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Moon to Mars
Architecture

white paper

Integrated Lunar Power Strategy Considerations

Introduction

Electric power is critical to lunar exploration. Almost every exploration asset requires power to function. The Artemis campaign will explore the lunar South Pole region,[1] which, despite offering abundant sunlight in some locations — ideal for photovoltaic power systems — also presents challenging environmental conditions for power generation and distribution.

NASA must develop a power strategy to overcome the lunar South Pole region's environmental challenges. That strategy must also consider a gradual buildup of infrastructure and growing power needs as the Moon to Mars Architecture progresses through segments of increasing complexity.[2]

During the Human Lunar Return segment, the architecture relies on self-sufficient elements (i.e., with no need for external power sources) — such as the Human Landing System, Lunar Terrain Vehicle, Pressurized Rover — to explore the lunar South Pole region. Increasing mission durations, crew complements, and traverse ranges — as well as accessing more difficult surface locations — in the Foundational Exploration segment will necessitate external power augmentation capabilities.

Beginning in the Foundational Exploration segment, NASA will implement external power augmentation to realize increasingly complex missions and maximize science and exploration returns. This paper outlines key considerations for generating, storing, and distributing power at the lunar South Pole and beyond, assessing environmental considerations, architecture drivers, and technologies that could meet lunar mission needs and pave the way for Mars missions.

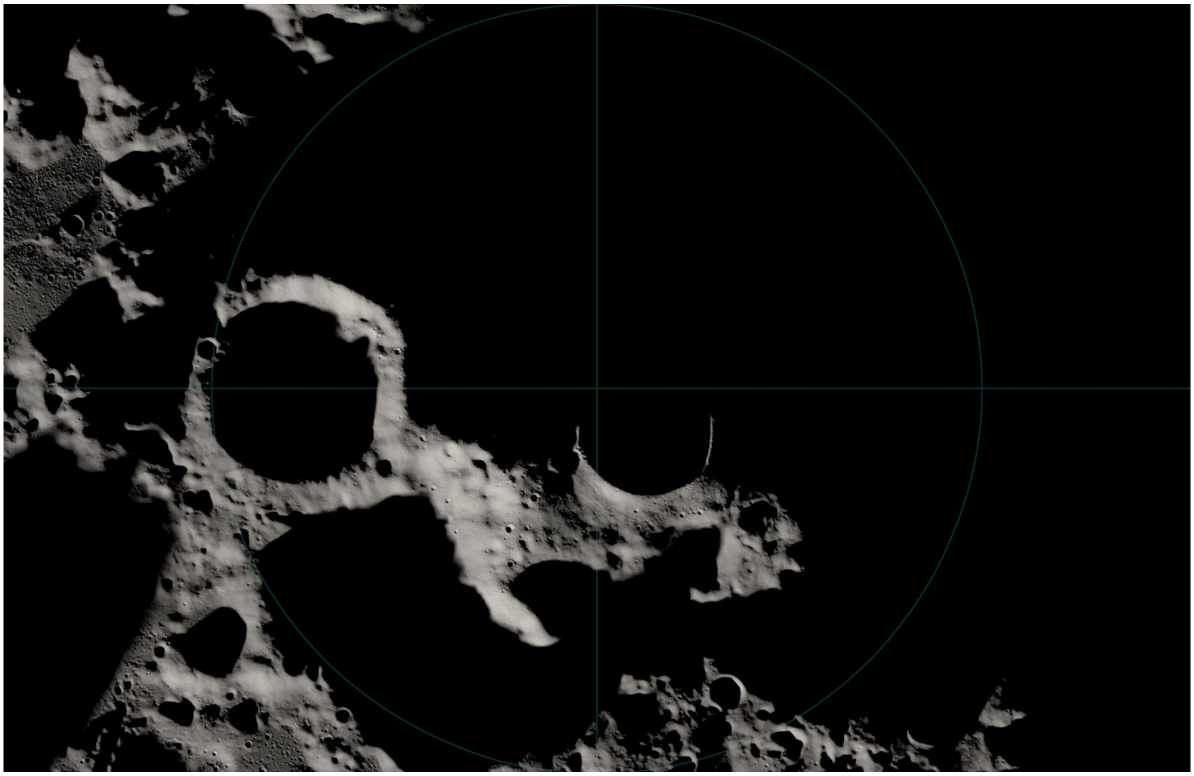

Figure One: *A rendering of sunlight and shadow within 2 degrees of the lunar South Pole on January 1, 2030. (NASA)*

Environmental Considerations

The Apollo missions, humanity's only experience in crewed lunar exploration prior to the Artemis program, only visited relatively flat mare near the lunar equator. NASA planned landings close to local sunrise, enabling entire missions to take place during the lunar day.

The lunar South Pole's geography and terrain create a variety of new exploration challenges and opportunities. While the lunar equatorial regions experience consistent day-night cycles, the lunar South Pole includes limited areas of near-continuous solar illumination and areas of continuous or near-continuous darkness due to the low angle of the Sun on the horizon and local topography.

NASA's integrated power strategy must consider how access to the Sun's energy at the lunar South Pole region might impact the overarching architecture and consider how to augment exploration capabilities beyond solar energy with technologies like nuclear fission.

Architecture Drivers

To support an evolutionary architecture, an integrated lunar power strategy should consider the long-term needs of lunar exploration. The strategy must be flexible enough to accommodate the many diverse exploration, science, technology development, and commercial activities that will take place on the Moon. Architectural considerations include supporting multiple regions, minimizing delivered mass, balancing performance and risk, and assuring extensibility to later lunar and Mars exploration campaign segments.

Multi-Region Support

NASA's integrated lunar power strategy should consider the long-term evolution of the architecture. No single site on the Moon will enable NASA to accomplish all its lunar exploration objectives; the lunar power grid must be extensible to multiple sites in the lunar South Pole region and beyond.

NASA will need to emplace power infrastructure across distributed locations of interest with different environmental conditions. Power systems will also need to support sites with longer periods of darkness, including non-polar regions, as the architecture progresses to segments of increasing complexity.

A key power architecture trade-off for supporting multiple regions is the comparison of larger, centralized systems versus smaller, distributed systems. Deploying larger systems requires landers and mobility systems with greater capacity, plus the need to transmit power greater distances. Smaller systems would be easier to land, move, and deploy in the near term, but might not necessarily meet long-term needs. An approach using a combination of systems distributed across multiple regions could meet a variety of needs but would require multiple parallel development efforts.

Minimizing Mass

External power augmentation at sites in the lunar South Pole region could reduce the mass of onboard power systems that exploration assets destined for those sites would need to include. Reducing energy storage requirements could replace significant power system mass with hardware focused on core architecture functions and enable access to regions with greater net energy storage durations (see Figure Two below).

The mass savings could also allow capacity for additional scientific payloads or technology demonstrations. External power augmentation could also provide backup power to ordinarily self-sufficient exploration assets, safeguarding against failures or contingencies.

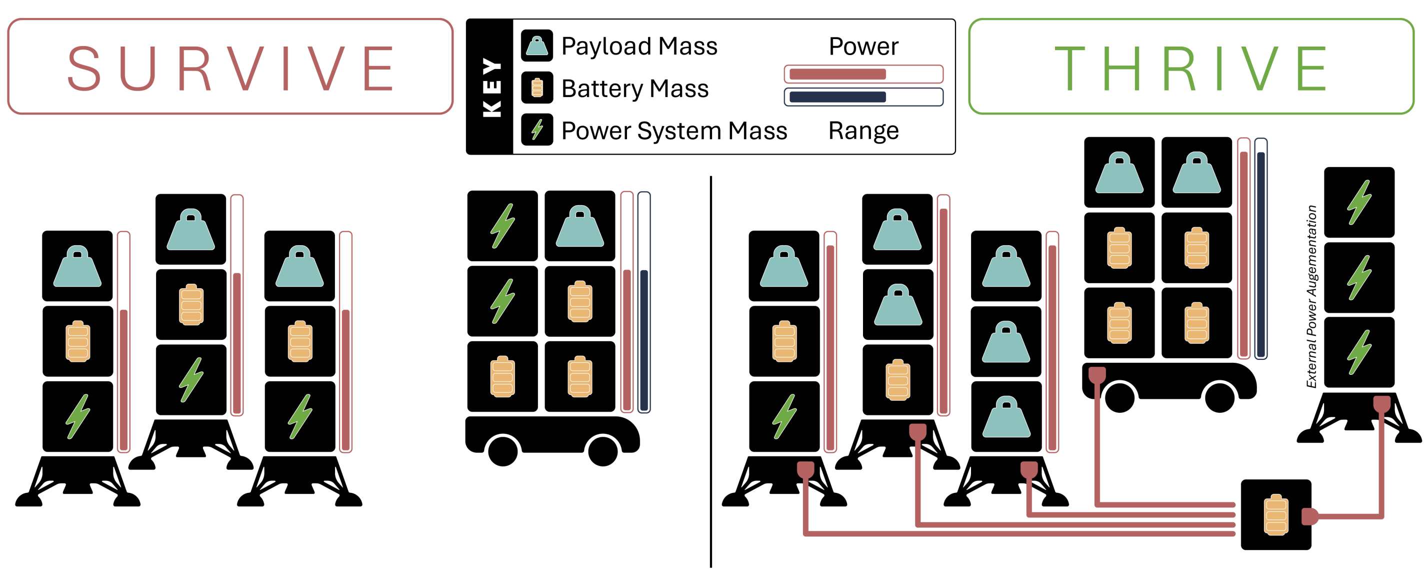

Figure Two: *Left: illustration of a power strategy that does not include power augmentation; exploration assets must generate and store their own power for survival. Right: Illustration of a power strategy that includes power augmentation. Exploration assets can rely on the power grid to meet their needs, increasing mass available for payloads and improving the range of mobility assets. (NASA)*

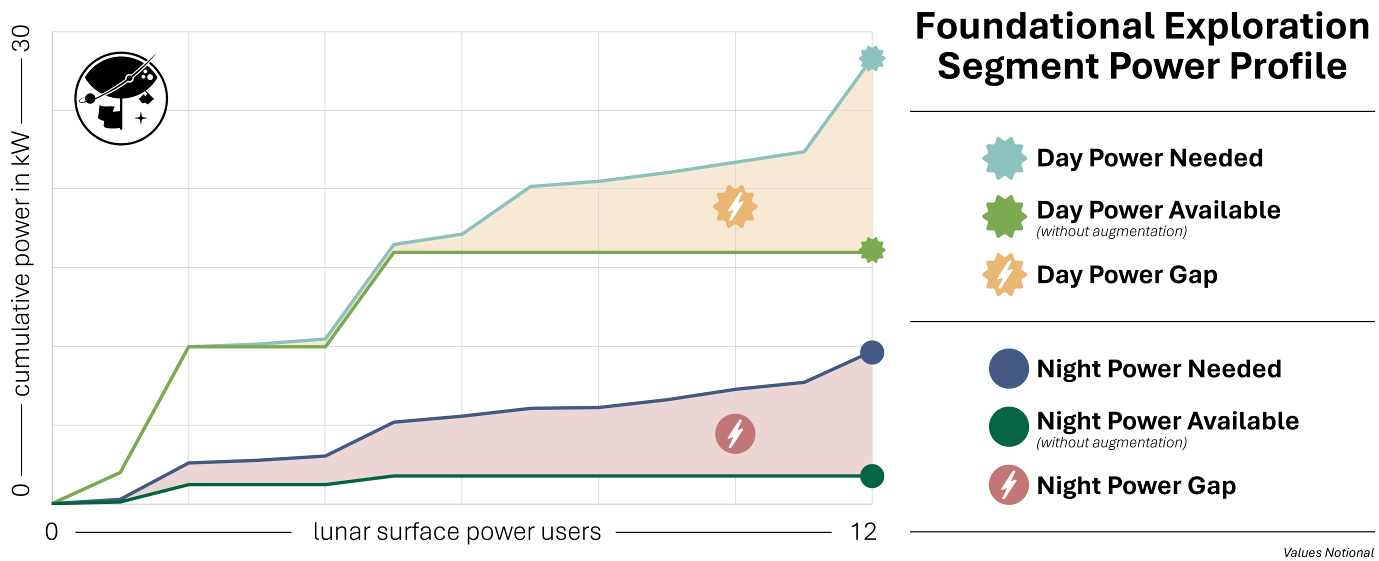

Figure Three: *Notional time-phased power needs with expanding surface power users during the Foundational Exploration segment. As the architecture evolves to include more users, power needs exceed power available without external power augmentation. Note: earlier users would be entirely power self-sufficient. (NASA)*

Balancing Complexity

External power augmentation creates manifest and power interface dependencies. Exploration assets that rely on external power will be constrained by the availability of power sources, influencing manifesting and landing order (i.e., NASA must emplace external power systems before landing assets that rely on external power).

Implementing a lunar power grid also adds complexity. An integrated lunar power strategy must consider additional deployments, connections between assets, concepts of operations, and flow-down impacts on mission planning.

NASA must understand where capability gaps exist for enabling systems, necessitating new technologies. New technologies have the potential to provide performance advantages, including lower mass, longer operational life, and higher reliability. But their immaturity introduces both development and operational risks. An integrated lunar power strategy must balance mission risk and system performance.

Lunar Segment Extensibility

While a combination of solar power generation and battery energy storage will support operations during the Human Lunar Return segment with no power augmentation, the architecture's evolution through the Foundational Exploration and Sustained Lunar Evolution segments will require power augmentation. NASA's integrated lunar power strategy must consider implementation timeline to maximize power augmentation's impact.

Thoughtful implementation of power augmentation systems in the near term could increase science and exploration returns in the long term. More available power enables the agency to not just survive, but thrive, seizing opportunities to explore more environmentally challenging areas of interest. External power augmentation enables longer-duration crew stays, expanded crew numbers, more utilization opportunities, more robust contingency options, and increased use of in-situ resources.

Figure Three illustrates how power needs could evolve beyond initial self-sufficient daytime users during the Foundational Exploration segment. External power augmentation could fulfill the growing gap between power needs and available power.

As lunar surface activities expand in the Sustained Lunar Evolution segment, more national, international, and commercial actors may generate additional needs. Commercial power services could meet these and other future needs, with power networks expanding alongside the exploration and industrial footprint.

Technological Considerations

What technologies can meet the power demand identified above? In developing a lunar power strategy, NASA evaluates the tradeoffs that different power technologies offer, as well as the need to transfer and store energy. NASA must also consider the demonstration and implementation of new technologies or capabilities that advance the technological state of the art. This is particularly true of technologies needed for initial human missions to Mars.

Power Generation Technologies

NASA considers two main power generation technologies for its crewed surface exploration architectures: nuclear fission power and solar power. Each offers advantages and tradeoffs.

Both power technologies introduce architecture dependencies, such as the need for offloading, emplacement, setup, and connection to a lunar power grid, and a potential, longer-term need for maintenance. Crew, autonomous systems, or some combination of the two could handle these tasks, depending on mission needs.

	Nuclear	Solar
Availability	Continuous	Only in sunlight
Maturity	Prior experience limited to low-power, radioisotope power systems	Extensive spaceflight heritage
Unique Factors	Human-rated radiation shielding; long-distance power cabling	Tall masts increase array height above the surface; needs energy storage for night power

Other factors are unique, such as technology readiness, robustness to the local environment, and operational capabilities. NASA's integrated power strategy will need to balance these factors to provide efficient, reliable power as the lunar exploration evolves to increasingly complex segments.

Nuclear Fission Power

Nuclear fission power harnesses energy released from splitting atomic nuclei. Unlike solar power, fission systems can produce continuous, predictable power regardless of access to sunlight or changing environmental conditions.

Nuclear technologies also scale effectively, offering a higher power-to-mass ratio than solar power, meeting power needs as they grow over the course of the exploration campaign. A single large reactor can provide power to multiple elements; multiple smaller reactors can enable exploration at many different locations.

While NASA has used nuclear power to support robotic missions and science instruments, developing nuclear fission systems qualified for human spaceflight and of sufficient power output to support human-class exploration elements requires technology development investments. NASA may also need to adapt or construct specialized facilities to build larger space-rated fission power systems. However, space fission technology development can leverage previous NASA and the U.S. Department of Energy research investments.

Processing, launching, deploying, and operating nuclear fission systems introduces additional engineering, safety, logistical (e.g., fuel availability), and regulatory considerations (e.g., ensuring that crew members are properly shielded from radiation).

Solar Power

Solar power systems convert energy from the Sun to electricity. Solar power systems have extensive flight heritage; the technology is reliable and well-understood (though NASA has yet to demonstrate the large, vertical systems needed for lunar polar applications). Using solar power systems to support a lunar power grid could leverage prior experience with space-based systems, potentially creating cost and schedule savings.

While sunlight is abundant for most of the year at the lunar South Pole, some regions — such as high-priority science targets in craters — experience extended periods of darkness or intermittent shadows from local terrain. NASA cannot rely on the continuous availability of sunlight for power in these locations and would need non-solar power solutions to survive the lunar winter.

Creative engineering techniques can maximize the availability of solar power in the lunar South Pole region. For example, raising the height of a solar array can overcome local terrain shadowing, but increases the system's mass and complexity. Regardless, an architecture that relies solely on solar power would need complementary energy storage systems to manage prolonged periods of extreme dark and cold.

Energy Storage Technologies

Adding energy storage capacity, in the form of batteries or regenerative fuel cells, to a lunar power grid that includes solar arrays could reduce the required mass of individual exploration assets and increase the flexibility of NASA's lunar architecture. For certain sites or operational scenarios, grid-based energy storage might be necessary for exploration assets to survive the lunar winter. However, the addition of a solar-based power grid with energy storage could introduce increased operational complexity (i.e., operations to deliver and connect power augmentation systems).

NASA quantifies the amount of energy that must be stored to supply power during a lunar night period as *effective energy storage duration*. This number reflects the performance required to maintain power delivery during night operations at a specific location.

Effective Energy Storage Duration	The number of hours of energy storage capacity needed to account for the annual worst-case recharge and discharge of solar-generated power (i.e., winter survival mode).

Lunar winter presents the driving conditions for engineers to apply the effective energy storage duration parameter, when elements cannot count on continuous solar illumination to provide energy for power or heat, placing significant demand on energy storage systems.

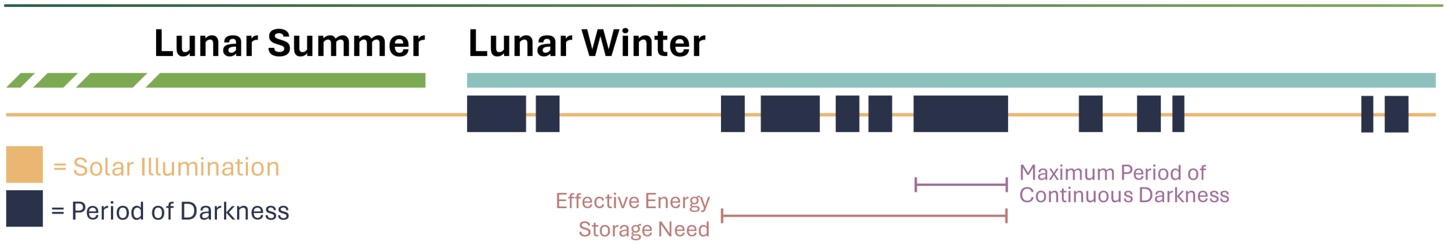

Figure Four: *Representative graphic showing periods of darkness in lunar winter in the lunar South Pole region. The illustration highlights how the effective energy storage need of an asset can be greater than the maximum period of continuous darkness. For illustrative purposes only; not meant to show actual illumination considerations at a proposed exploration site. (NASA)*

Effective energy storage duration varies greatly across lunar South Pole sites. As such, an integrated lunar power strategy must consider site selection as a key design factor in assessing power system options. Solar power systems must account for this environmental factor, while nuclear power's continuous output reduces the net energy storage requirement.

An integrated lunar power strategy must consider that the energy storage mass required to achieve a given effective energy storage duration can have a major impact on the architecture. Analyses have shown that conventional lithium-ion batteries would account for more than one-fourth of the mass of a theoretical 15-metric ton habitation asset delivered to the lunar surface.

Finally, the lunar power strategy should consider energy storage technologies other than conventional batteries. For example, regenerative fuel cells use chemical reactions to store energy. While these newer technologies have less flight heritage than traditional batteries, innovative approaches for energy storage could transform the power trade space for crewed surface exploration.

Power Transfer Technologies

For external power augmentation to provide maximum architectural benefit, NASA must address the technologies for power transfer from sources to users as the architecture evolves. Separation distances could range from several meters between co-located assets at a single site to several kilometers. NASA analyses to support development of an integrated lunar power strategy consider two approaches to transfer power: cabling and power beaming.

While cabling is ubiquitous on Earth, the lunar environment presents unique design challenges. Cabling and associated electronics, (e.g., converters, connectors, etc.), must be robust to the lunar environment, accounting for extreme temperatures, dust, vacuum, and lower gravity. Cable connectors must also be interoperable with the wide variety of exploration assets. Finally, engineers must design cabling and connectors for easy handling during deployment by astronauts and robotic systems, with provisions for maintenance in case of damage.

Power beaming is a relatively new technology that needs further research and development for lunar applications. The leading technology approaches for power beaming use lasers or microwaves to wirelessly transfer power from sources to exploration assets. Power beaming use cases could include beaming power from a crater rim into the crater valley or from an orbiting asset to a surface user. For close-proximity charging, wireless transfer with inductive coupling could eliminate the need for hard-wired power connectors.

Mars-Forward Considerations

In 2024, NASA identified nuclear fission as the primary surface power generation source for initial human missions to Mars. The agency selected the technology based on its robustness to the Martian environment and a host of other considerations outlined in a 2024 architecture white paper.[3]

Wherever possible, the Artemis campaign uses lunar exploration to prepare for human missions to Mars. NASA's integrated lunar power strategy must consider how and when to use the Moon as a testbed for Mars-forward technologies.

Proving new capabilities and concepts of operations closer to Earth is safer, faster, and less expensive than performing them for the first time on Mars. NASA needs to develop proficiency in deploying, connecting, and maintaining power systems with humans and robotic systems in challenging environments. Some of these tasks may require new autonomous technologies, since the one-way light-time communications delay can range from 4 to 24 minutes.

The Moon offers an ideal testing ground for building these capabilities ahead of human missions to Mars. Research and development toward lunar power systems can also feed forward benefits for other aspects of Mars exploration, like in-space power generation and nuclear- and solar-electric propulsion systems.

Including the development of nuclear power systems for lunar applications in the agency's integrated lunar power strategy reduces risk and builds operational competencies for its use on the Red Planet. In addition, designing common nuclear systems and technologies for both Moon and Mars exploration can offer cost and schedule benefits. Development supporting both parallel exploration campaigns would avoid duplicative work and maximizes the return on NASA's investment.

Conclusion

NASA is developing an integrated lunar power strategy that enables access to a wide range of locations in the lunar South Pole region, and beyond. External power augmentation will make the architecture more effective and resilient, enabling science and exploration at more locations than self-sufficient elements could accomplish alone while also reducing the energy storage mass for individual landed surface elements. The strategy will consider environmental, technological, architectural, and Mars-forward considerations, and maximize NASA's achievement of the Moon to Mars Objectives.[4]

In August of 2025, acting NASA Administrator Sean Duffy announced plans to develop a nuclear power system for the lunar surface. This directive helps to address the power considerations addressed in this paper and leverages prior technology investments and architecture integration studies.

NASA plans to debut its full integrated lunar power strategy based on the considerations outlined in this paper in the coming years. Alongside that strategy, the agency will initiate an integrated surface power element into the architecture to realize functional capabilities for external power augmentation.

Key Takeaways

NASA is performing trade space analyses to support the development of an integrated lunar power strategy. That strategy will address critical environmental, technological, architectural, and Mars-forward considerations.

The environment at the Moon and our scientific objectives present new challenges for power generation and distribution.

An integrated lunar power strategy must consider the long-term needs of lunar exploration; these architectural considerations include minimizing delivered mass, balancing complexity and risk, and assuring extensibility to later lunar exploration campaign segments.

The technological trade space includes variety of power generation, energy storage, and power transfer systems and capabilities. Each has benefits and drawbacks that must be weighed against one another and analyzed in the broader context of the architecture.

The Moon offers unique opportunities to test power technologies and operational concepts that inform missions to the Red Planet. NASA's integrated lunar power strategy will consider the value of Mars-forward research and development on the lunar surface.

NASA is developing its lunar power strategy based on these considerations and is initiating new power elements into the architecture that meet architecture needs and close capability gaps.

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