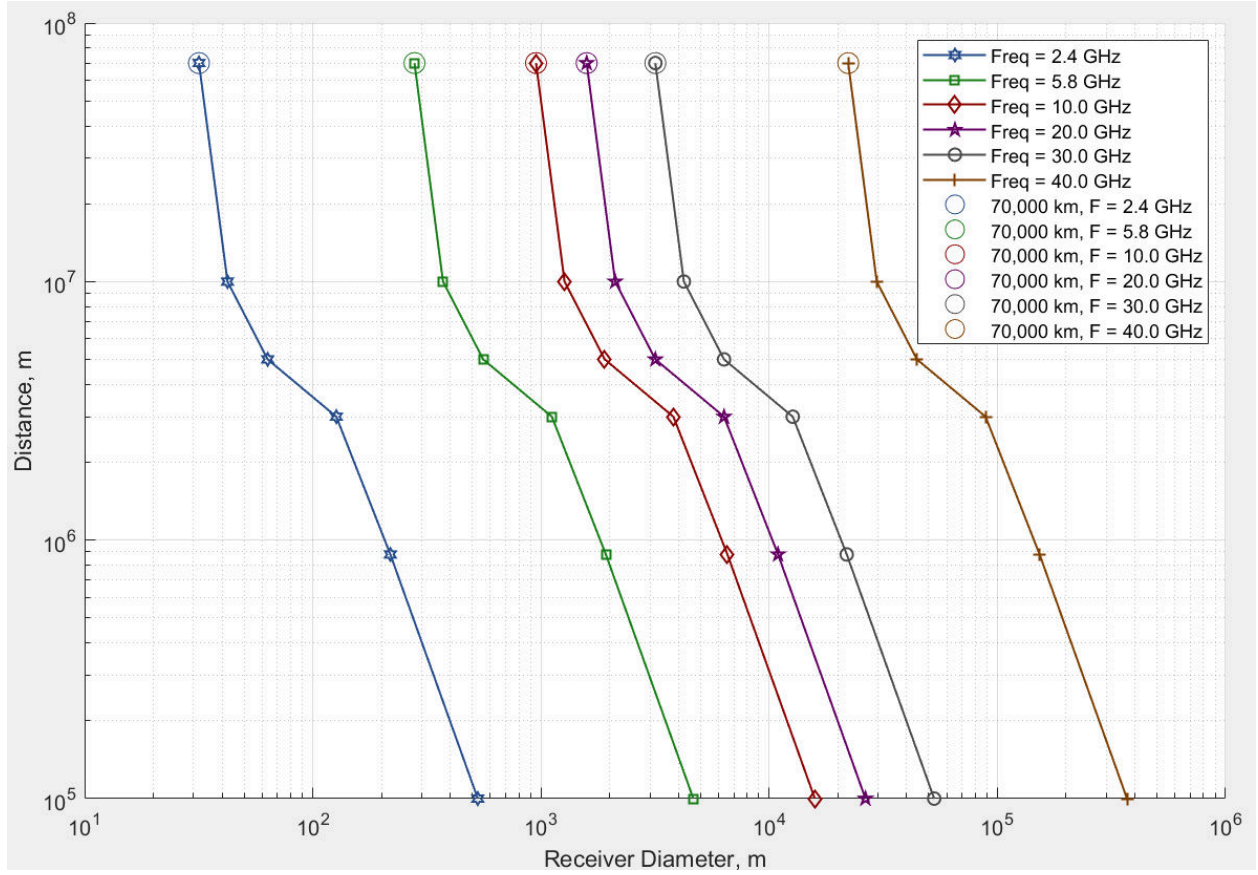


Fig. 5 The Receiver Diameter vs Distance of the Selected Concept MATLAB Simulation

1. WBS of the proposed concept

- Focuses on developing the planned SBSP system with currently available hardware for space and ground segments. This phase acts as a proof-of-concept, utilizing current technologies to lay the groundwork for the technology development.
- Assuming an origami design technique for designing the system capable of producing 84 kW power from each satellite in the proposed constellation, the ground receiver receives 16.8 kW of power after transmission and conversion losses. Each space segment has an 18-meter-diameter transmitter in orbit and a 31.7-meter-diameter receiver on the lunar ground. The compactness of space and ground components allows limited launches, maybe via ride-sharing options, to progressively deploy the system over time.
- Reflects the full-scale deployment of the system via a constellation technique. Assuming a hardware lifespan of 15 years, orbital maintenance becomes crucial. An EOL strategy entails transferring obsolete space segments to a remote location on the lunar surface or pushing them into a graveyard orbit [11]. Furthermore, additional SBSP space segments are presumed to be deployed frequently or to fulfill the lunar ecosystem's power demands on a need basis.

2. Architectural Overview

- Lunar Space Segment (LSS): Solar collectors, power conversion units, and wireless power transmitter (18m diameter).
- Lunar Ground Segment (LGS): Rectenna-based receiver (31.7 m diameter) designed to operate on the lunar surface.
- Each unit produces 16.8 kW of usable power at the lunar ground receiver, assuming all 10 satellites pass over the receiver within an hour.
- Deployment Style: Compact, origami-inspired folding structures suitable for ride-share launches.

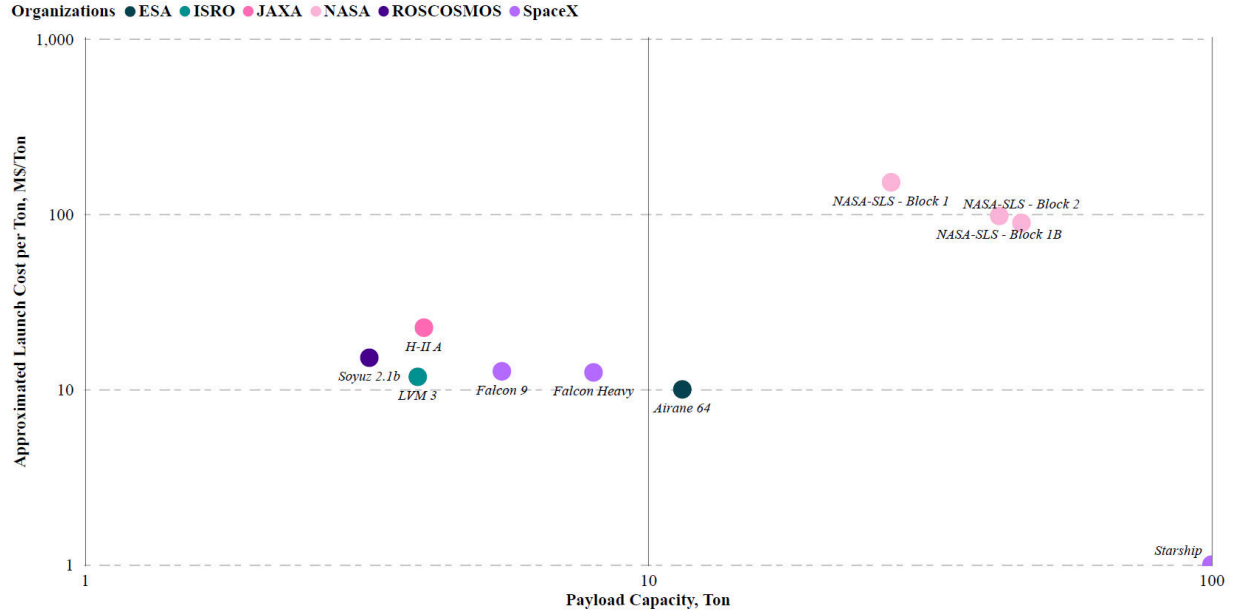


Fig. 6 Launch Cost Analysis

- EOL: transferring the obsolete space segment into the remote site on the lunar surface or the graveyard.

3. Lunar Launch Cost Analysis

The following figure showcases the most capable rocket launchers analyzed in the lunar launch cost study. These launchers are categorized primarily by payload capacity, organizations, and specific vehicle types. However, launch costs are predominantly dependent on data availability from publicly accessible information. This launch analysis presents rocket launchers capable of launching satellite systems into GTOs, as it is a significant phase of planning in the lunar orbital pathways.

Based on the SBSP estimations for the Earth's environment, data was adjusted to support the architecture in the lunar ecosystem. The overall launch costs are derived by concerning the required payload capacity, with each launch's mass carefully reviewed to ensure that the complete system is deployed effectively in the lunar environment. Based on current mass estimations, each unit is around 3.7 Tons. A combination of launchers can be opted for the need and deployment period in the lunar environment. Assuming that the system needs to be operational from 2035, using Ariane 6 is the best way to deploy the system in a total of 5 launches with a cost per ton expected to be around \$ 10 M as per the need on the basis with initial operational validation for the proposed architecture.

Due to the limitations of the data, the NASA SBSP document [10] data is taken and altered to understand the presented architecture. Current developments and testing of MPT by CALTECH – SBSP, Space Solar Pvt Ltd, and various data availability from various research reports, TRL 6 is considered for SBSP. Additionally, a learning curve rate is applied to compute the Crawford Learning Curve rate owing to production needs.

The succeeding Tab 4 provides an overview of how and what type of costs are involved in the proposed architecture. It expresses that the total life cycle cost is around \$ 2.47 B.

As per the energy industry, LCOE is used to comprehend the overall cost analysis for the proposed lunar SBSP architecture. Where LCOE stands at 112.03 \$/kWh, refer to Tab 5.

Table 4 Development & Life Cycle Cost Analysis for the Selected Lunar SBSP Architecture (All costs in billions of USD)

Elements	Data	Units	Remarks
Technology Development Cost	1.00	B\$	TRL 6 (NASA OTPS Modified, SBSP); 50% of NASA SBSP RD2 cost considered due to lunar intricacies
No of Satellites	10		Constellation of satellites for SBSP lunar architecture
Each Satellite Module Cost	0.001	B\$	Estimated using NASA SBSP analysis
Manufacturing Learning Curve Rate	0.75		Based on aerospace norms [10]
X th Unit Cost	0.000385	B\$	Crawford Learning Curve formula result
Total Cost of Planned Architecture	0.00559	B\$	Derived via MATLAB based on learning curve and cumulative cost
System Engineering, Program Management, and Mission Awareness	0.25	B\$	Assumes 25% of hardware + tech dev cost [10]
Total Maintenance	0.22	B\$	Software/remote maintenance only, based on current space mission costs
Total Launch Cost	0.50	B\$	Based on per-ton launch costs for estimated system mass
Lunar Ground Station Cost	0.50	B\$	Estimated from NASA CLPS contract costs and lunar requirements
Total Life Cycle Cost	2.47	B\$	CAPEX + Fixed Ops + Maintenance + Launch + Other Costs

Table 5 LCOE Analysis for The Selected Lunar SBSP Architecture

Parameters	Data	Units
L SBSP Power Output	168	kWh
Total Lifetime Energy Produced (15 Years)	2.21×10^7	kWh
Total Life Cycle Cost	2.47	B\$
LCOE (Levelized Cost of Energy)	112.03	\$/kWh

V. Conclusion and Future work

This study lays the foundation for SBSP's comprehensive technical and economic evaluation of the lunar SBSP architecture that can support lunar surface power demand and operational needs of expected lunar exploration. A morphological matrix helps to promote an assortment of notions. A weighted decision matrix is used to carry out a comparative examination. Based on the weighted choice matrix, *the Constellation of SBSP Segments - Transmitter and Multi-Point Receivers (MPT)* received the highest score.

The economic budget analysis implies that this concept incurs higher initial costs and management challenges with superior scalability and operational resilience, making it favorable for long-term lunar infrastructure. A total lifecycle cost analysis estimated the total expenditure at \$2.47 billion, with a corresponding LCOE of \$112.03/kWh over a 15-year operational period. These findings underscore the critical role of modularity and technological maturity in designing economically viable SBSP systems for the lunar economy.

Future work should focus on high-fidelity simulations of orbital analysis, detailed design development of SBSP, lunar dust mitigation technology, operational investigation of power beaming under lunar environmental constraints, rover mission energy demands integration and validation with SBSP concept, further towards crewed mission demands

integration and validation with SBSP concept, and optimization of the system.

Appendix

Fig 7 refers to the estimated power demand in the lunar economy by NASA, and it also represents anticipated lunar exploration and industrialization, and their respective power demand for the varied missions' operational needs around the clock.

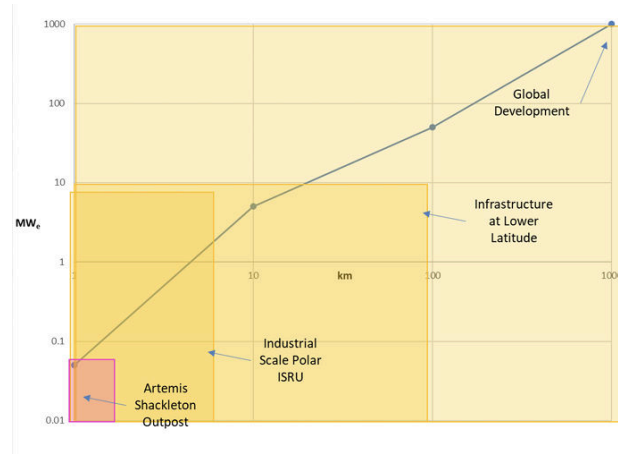


Fig. 7 Predicted Lunar Power and Energy Growth by NASA

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