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

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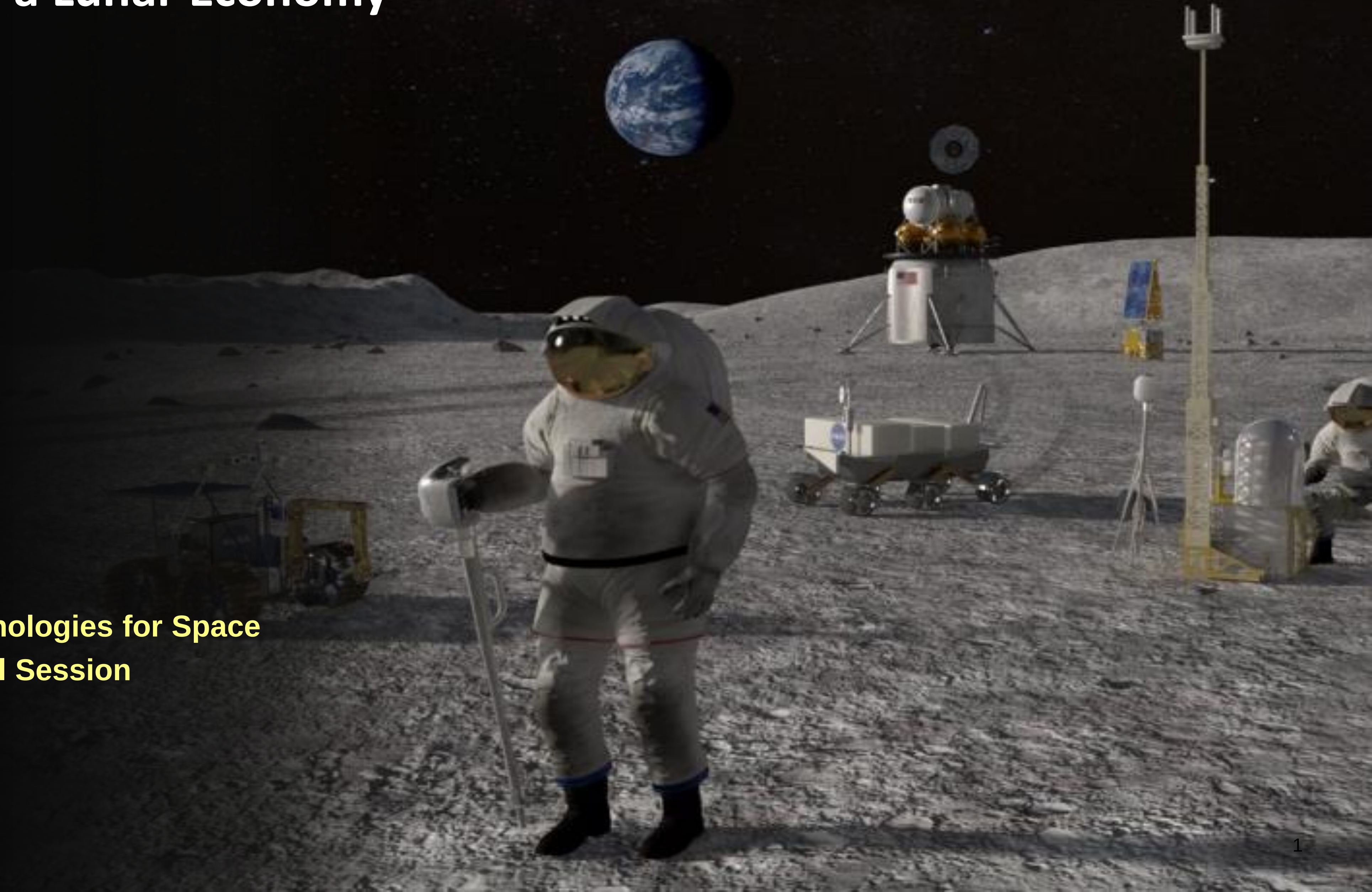

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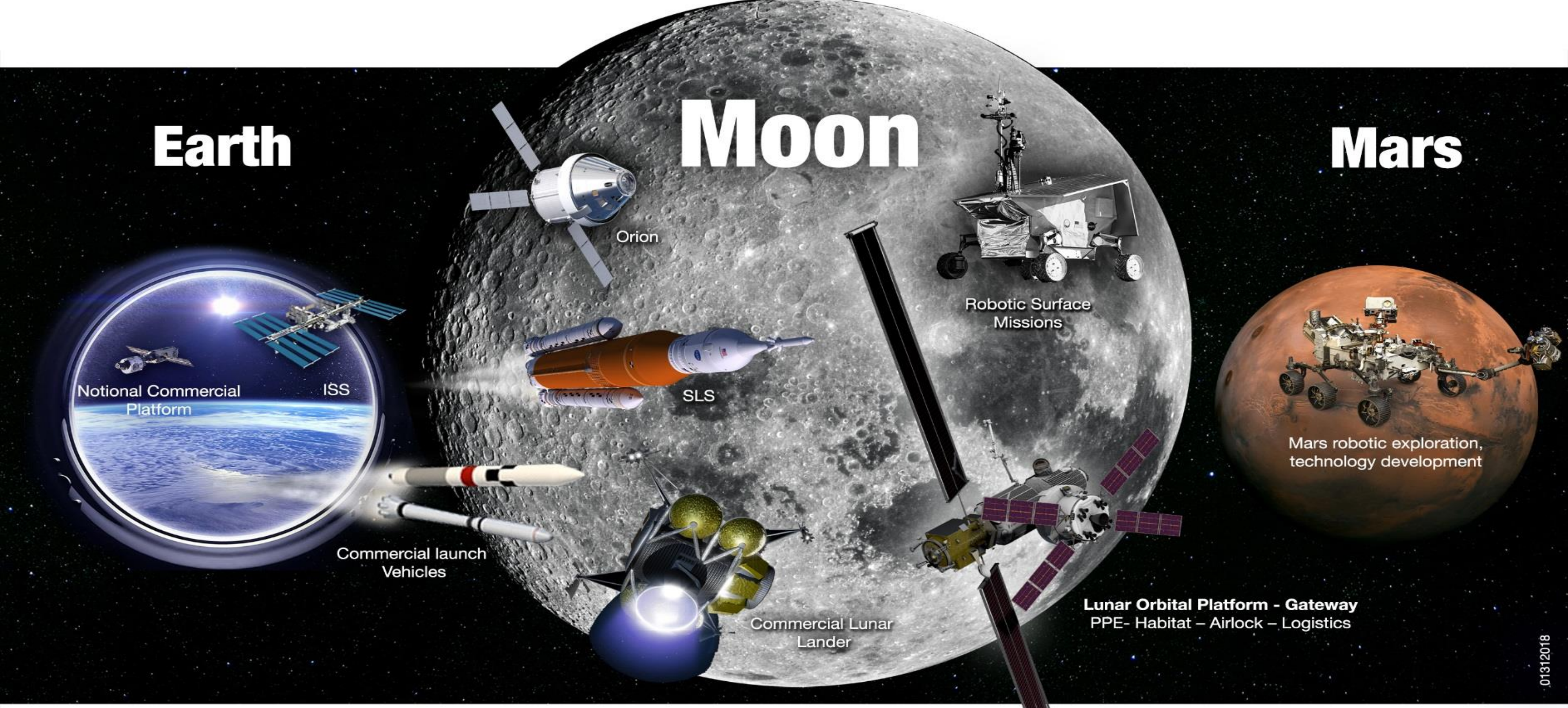
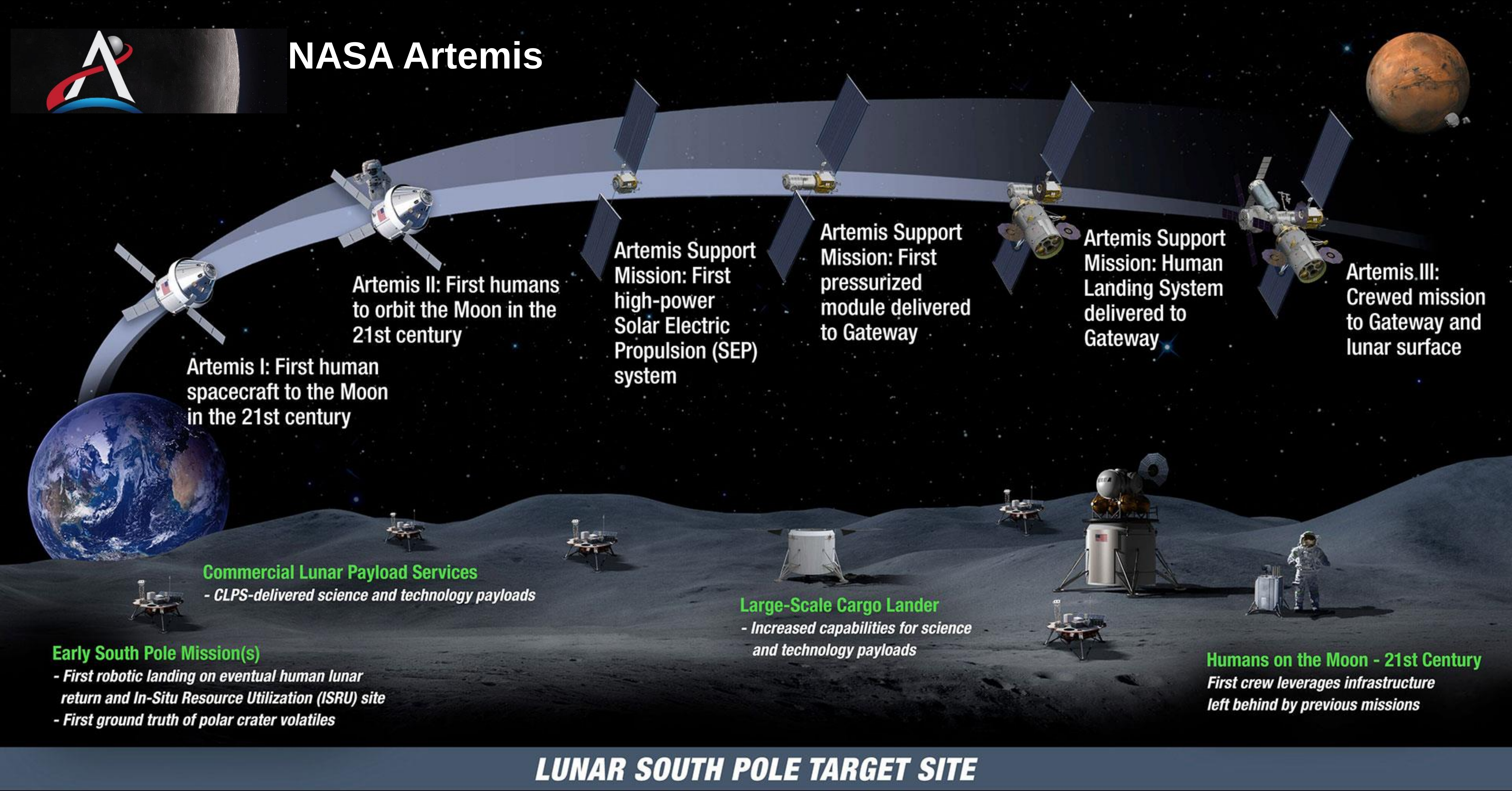


In LEO
Commercial & International partnerships

In Cislunar Space
A return to the moon for long-term exploration

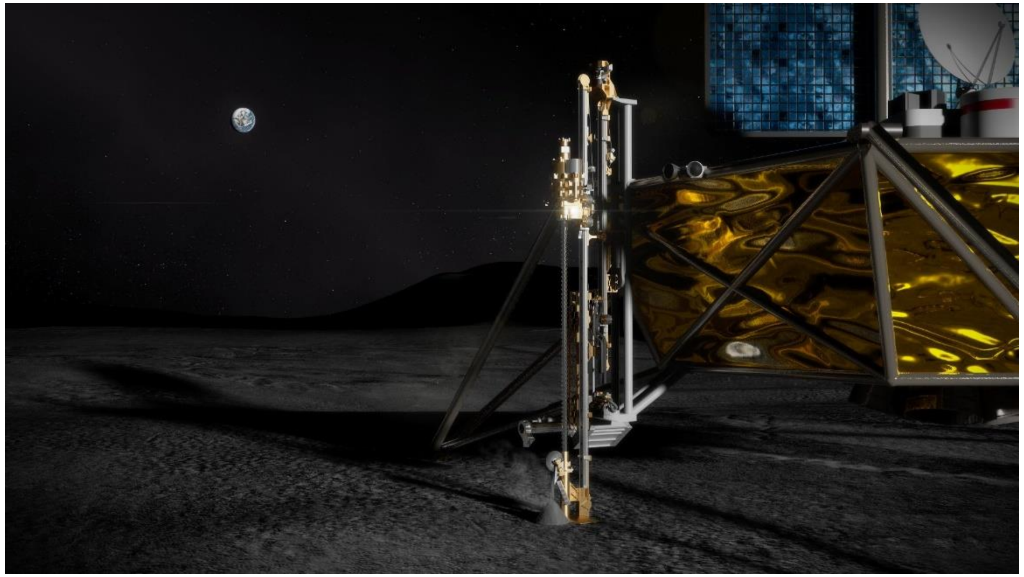
On Mars
Research to inform future crewed missions

NASA Artemis



Artemis Lunar Surface Power Users

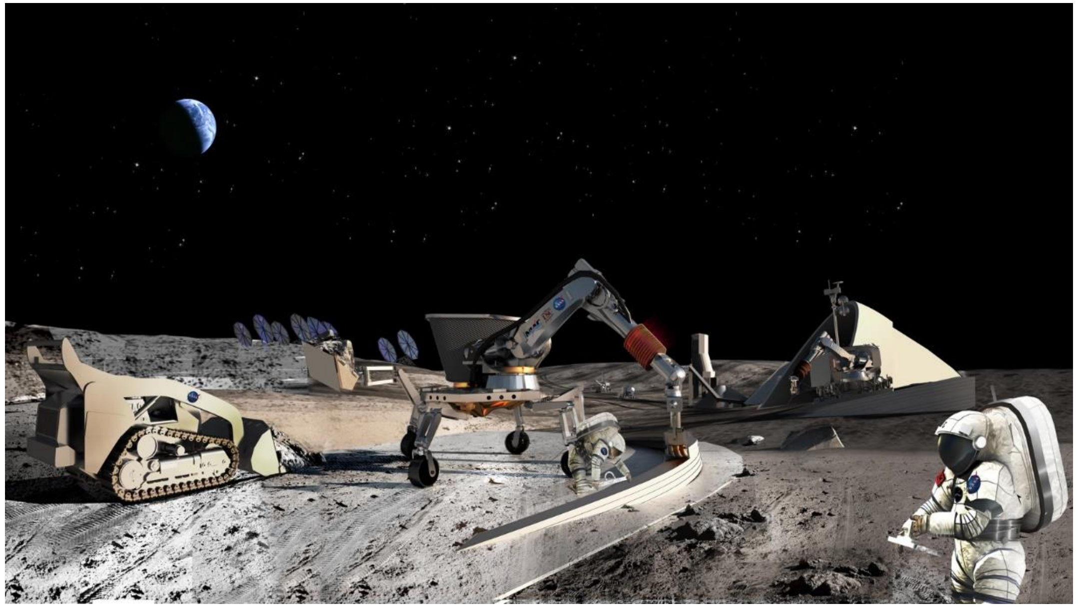
Polar Resources Ice Mining Experiment-1 (PRIME-1)
- Robotically sample and analyze for ice from below the surface.
- The Regolith and Ice Drill for Exploring New Terrain (TRIDENT)
  - Drill up to 3 ft below surface and extract lunar regolith
- Mass Spectrometer observing lunar operations (MSolo)
  - Evaluate for water and other chemical compounds
- Power Demand: ~200 Watts (nominal)
- Power Source: Solar



Volatiles Investigating Polar Exploration Rover (VIPER)
- Explore terrain that is more or less likely to hold water.
- Resolve if there is ice present, and in what quantities, at and below the surface in areas that receive short periods of sunlight – expanding the known range in which water is present on the Moon.
- Power Demand: ~500 Watts (peak)
- Power Source: Solar

Artemis Lunar Surface Power Users

Foundation Surface Habitat
- Primary asset to achieve a sustained lunar presence
- 2-4 crew, 30-60 day capable habitat
- Medical, exercise, galley, crew quarters, stowage
- Power generation, recharge capability for surface assets
- Power Demand: ~20kW (crewed) / ~2kW (un-crewed)
- Power Source: Solar and Fission Surface Power (tech demo)



In-Situ Resource Utilization (ISRU)
- Largest power user: 60+ kW
- Power is needed over long distances (3- 5km)
  - Mine water ice in crater, transport to crater rim, process into H_2, O_2
- Restricted to operate during periods of heavy insolation
- Power Demands during operations:
  - Ridge: ~46 kW
  - Inside crater: ~22 kW
- Power Source: Solar

Evolution of Lunar Power Systems

Artemis
Beyond Artemis

- **Initial Lunar Power Needs (~1 – 5 kW)**
  - Exploration and lunar science (robotics, rovers, etc.)
  - Sources: solar arrays, primary fuel cells, and batteries
- **Initial Demonstrations (~10 – 20 kW)**
  - Lunar habitat, first ISRU systems, exploration, and lunar science
  - Sources: solar arrays, primary fuel cells, and batteries
- **Advanced Demonstrations (~80 – 100 kW)**
  - Lunar habitat, full scale ISRU, exploration, and lunar science
  - Sources: solar arrays, primary fuel cells, <u>fission surface power</u>, <u>regenerative fuel cells</u> and batteries
- **Lunar Expansion / Globalization (~1 MW – 100s MW)**
  - In-space: In-space manufacturing demonstrations
  - Sources: solar arrays, primary fuel cells, <u>fission surface power</u>, <u>regenerative fuel cells</u> and batteries
- **Full Lunar Economy (~100s MW – 1 GW)**
  - In-space manufacturing, commercial operations, etc.
  - Sources: solar arrays, primary fuel cells, <u>fission surface power</u>, <u>regenerative fuel cells</u> and batteries

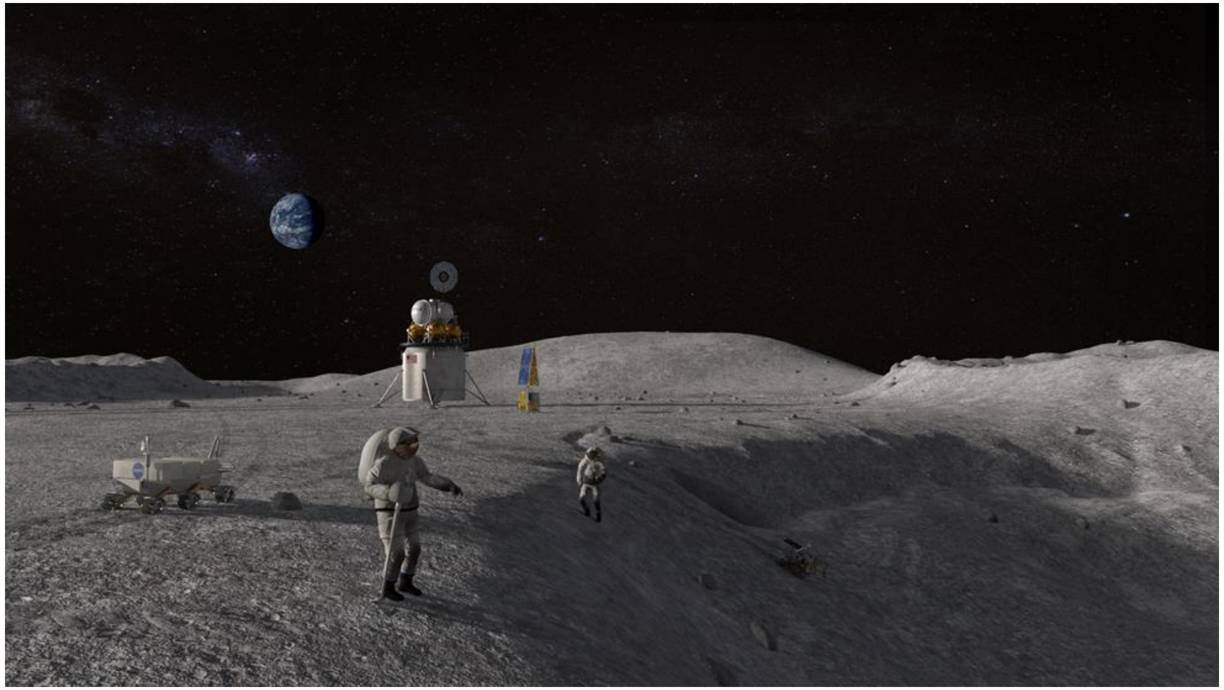
Lunar surface activities and the need for power will continue to grow and evolve

Lunar Surface Sustainable Power Challenges

- **Power Architecture Challenges**
  - Power strategy (generation and storage)
    - Meet power demand (night-time, day)
    - Include dissimilar power sources
  - Distributed architecture
    - Support lunar growth and evolution
    - Mix of generation, storage, and loads

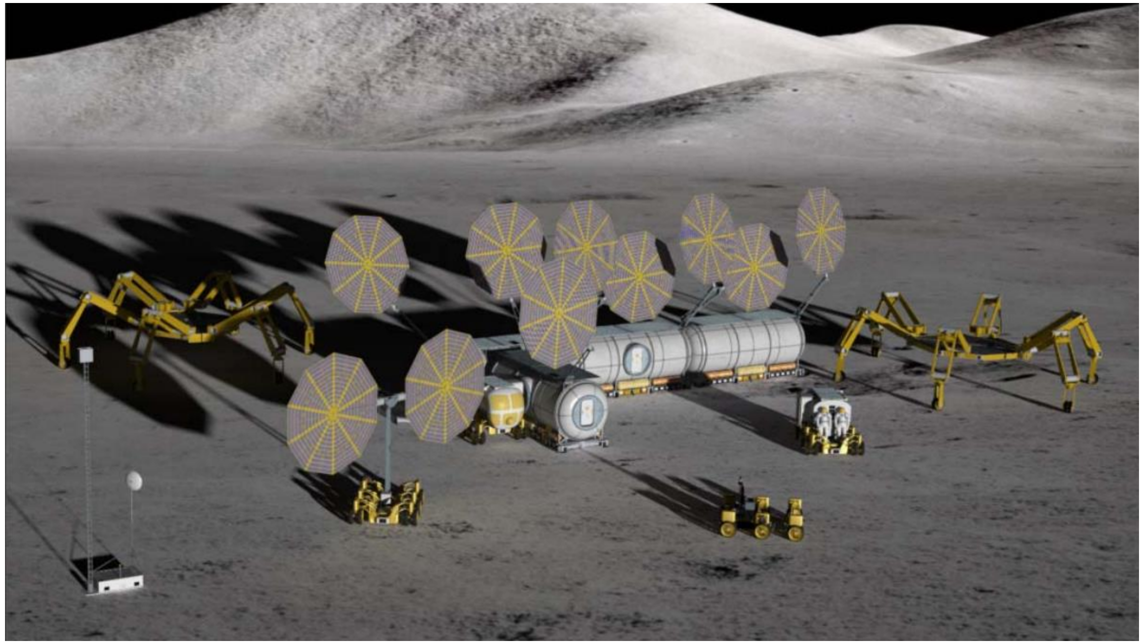
- **Power Availability Challenges**
  - Night-time power demand

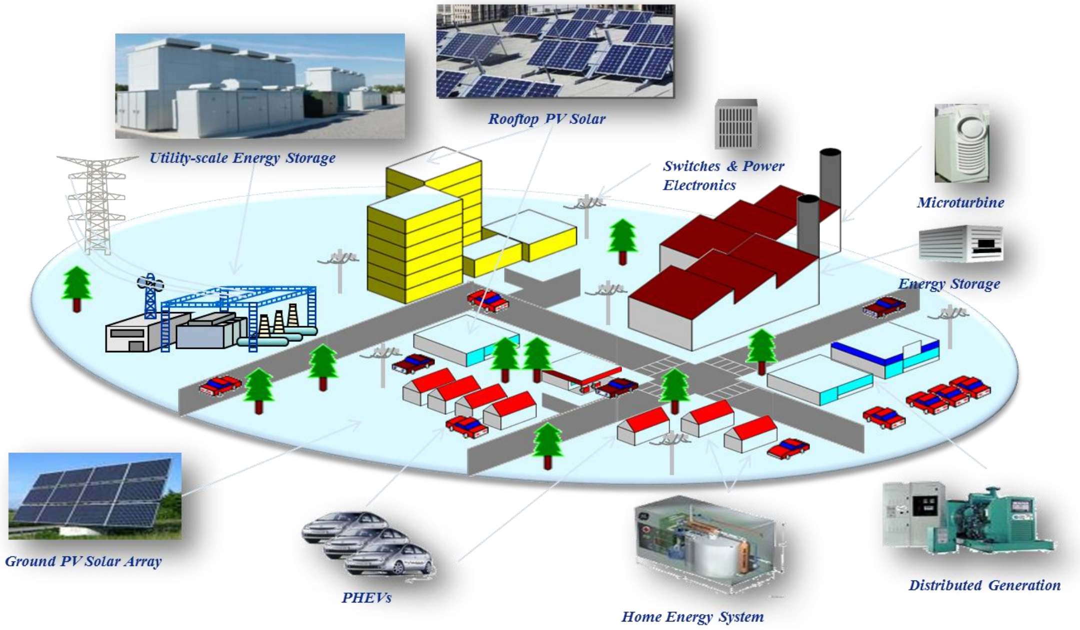
- **Operational Challenges**
  - Robotically deployable PMAD / power systems
  - Autonomously operated PMAD systems



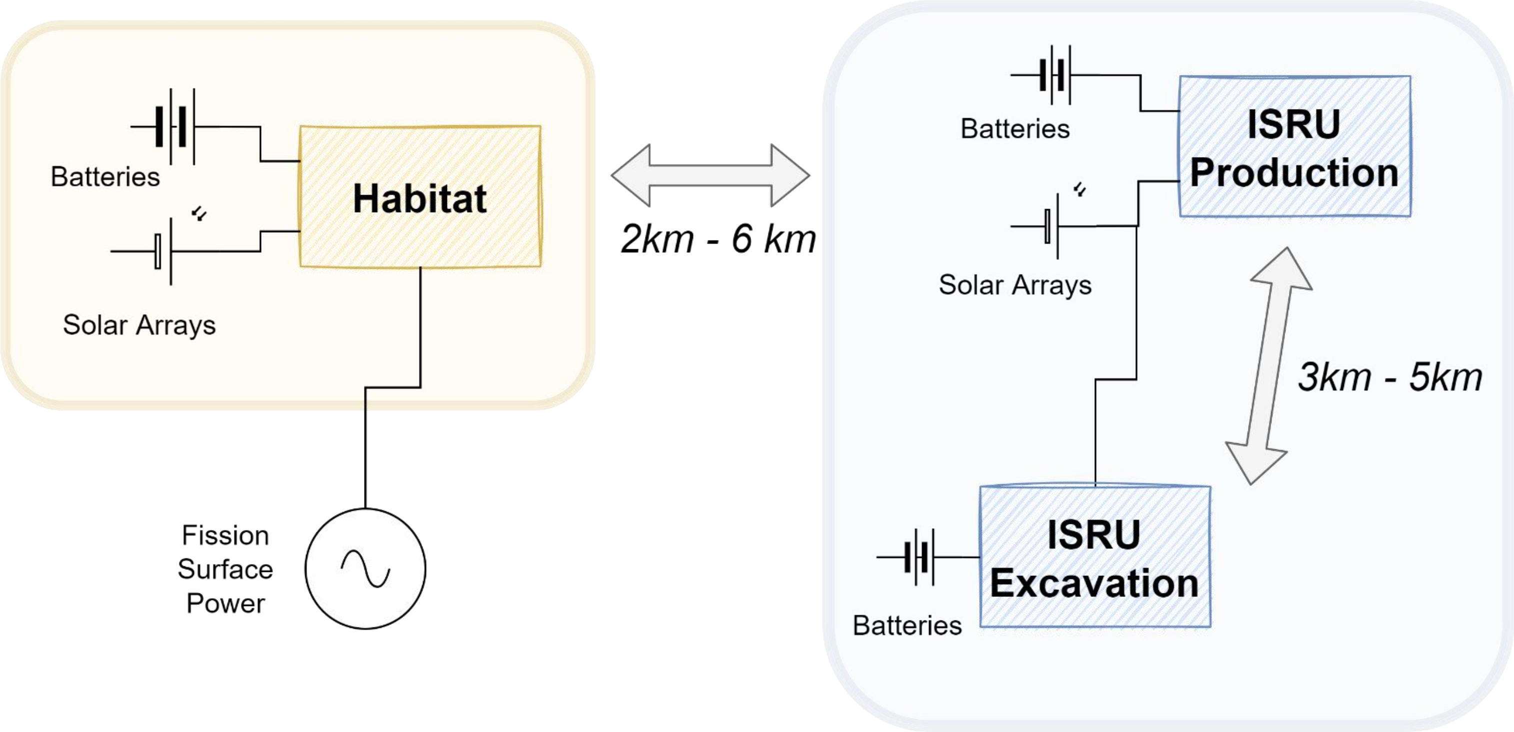
Case for a Lunar Power Grid

- **Lunar power grid to provide electrical power**
  - Flexibility, evolvability, and reconfiguration
  - Optimal dispatch of power sources and energy storage to service loads & enhance reliability
  - Systematic integration of new sources and loads
  - Allow development and use of a common grid interface
  - **Allows for the deployment of future loads that do not need to carry their own power generation**



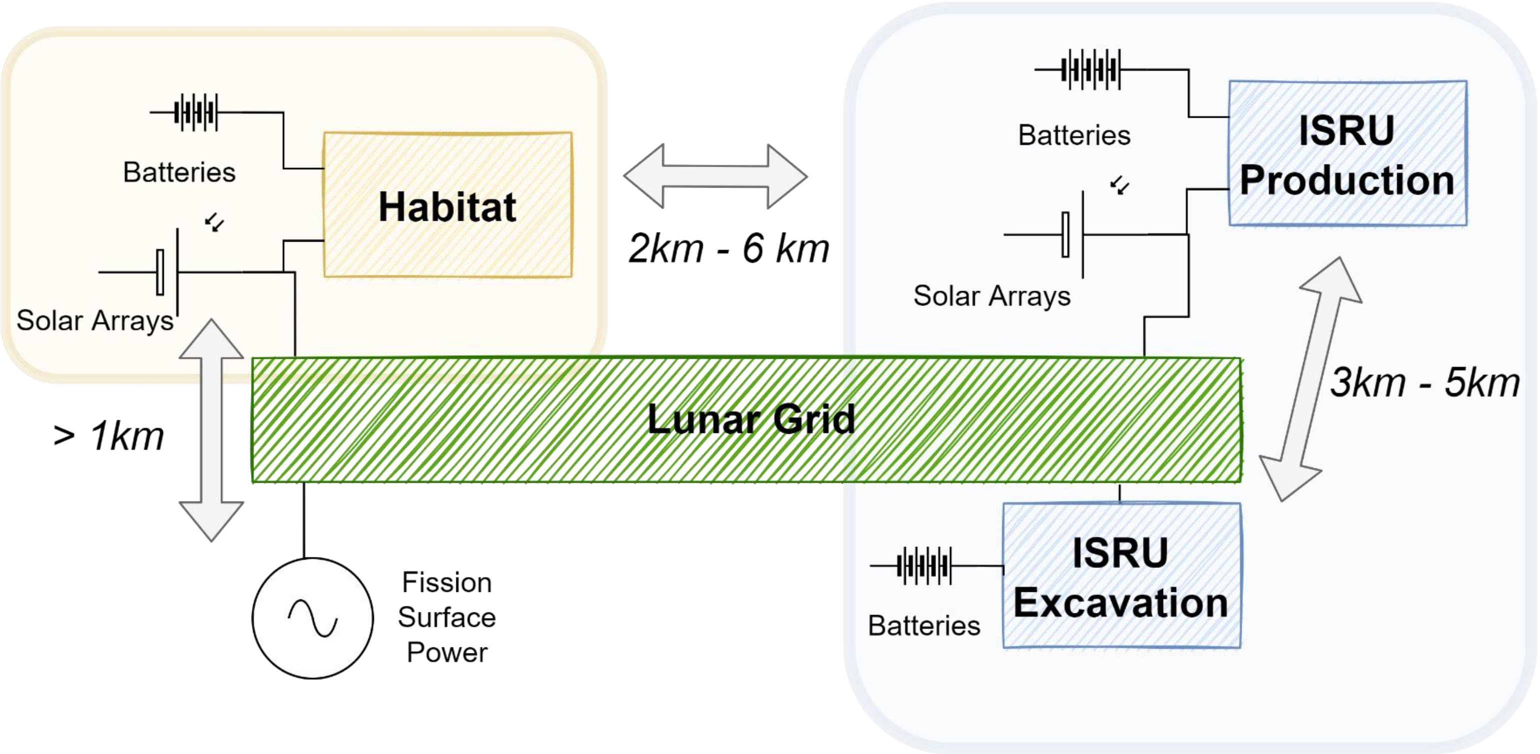


Baseline Artemis



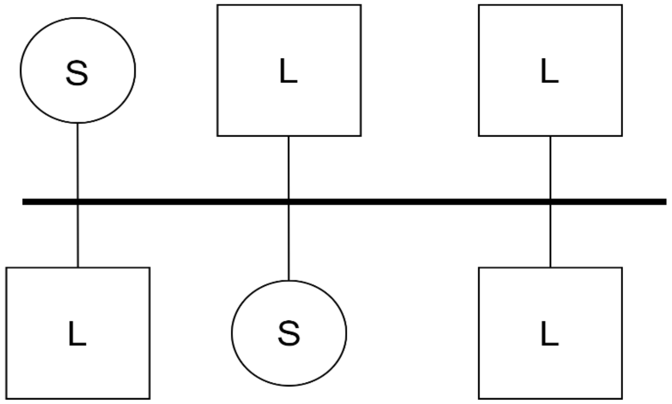
- **Two independent power systems (microgrids)**
  - Each user has their own power (power generation and energy storage)
  - Independently manage their own power

Baseline Artemis with a Lunar Microgrid

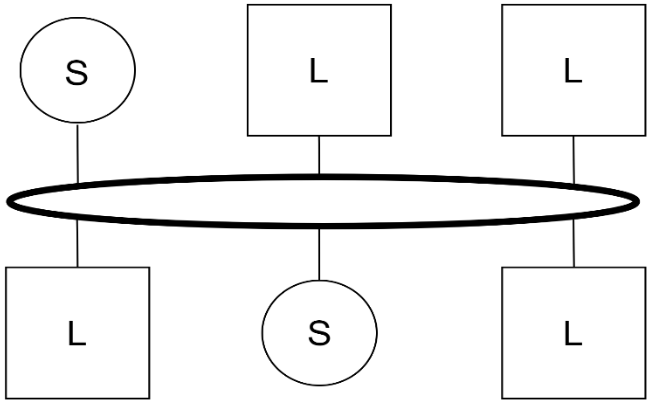


- **Create a regional lunar grid with:**
  - Primary distribution system to enable power sharing between local microgrids
  - Additional power source (FSP) that can be utilized by local microgrids

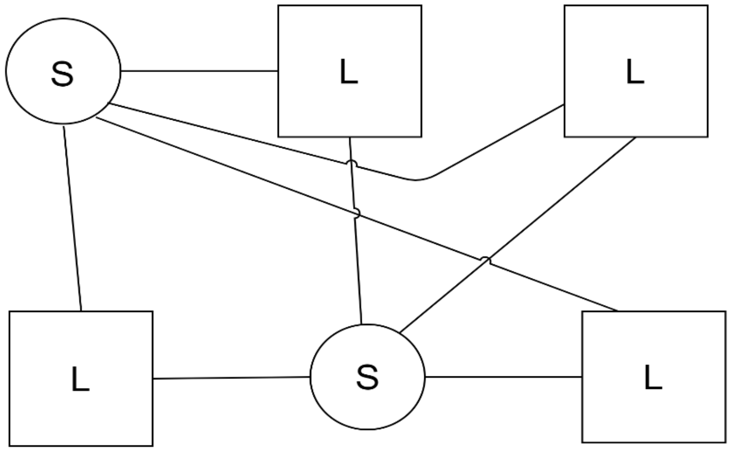
Power System Architectures



a) Radial Network



b) Ring Network



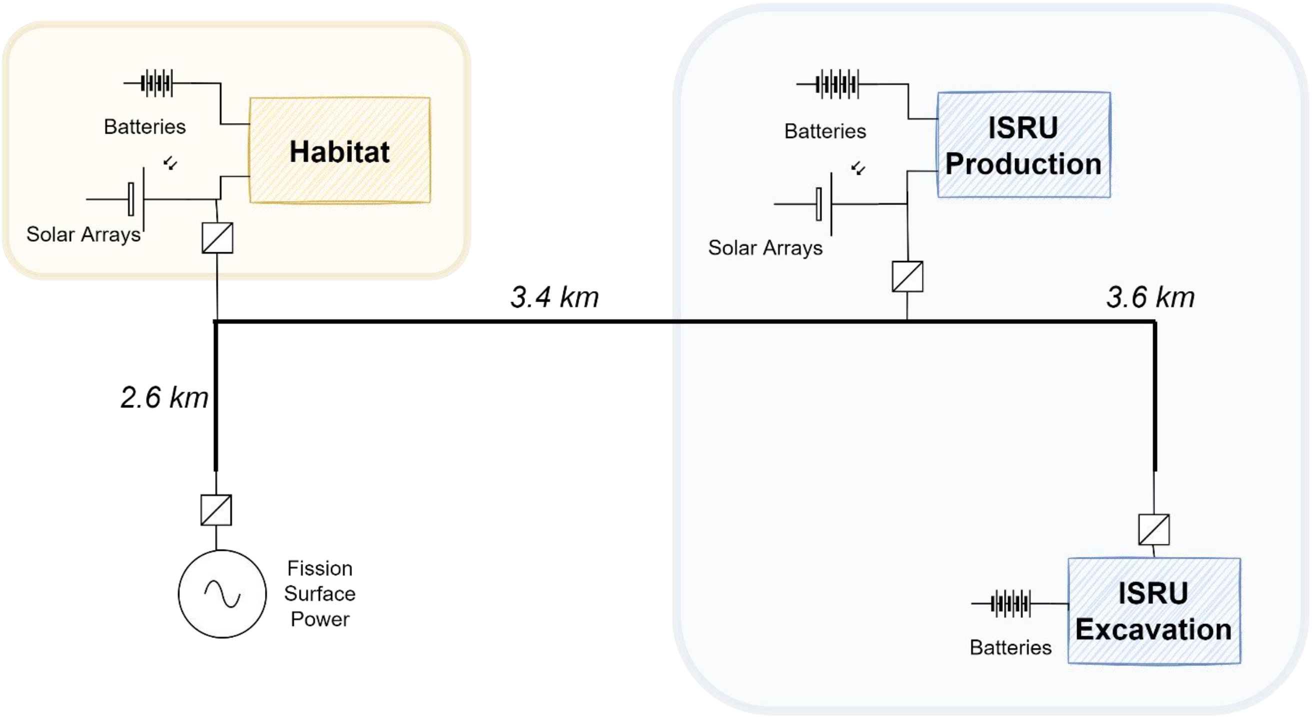
c) Mesh Network

Radial Architecture

- **Radial System Assumptions**
  - Assume high voltage bus is near habitat
    - Brings ISRU and FSP power to habitat, to serve as a backup
  - Excess FSP power can flow to ISRU if habitat power needs are satisfied first

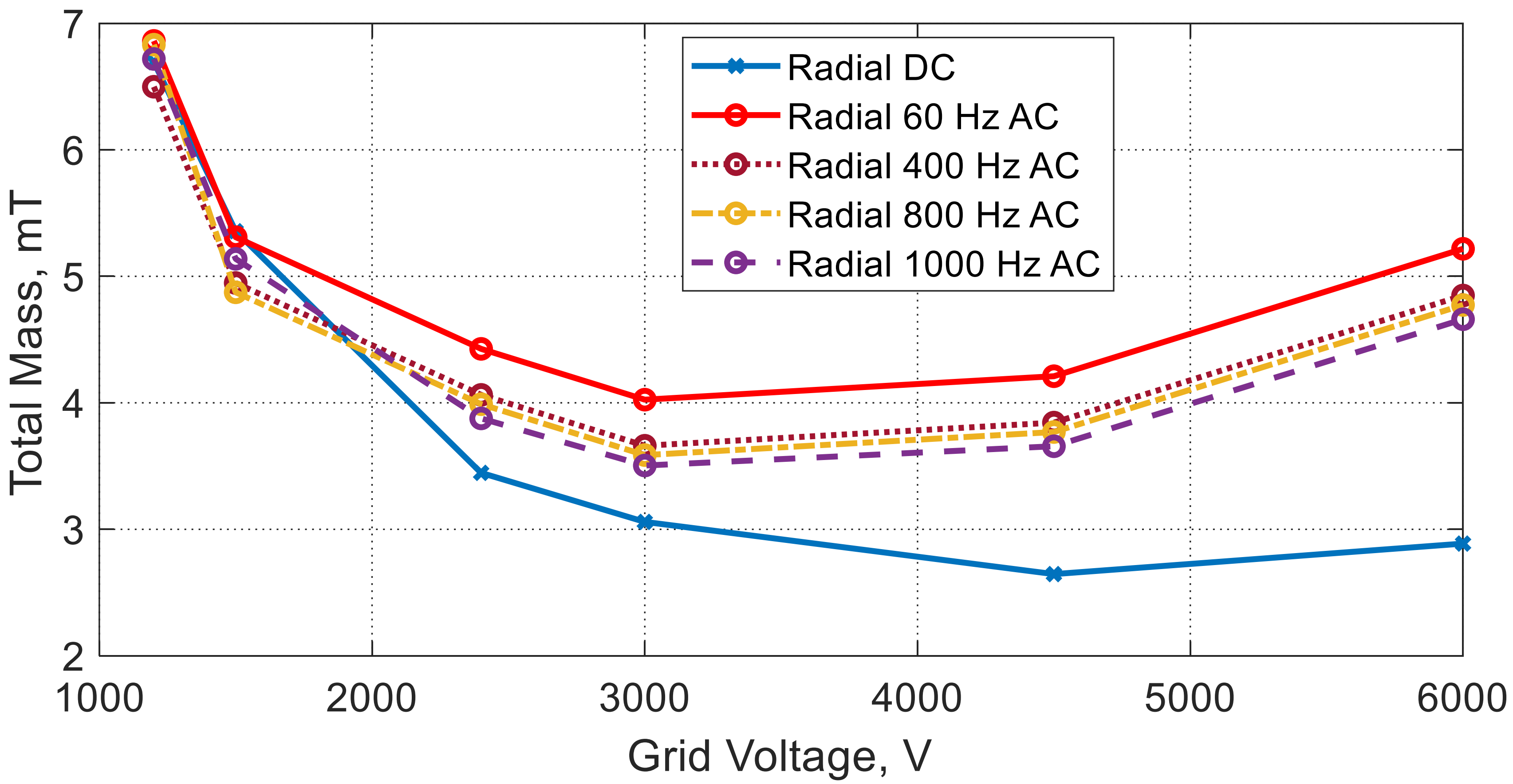
- **Radial Advantages**
  - Simple (lower implementation cost)
  - Lightweight

- **Radial Disadvantages**
  - Lack protection / redundancy during failure



Radial Architecture Results

- **Total transmission mass (converter + cables) versus grid voltage**
  - AC options showing various frequencies
    - 1 kHz had lowest mass (will only present the 1 kHz going forward for AC)

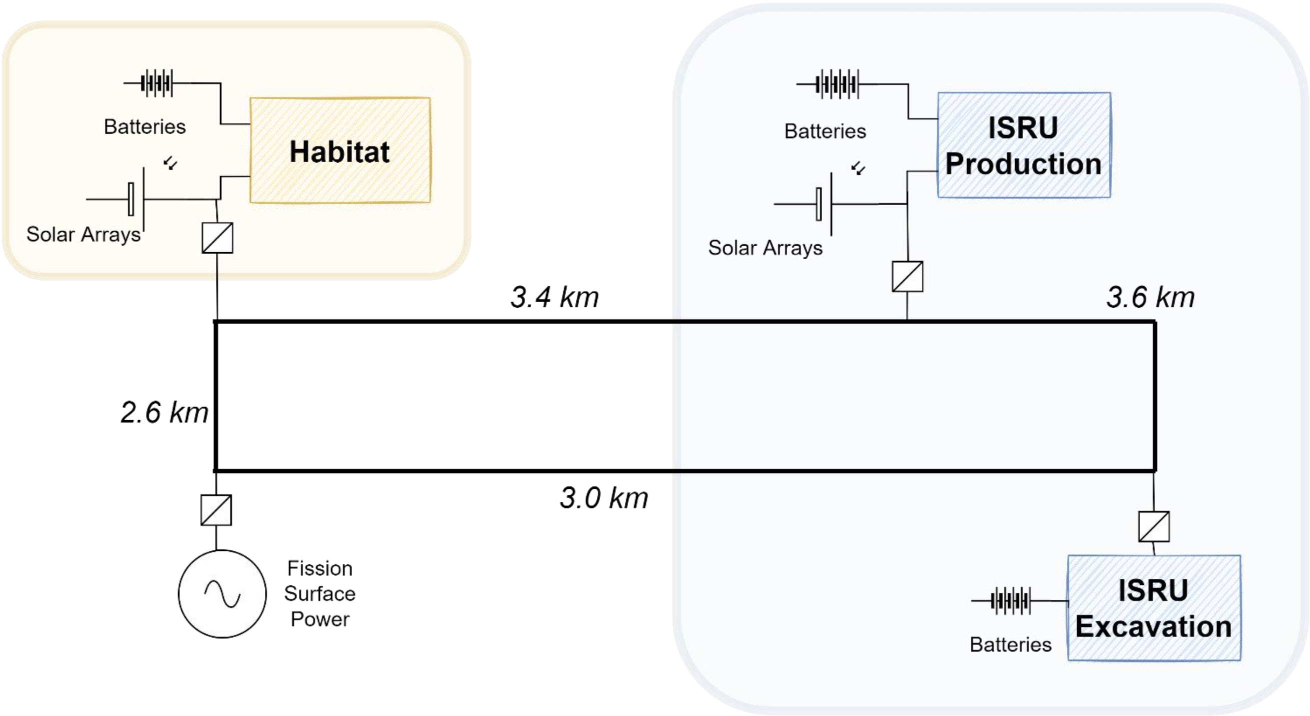


Ring Architecture

- **Ring architecture adds a second tie line between FSP and ISRU**
  - Assume FSP to Habitat line matches overall grid power type

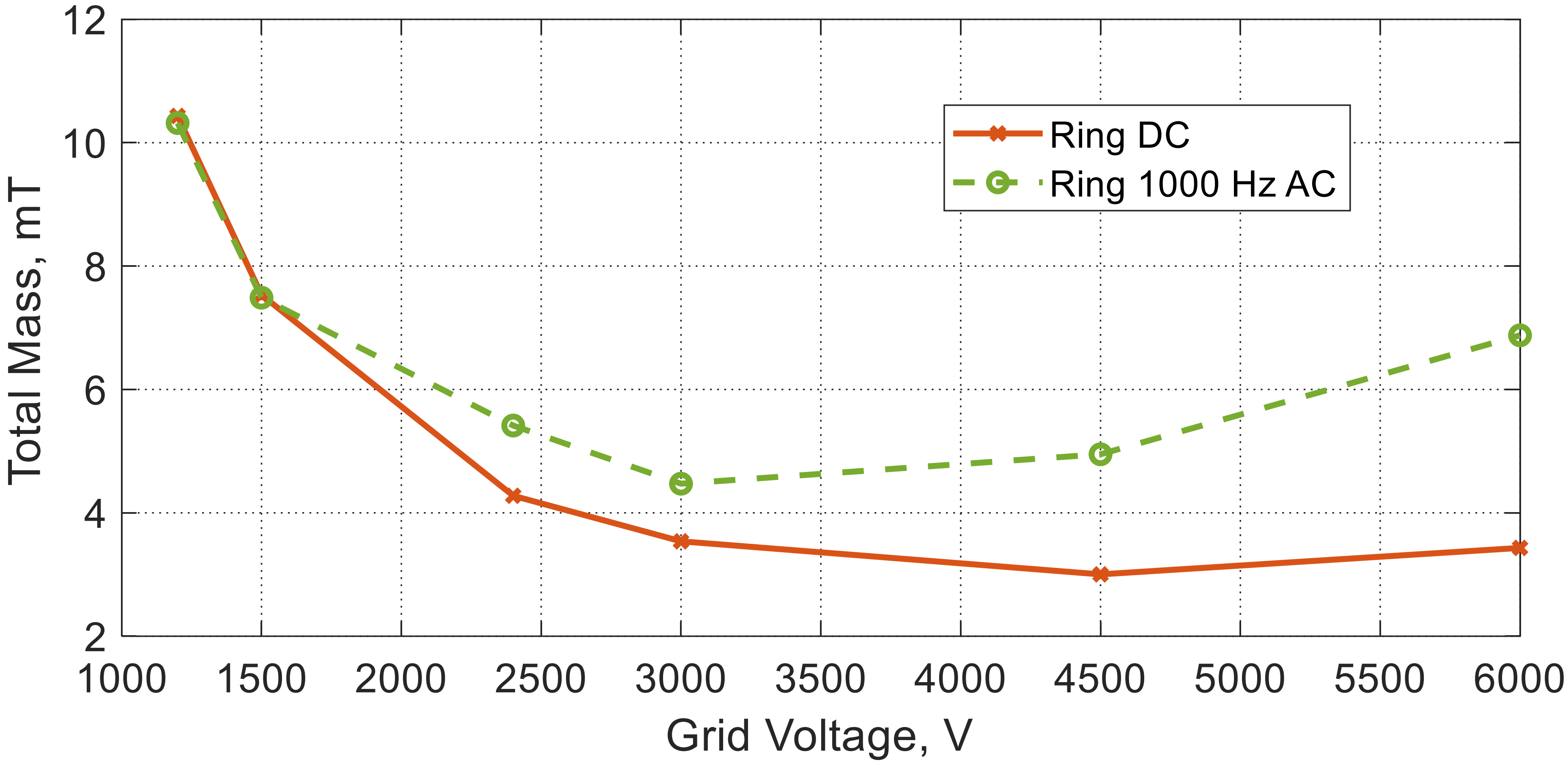
- **Ring Advantages**
  - Adds single line tolerance for only one more tie line
  - Adds more efficient path for FSP power to get to ISRU mining which has no power of its own

- **Ring Disadvantages**
  - ~50% heavier than radial network
  - Can only lose one line and maintain ability to transmit power between any two assets



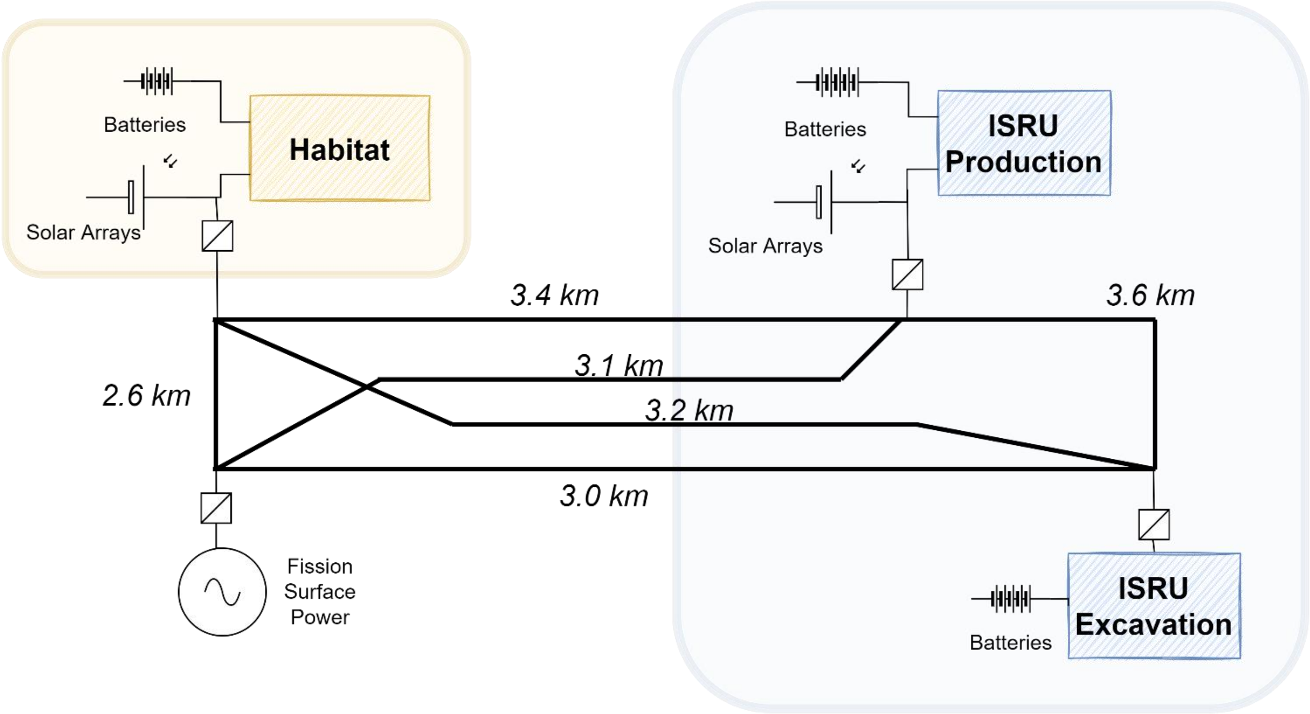
Ring Architecture Results

- **AC and DC show same trends with ~30% to 50% more overall mass**
  - Adds 1 additional long-distance cable



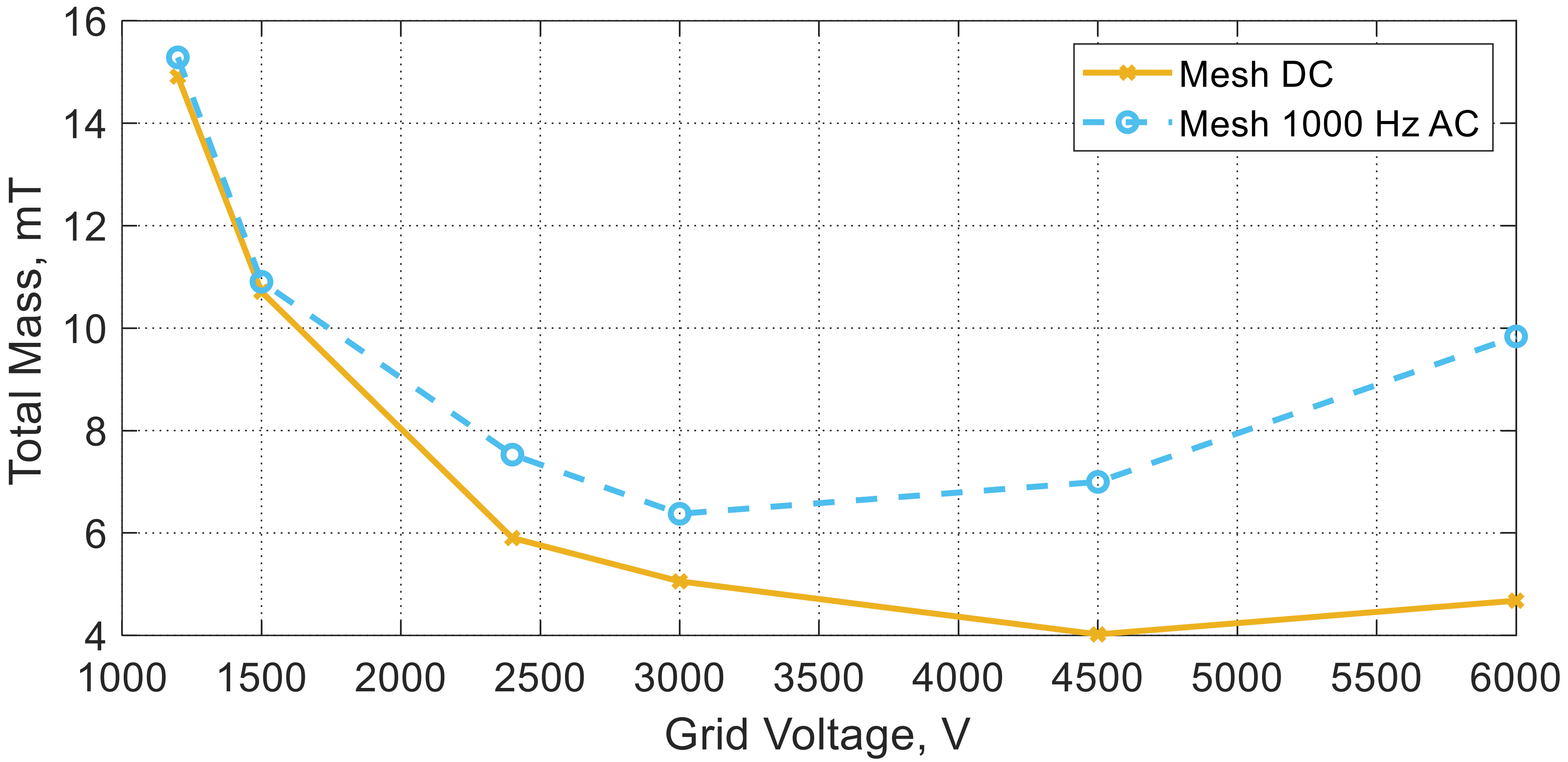
Zonal Architecture

- **Mesh adds two additional tie lines**
  - FSP to ISRU Production
  - Habitat to ISRU Mining
- **Mesh Advantages**
  - Additional lines add more efficient paths to transmit power throughout network
  - Dual line fault tolerance
- **Mesh Disadvantages**
  - ~100% heavier than radial network
  - ~50% heavier than ring



Mesh Architecture Results

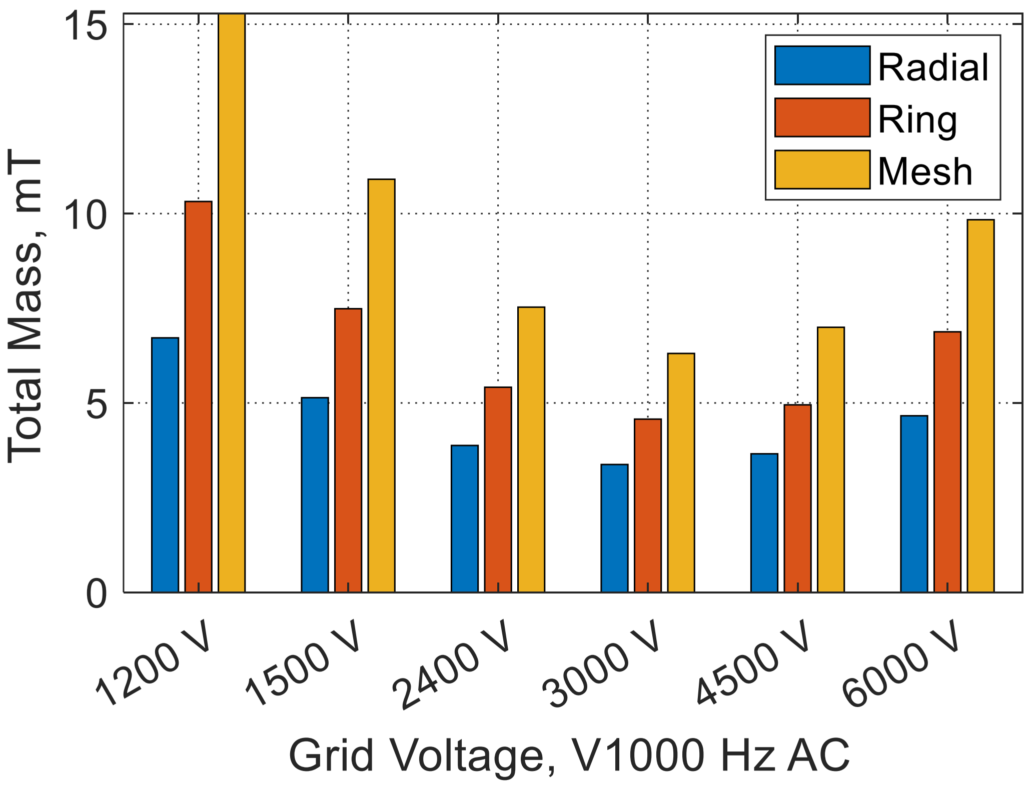
- **Same trends with more mass**



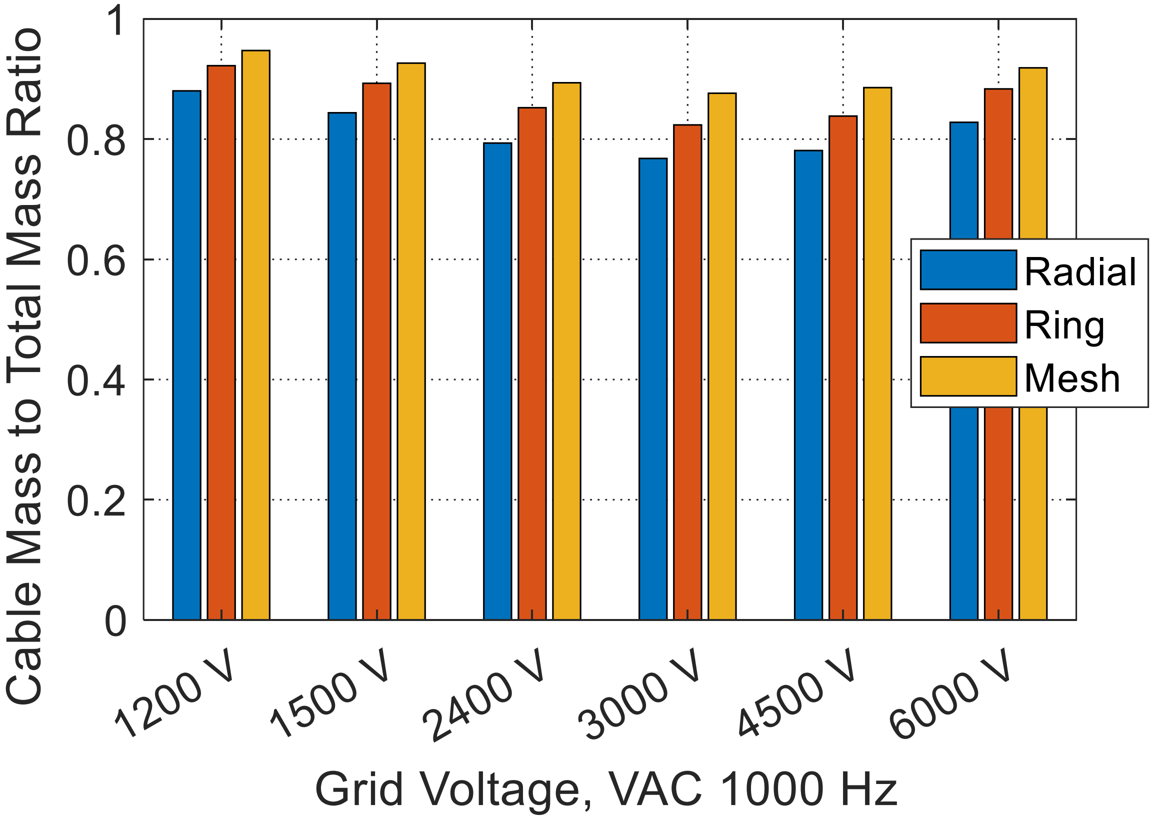
Architecture Comparison

- **Comparing radial, ring, and mesh architectures for 1 kHz AC**

Mass vs voltage and architecture



Cable-to-total mass ratio vs voltage/architecture



Overall Analysis Results

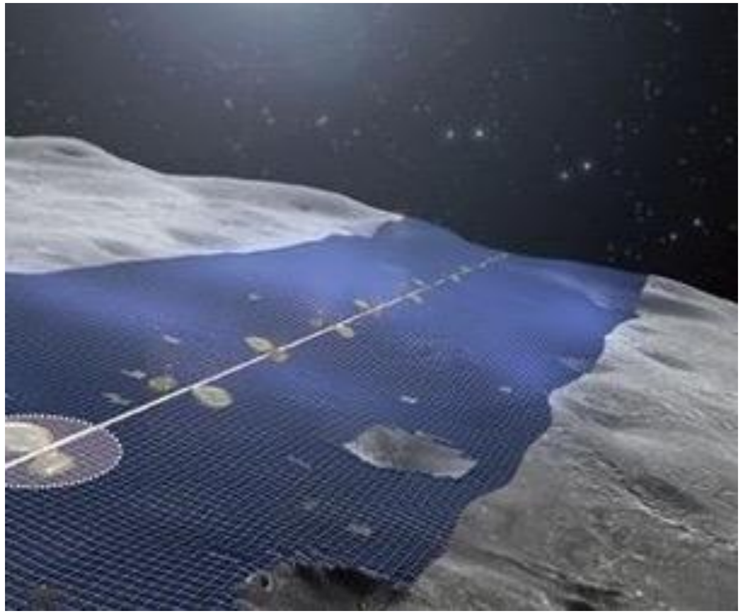
- **Summary**
  - AC and DC grid masses comparable over useful voltage range (1 kV – 3 kV)
    - Ring architecture mass 50% higher than radial, achieves single line fault tolerance
    - Mesh architecture mass 100% higher than radial, achieves dual line fault tolerance

- **Architecture Selection**
  - Driven by mass and fault tolerance requirements/constraints
    - Early lunar missions/operations bring their own power – no requirement for grid
    - Start with radial and expand over-time to achieve increased reliability (fault-tolerance)

- **Voltage Selection**
  - DC grids at this point may not achieve voltage needed to minimize mass (3 kV)
    - DC parts availability limits DC voltage (< 2 kV)
  - Select 3kV AC with 1kHz frequency
    - AC lightest solution

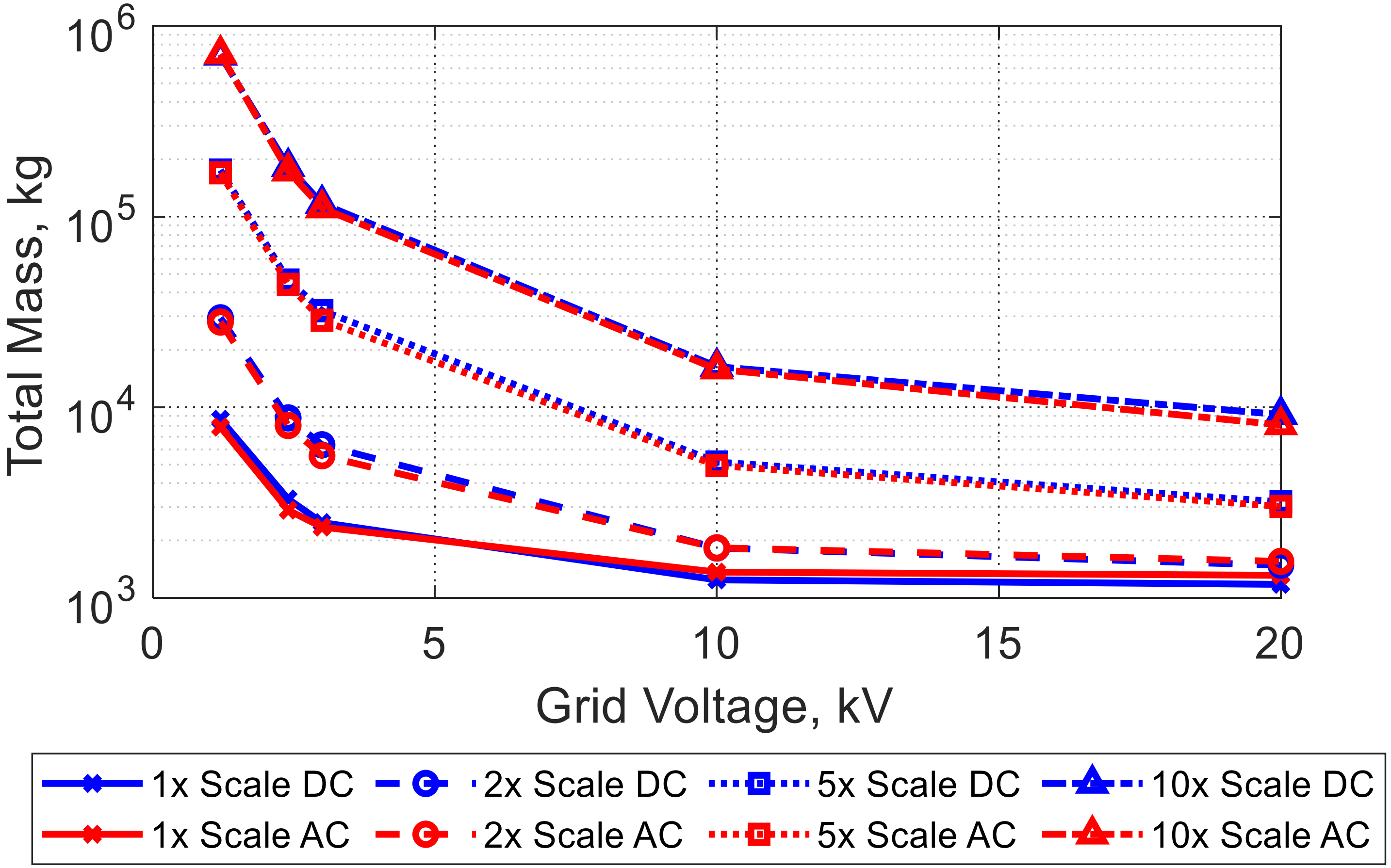
Beyond Artemis

- **Commercial lunar economy**
  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 (solar arrays, power cables, etc)
  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.
- **Expansion beyond lunar south pole (Globalization)**
  - Massive increase in distance (10x)
  - Massive increase in power demand (100x)
  - Require power utility that can provide and sell power



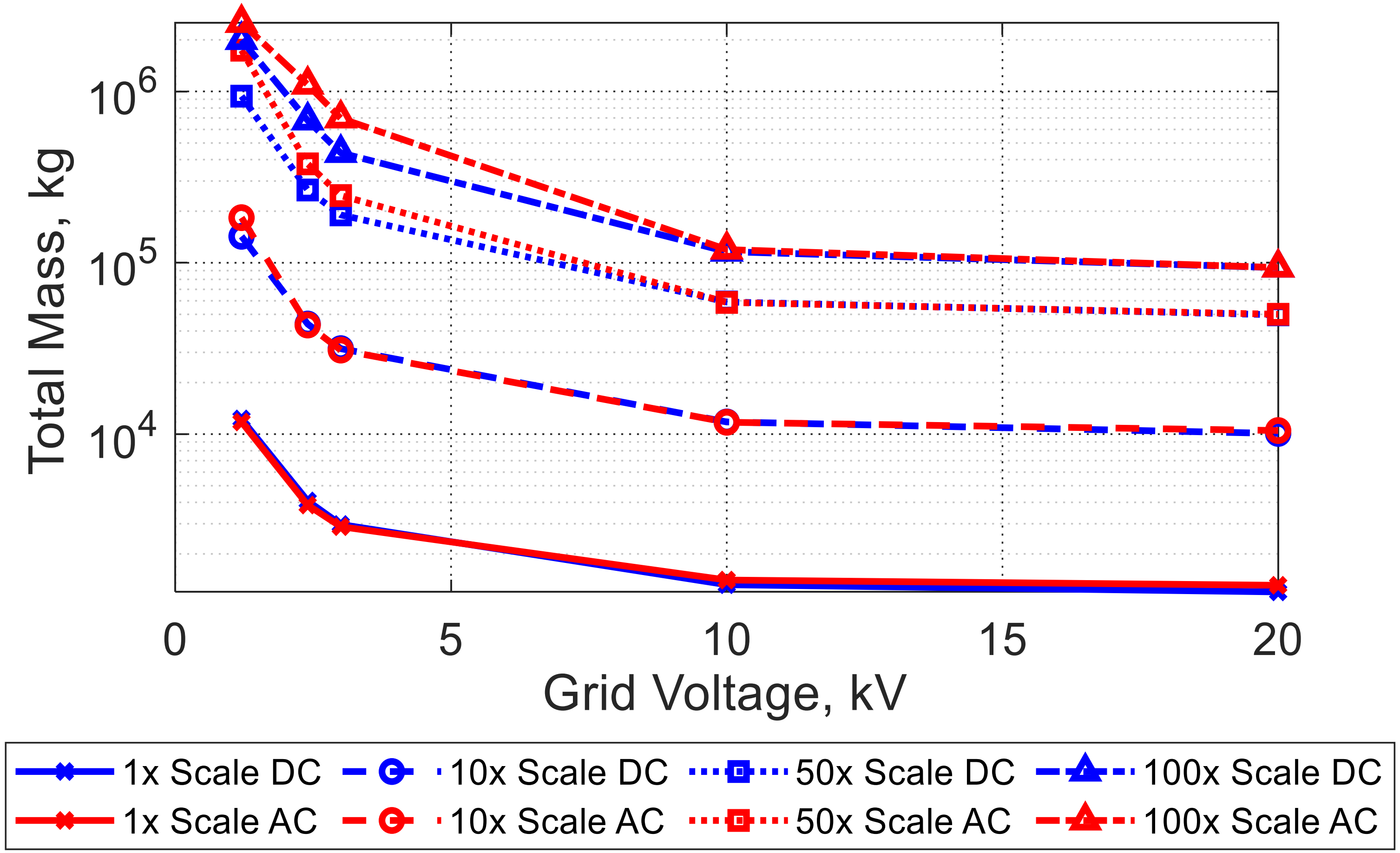
Radial Architecture Mass for Increased Distance

- **Total distance scaled up to 10x (~100 km)**



Radial Architecture Mass for Increased Power Demand

- **Total Mass for increased power demand up to 100 x (1 GW)**



Commercial Lunar Economy

- **Power demand and size of the power system will grow**
  - Mass benefits to increasing voltage
    - There is a point of diminishing returns for the distribution system
    - Increasing efficiency (helps reduce the number of power sources)

- **AC vs DC Power Type**
  - Marginal mass difference between AC vs DC at a particular voltage
  - Equipment / component availability will play a role
  - AC has benefit in stepping up/down voltages
    - Long distance transmission (20 kV)
    - Regional transmission (3 kV)
    - Secondary Distribution (120 V)

Conclusions

- **Lunar Surface operations will grow and evolve over time**
  - Small lunar science missions (VIPER, PRIME-1)
  - Lunar Surface Habitat and In-Situ Resource Utilization demonstrations (Artemis)
  - In-Space Economy & Commercialization of Lunar Surface
- **Lunar Surface Power System**
  - Power system needs to grow and evolve and be able to reconfigure
  - Complex power strategy to meet unique power demands
  - Lunar microgrid can achieve this
- **Lunar Microgrid**
  - Meet the needs of a lunar surface power system
  - Start small (radial system) and grow over time
  - Analytical studies demonstrate marginal difference between AC/DC power distribution
    - Driven by technology availability (Rad-Hard availability limits DC voltage)
    - AC has extra benefit of being able to easily step up/down voltage (terrestrial power system)
      - Maybe critical in lunar globalization

Thank you