Powering the Moon: From Artemis Technology Demonstrations to a Lunar Economy

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The National Aeronautics and Space Administration (NASA) is working towards developing and demonstrating new technologies, capabilities, and business approaches that are needed for future human deep space exploration missions. This includes collaborating with commercial and international partners to establish the first long-term presence on the Moon under the Artemis mission. Artemis lunar surface operations begin with robotically exploring the lunar south polar region for locations suitable for harvesting lunar surface resources. Over time, activities will expand beyond robotic operations, increasing the need for highly reliable and available electrical power. Beyond Artemis, there are interests in full commercial lunar surface activities. A lunar microgrid is being proposed to deliver highly reliable and available electrical power on the lunar surface and meet the power needs. Microgrids are of interest in terrestrial applications due to their ability to integrate a variety of renewable power sources. A similar approach can be taken for the lunar surface. A lunar microgrid would offer the ability to integrate various power sources to maximize power availability, including nuclear, solar arrays, batteries, and regenerative fuel cells. Microgrids are flexible and can be designed to allow for islanded operation, where power is utilized near the loads to minimize power distribution losses, or in a power sharing mode where power is transmitted longer distances. This capability is crucial during failures where overall power availability is reduced. Microgrids will also allow for the power system to grow and evolve over time, meeting the need to expand beyond initial lunar surface activities.

I. INTRODUCTION

The National Aeronautics and Space Administration (NASA) has a long-term vision of sending humans to explore Mars.[1] As part of this long-term vision, there is a nearer term goal of developing and demonstrating new technologies, capabilities, and business approaches that are needed for future human deep space exploration missions.[2] Collaborations with commercial and international partners will be needed to establish the first long-term presence on the Moon, further American leadership on the moon, and expand the United States global economic impact.

Under the Artemis plans,[2] lunar surface operations begin by robotically exploring the lunar south pole region for locations suitable for harvesting lunar resources, such as water-ice. This is accomplished using the Volatiles Investigating Polar Exploration Rover (VIPER)[3] and other mobile robots. Over time, activities on the lunar surface will grow beyond robotic operations towards demonstrating full lunar surface operations with the delivery of a lunar habitat and in-situ resource utilization (ISRU) assets. These demonstrations are focused on technologies needed to support deep space human exploration, such as the mission to Mars and humans living on another planet.

There is growing interest in lunar surface activities and demonstrations beyond the current Artemis plans such as manufacturing and agriculture on the lunar surface. Growing beyond the initial Mars focused technology demonstrations will require relatively large increases in power, reliability, and availability, which most likely will include more power during the lunar night.

This paper discusses how an Artemis based power system can expand and grow to meet the future power needs of full lunar surface operations including commercial use. Baseline Artemis plans and power system design goals are discussed in Section II while full Artemis operations are discussed in Section III. Plans for lunar operations and power needs are discussed in Section IV with a summary in Section V.

II. ARTEMIS BASELINE POWER NEEDS

Early surface exploration robots and rovers, such as VIPER and the Polar Resources Ice Mining Experiment-1 (PRIME-1)[4] require power in the range of 200 W to 500 W and contain their own power generation (solar arrays) and energy storage devices (batteries). The amount of electric power consumed on the lunar surface increases with the arrival of the lunar habitat and ISRU[5] systems, which will bring their own power generation (solar arrays) and energy storage devices (batteries or fuel cells). In total, ISRU requires about 68 kW of power with 22 kW of that total power to be used for mining and excavation activities. The mining and excavation site will most likely be in a cold trap or crater located 3 to 5 km from the other ISRU assets and power generation. The remaining ISRU power will be used outside of the cold trap for converting the lunar regolith. This location is referred to as the ISRU production site. For this paper, assume the lunar habitat requires about 20 kW of power. Note that the stated powers are maximum (peak) values and much of the time these assets will operate at a lower power rating with excess power being available. The conceptual Artemis base with human astronauts working on the lunar surface and robotic ISRU and exploration activities requires a total of about 90 kW of electric power. The baseline Artemis power system architecture is shown in Fig. 1. Note that the rovers and science experiments are not shown in this diagram.

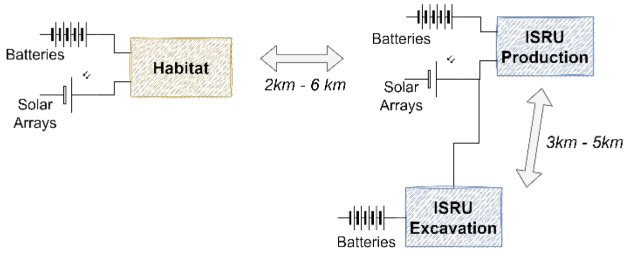


Fig. 1. Conceptual Artemis baseline power system

III. FULL ARTEMIS OPERATIONS AND A LUNAR MICROGRID

As Artemis advances beyond initial operations, there will be additional assets and technology demonstrations arriving on the lunar surface. One such technology demonstration is Fission Surface Power (FSP).[6,7,8] A request for proposal from Battelle Energy Alliance, LLC,[9] requests a fission surface power system that can generate 40 kWe end-of-life. The power generated by the FSP system is not designated for a specific use, but the demonstration will provide power to a load near the habitat. Once the FSP demonstration is complete, there will be an additional 40 kW of power available for use. There is also power available from the habitat and ISRU when those systems are operating at less than the maximum power.

The ability to share excess power generated from one system or site and transmitted to another system or site has benefits. Power can be shared to a system that contains some type of failure, either in the generation or distribution, that would normally lead to a brownout or blackout. This would also include situations where certain solar arrays are shadowed and generate less power and sharing power can account for that power deficit. The ability to make power available for loads that support human life is critical. Future systems can arrive on the lunar surface without the need of carrying their own power, which saves mass. For power sharing to occur on the lunar surface, a power distribution and transmission system must be designed. One proposed solution is a lunar microgrid as shown in Fig. **2**.

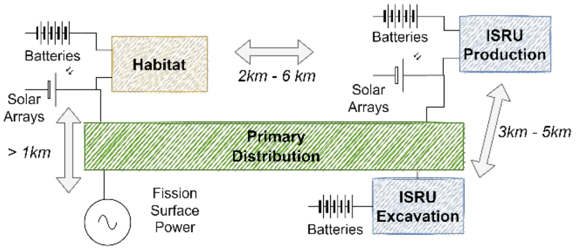
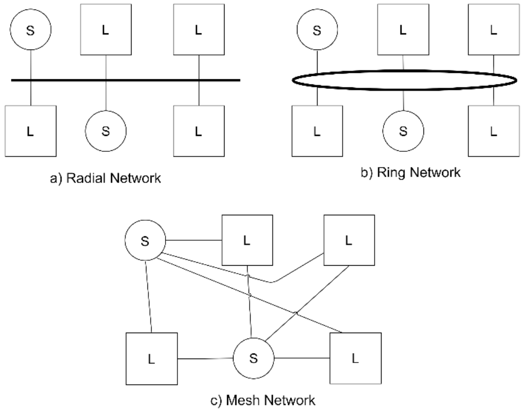


Fig. 2. Proposed Artemis power system with microgrid.

A unique feature of the proposed microgrid shown in Fig. 2 is that the primary distribution connects two islanded microgrids, one for the habitat and one for ISRU production. In these two islanded grids, the solar arrays and batteries operate in the same voltage range that the loads require, so no power conversion is needed. Excess power from one of the "islanded" microgrids can be shared to the rest of the lunar microgrid. Compared to a terrestrial transmission system, this concept of operation reduces the total number of power conversions since all the source power is not stepped up to the primary distribution voltage first before converting down to the load voltage.

A microgrid architecture needs to be selected. For this application, there are three generic architectures that are considered and shown in Fig. 3. The sources are denoted with an "S" and loads with an "L". The simplest and lowest mass option is a radial network in which all sources and loads are connected to single bus as shown in a). The radial network also has the lowest reliability as there are no redundant feeds. The second option, b) is a ring network which allows power to flow in either direction around the ring. Because of this, the ring network has better reliability, but has higher mass. The last option, shown in c), is the mesh network where each source is connected to each load. The mesh network has the best reliability but also the highest mass.



a) Radial Network

b) Ring Network

c) Mesh Network

Fig. 3. Generic microgrid architectures.

A topic of debate is the type of power for transmission on the lunar surface: alternating current (AC) or direct current (DC). The debate over power transmission on Earth dates back to the 1880s war of the currents between Thomas Edison and Nikola Tesla. The debate between AC and DC for lunar surface power distribution has gone back to the early 90s and is included in the investigation between centralized and decentralized power deployment[10] and early lunar designs,[11, 12] and recent designs of a lunar base.[13, 14, 15] The following subsection details a trade study comparing AC and DC for the proposed Artemis microgrid power system using the Electrical Power System – Sizing and Analysis Tool (EPS-SAT).[16]

III.A AC vs. DC for Power Transmission

This subsection details AC vs. DC trade studies for the Artemis power system using models of the three microgrid architectures (radial, ring, and mesh). The first goal of the study is to identify which power type is more advantageous from a mass perspective, AC or DC. The second is to highlight the relationships between system design variables. The third goal is to show how the mass of the three architecture options differ in order to provide some of the necessary data for selecting the architecture.

In this study, the cables and all grid-to-load and grid-to-source converters are sized for 40 kW. Note that 40 kW is the largest power intended to be transmitted through the grid, which is set by the power capacity of the FSP plant. Line lengths for the cables are estimated based on a notional layout for the Artemis electrical power assets and may be subject to change. The main output variable for each design solution is total microgrid mass, which is obtained by summing the masses of the cables and converters in each system design. Cables are assumed to be ETFE (ethylene tetrafluoroethylene copolymer) insulated twisted bundles laid on the lunar surface. Converters are assumed to be bidirectional DC-DC or AC-DC converters with efficiencies equal to 95% or 96.5% respectively. Cable mass is assumed to include conductor and insulation mass. Converters masses include the enclosure, radiator, magnetics, filters, and power electronic components based on curve fits of existing space power electronic systems.[11]

Note that other components or infrastructure may be needed to create these lunar microgrids (e.g., switchgear, control and communication hardware, cable deployment robots, cable spools, etc). These additional items are not included in this study, at risk of underestimating system masses, because they are either expected to be insignificant in terms of mass compared to the cabling and converters, or not enough information on that given item was available to the authors at the time of writing.

The first step towards conducting the study was to define all architectures. All architectures feature a line between the habitat and FSP (forming the Habitat Microgrid), and one between the ISRU mining and production facilities (forming the ISRU Microgrid). The radial architecture adds a single tie line between the two microgrids (specifically between the habitat and ISRU production). A block diagram of the radial architecture with line lengths is shown in Fig. 4.

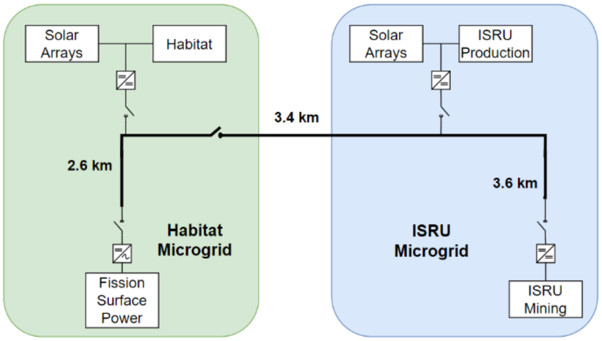


Fig. 4. Radial Artemis microgrid.

The ring architecture includes the lines from the radial microgrid and adds a second tie line between FSP and ISRU mining as shown in Fig. 5. The ring architecture is single line fault tolerant, because any one transmission line in the system can fail and power can still be transmitted between any two assets using an alternate path.

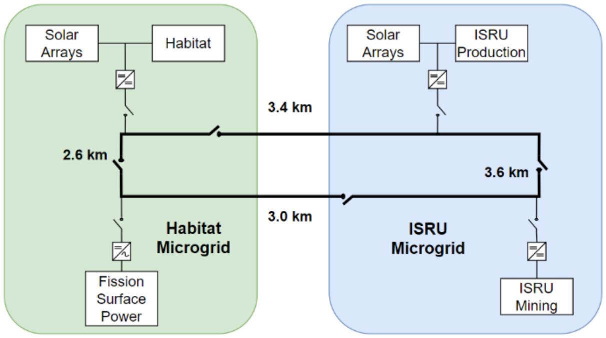


Fig. 5. Ring Artemis microgrid.

Finally, the mesh architecture features transmission lines between each pair of assets. This architecture is dual line fault tolerant, because any two lines can fail and power can still be transmitted between any two assets. It adds an additional two tie lines to the ring architecture (habitat to ISRU mining, and FSP to ISRU production). This architecture is shown in Fig. 6.

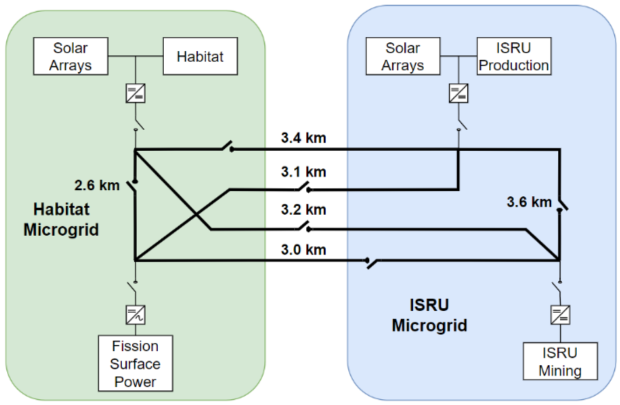


Fig. 6. Mesh Artemis microgrid.

These architectures were then sized for both DC and 1 kHz three-phase AC over a range of voltages between 1.2 kV and 6 kV. This range of voltages was chosen based on an initial exploratory study that showed that 1.2 kV is the lowest voltage that results in cables with reasonable mass, and that 6 kV is consistently beyond the point when mass begins increasing with voltage (due to the insulation mass increasing rapidly with voltage). This exploratory study indicated an optimal voltage (minimum mass) can be found for each power type and each architecture consistently within this range. Fig. 7 shows the mass vs. voltage trend for AC and DC radial microgrid architectures.

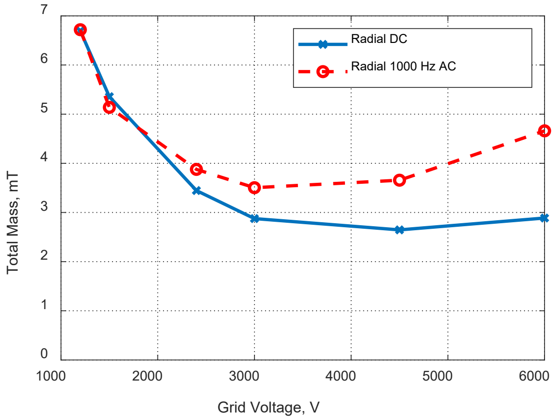


Fig. 7. Total microgrid mass versus voltage for radial architecture

This figure shows that for voltages at or below 3 kV, which is near the optimal voltage for minimum mass for AC, DC and AC transmission systems have comparable masses. It is unlikely that voltage designs above 3 kV would be picked for Artemis because AC microgrid mass increases beyond 3 kV, and the converters for DC microgrids running beyond 1.2 kV will require a large number of series stacked components, compromising reliability. Note that for ring and mesh systems, the DC vs. AC trends are similar, though ring and mesh systems have more mass compared to the radial systems as shown in the AC data in Fig. 9 (50% and 100% greater mass respectively).

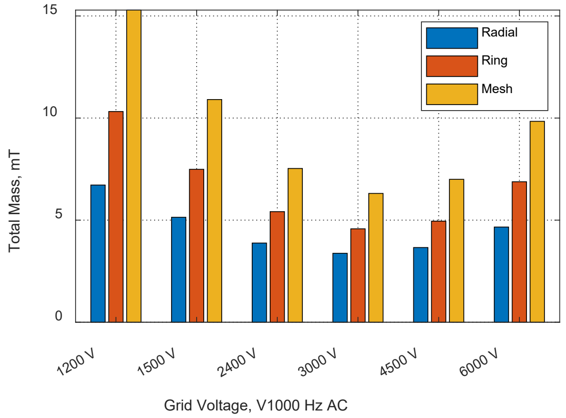


Fig. 8. Total mass for all AC systems.

Several conclusions can be made from the data. Assuming voltage and all other parameters are equal, there is no clear mass advantage between AC and DC Fig. 9 indicates the cables are by far the heaviest part of the microgrid, which ranges between 70% and 95% of the total mass. The transmission voltage is the design variable that most strongly affects system mass, as increasing voltage significantly decreases the amount of current, and therefore cable mass. Lastly, the study shows that the ring architecture adds roughly 50% more mass vs. the radial architecture to add single line fault tolerance. The mesh architecture roughly doubles the system mass and adds dual line fault tolerance. Future work may include a risks and reliability study to estimate the likelihood of line faults, which will help drive the architecture selection.

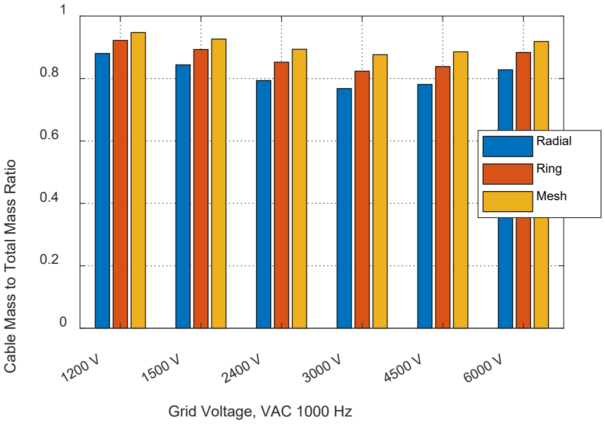


Fig. 9. Ratio of cable mass to total mass for all AC designs.

IV. BEYOND ARTEMIS

There is growing interest in creating an economy beyond Earth for in-space operations.[17, 18, 19] Categories for in-space economies has been proposed in (17) and the following are applicable to planetary surface (Moon and Mars) operations:

1. *Surface Habitats & Surface Structures – Includes all facilities on a planetary surface, such as habitats, factories, storage buildings, etc.*
2. *In-Space Manufacturing – Includes manufacturing products that are brought back and sold on Earth and larger-scale structures that will remain in space.*
3. *Space Resources – Includes prospecting, mining, beneficiation, processing, ISRU, and recycling of natural or artificial resources in space.*
4. *In-Space Utilities - Supply chains and physical infrastructure for common goods like energy, communication, water, etc.*

These advanced lunar operations that are beyond the current Artemis plans will require additional electrical power. Power estimates for Artemis is in the 100s of kW where estimates of power to support commercial lunar operations range exceed the 1 MW level.[20]

Initial Artemis plans require power users to supply their own power. There are technology development efforts focused on lunar surface power generation technologies that maybe used to meet this requirement, such as the Vertical Solar Array Technology (VSAT).[21] This type of operation may not be conducive towards creating a commercial lunar economy. Another option is to create an electric power utility where power is generated, distributed, and sold to users who are willing to pay the best price allows. This type of operation can reduce the number of power generation assets, offer a simpler concept of operations, increase reliability and availability, and reduce life cycle costs.

As lunar surface operations expand and require more power, so will the footprint of the lunar base. The Artemis mission is targeting the lunar south pole near Shackleton crater, where sunlight is available over 80% of the lunar year.[22] At these locations, the sun sits very low on the horizon and therefore creates very long shadows, so solar arrays will need to be spaced relatively far apart to avoid them shadowing each other. In addition, the mountains, valleys, and craters reduce the area available for solar power generation. These factors mean the footprint will have to increase over time and include regions beyond the lunar south pole, increasing the overall distance power needs to be distributed.

If the total power demand on the lunar surface is increased to 1 MW, then the power shared between assets would likely be increased to 100s of kW (a factor of 10 greater than the current 10s of kW level). It is also expected that the transmission distance may increase by a factor of 100 times the current 2-4 km. To understand the effect that these changes will have on the lunar power system design, several additional studies were conducted on the radial architecture. In these studies, the powers and distances in the system were scaled up to determine how mass varies with these variables. The data suggest that cable mass scales roughly linearly with power level as seen in Fig. 10, and that cable mass scales almost quadratically with distance as seen in Fig. 11. These data show that to mitigate an explosive growth of cable mass as distance and power level are increased, the voltage must be increased significantly. With limitations of radiation hardening and the challenges in developing power electronics to support a 1.2 kV DC system, it is not feasible to assume a higher voltage is possible. Therefore, as lunar surface operations approach the 1 MW total power demand and 1,000 km distance the only real possible solution is for an AC transmission system.

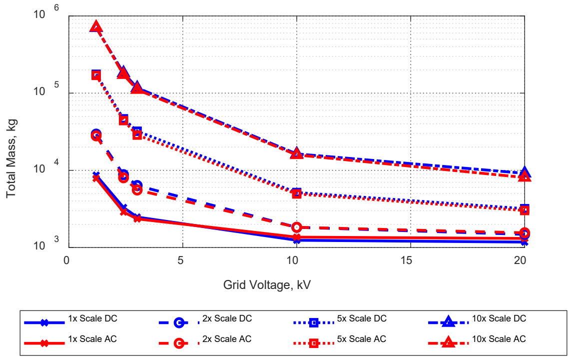


Fig. 10. Radial microgrid mass vs. voltage trend with all cable lengths scaled by 1, 2, 5, or 10.

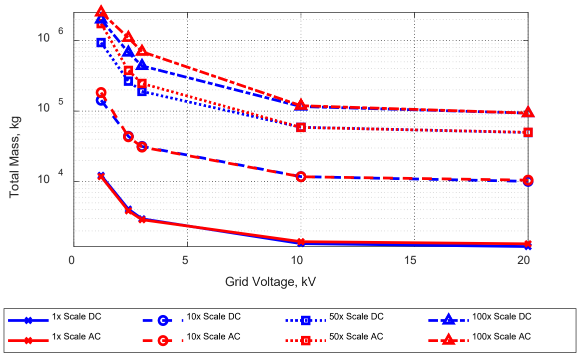


Fig. 11. Radial microgrid mass vs. voltage trend with all cable design power values scaled by 1, 10, 50, or 100.

Since an AC system is the likely choice for a power transmission system to support a commercial lunar economy, it would be advantageous for the Artemis distribution system to be AC as well. Voltage conversion in AC (using transformers) is more efficient than converting between AC and DC. For this reason, the best solution may be to distribute primary power as AC and convert to the established 120 V DC power for secondary systems, such as in the habitat or ISRU subsystems.

V. SUMMARY

Lunar surface activities are going to grow and evolve over time. Under NASA Artemis missions, lunar activities will grow from initial small rovers searching for lunar resources and places to establish a permanent presence to demonstrating survivability and the ability to live off native resources on another planet. Beyond Artemis, there is interest in creating an economy beyond Earth and commercializing the lunar surface for in-space operations and even bringing products back to Earth.

These types of operations will require a power strategy and system that can evolve and grow over time. Initial lunar power surface users will be DC, either at 28 VDC or 120 VDC, and therefore initial power distribution system will be DC. As the need for power increases and the distance increases, power distribution at 120 VDC is not feasible. A higher voltage transmission system is required to reduce cabling mass. Technology limitations associated with high voltage DC parts make AC a very attractive solation for high power and long-distance power distribution. This especially true as a lunar surface economy begins and requires an electric power utility.

VI. ACKNOWLEDGMENTS

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