Microgrids on the Lunar Surface

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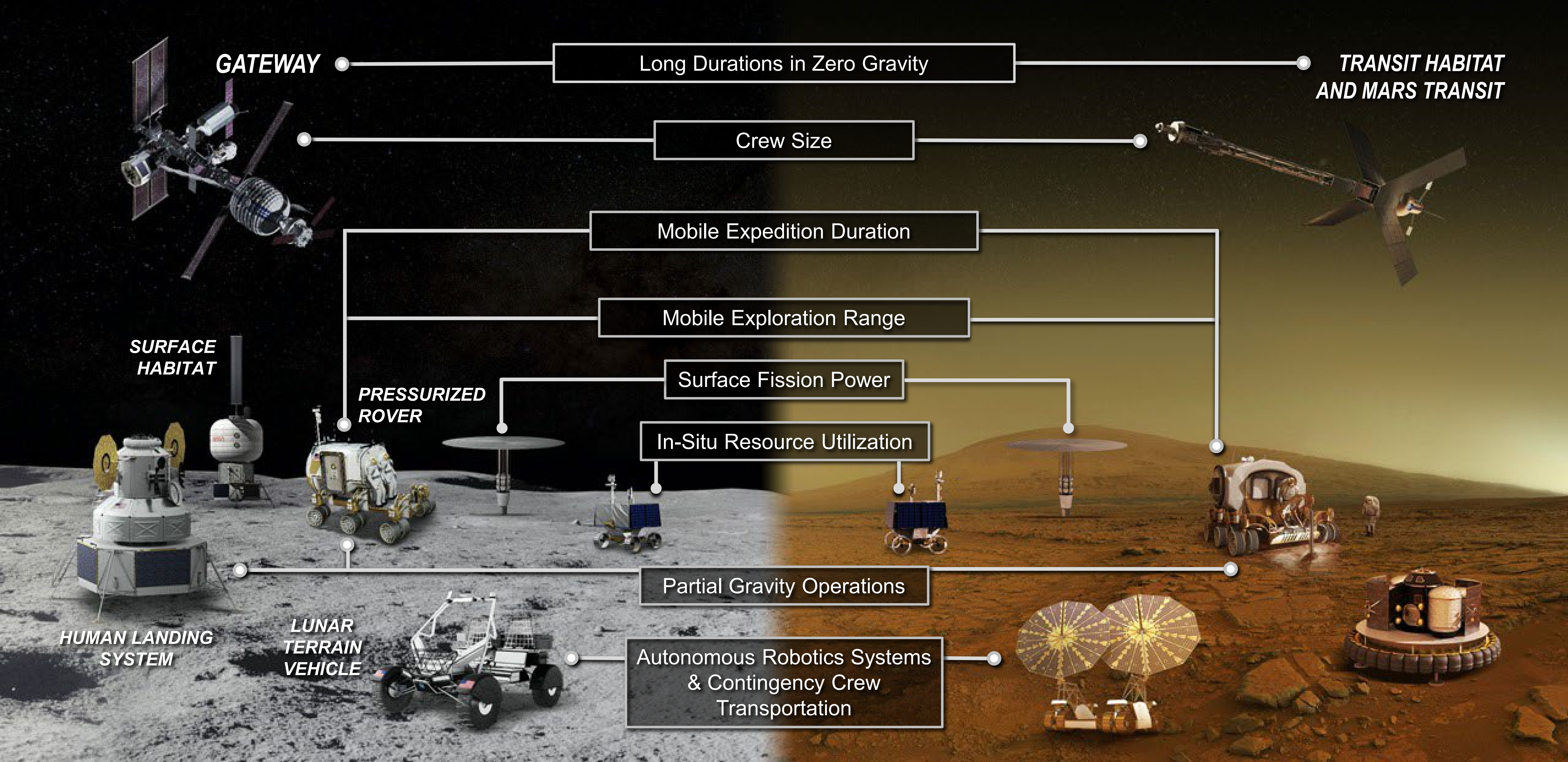
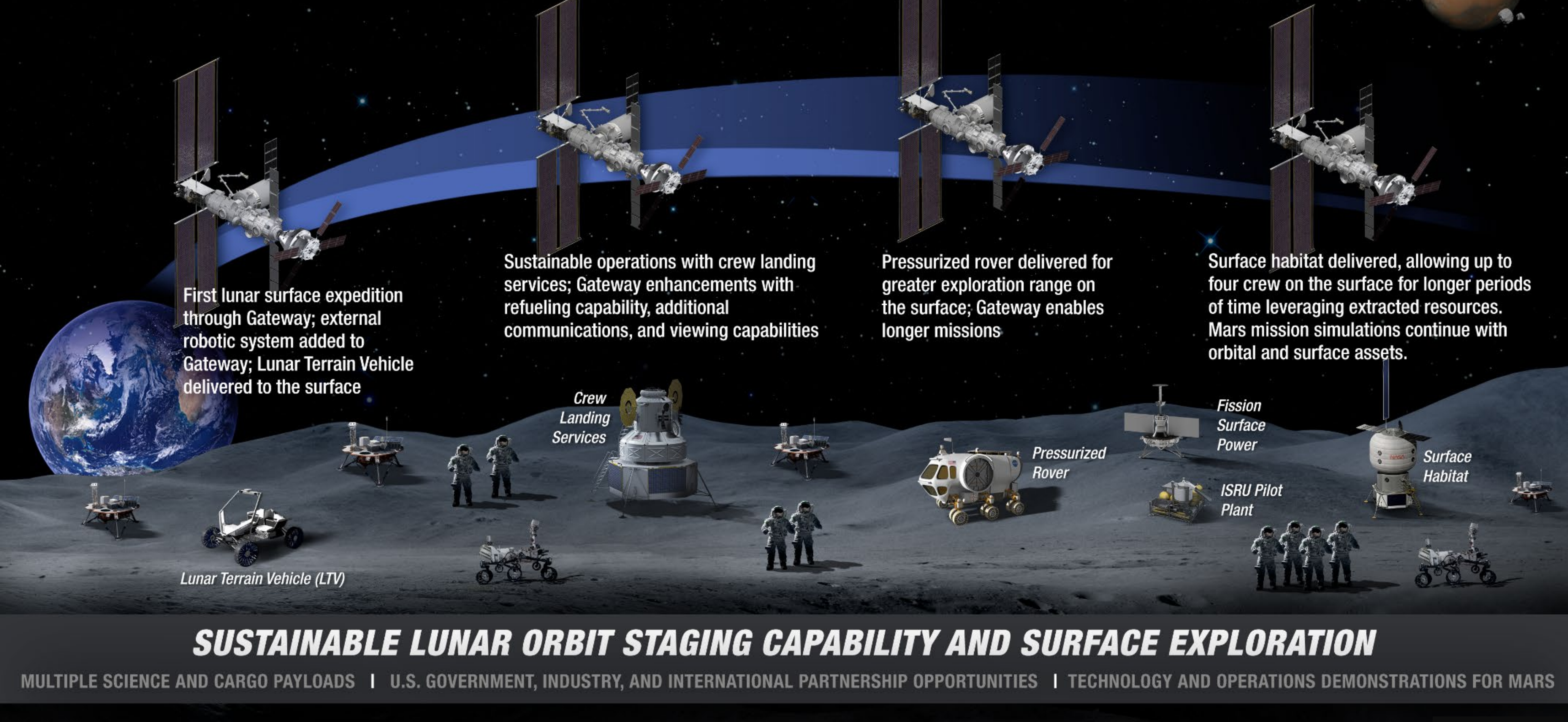
Moon to Mars Exploration

Operations on and around the Moon will help prepare for the first human mission to Mars



Artemis Base Camp Buildup



31 March 2022

POWER

The key commodity needed to exploit the Lunar Surface

Equatorial Illumination Limits

- Cyclical periods of 14 days illuminated, 14 days dark
- Consistent

Illumination

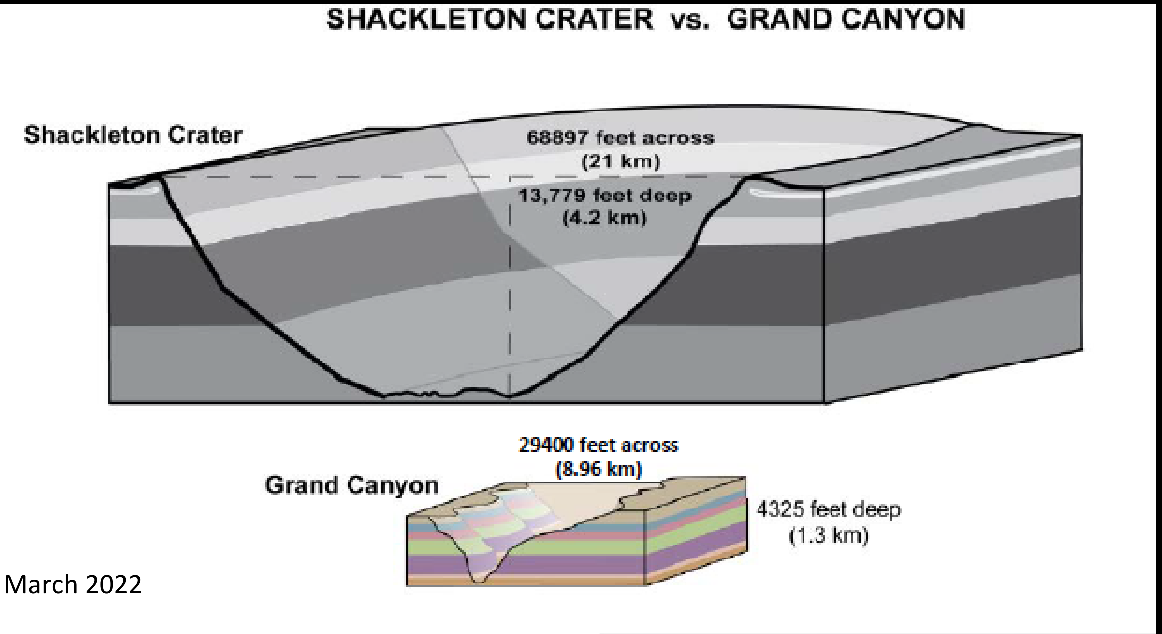
The scarce resource needed to produce power

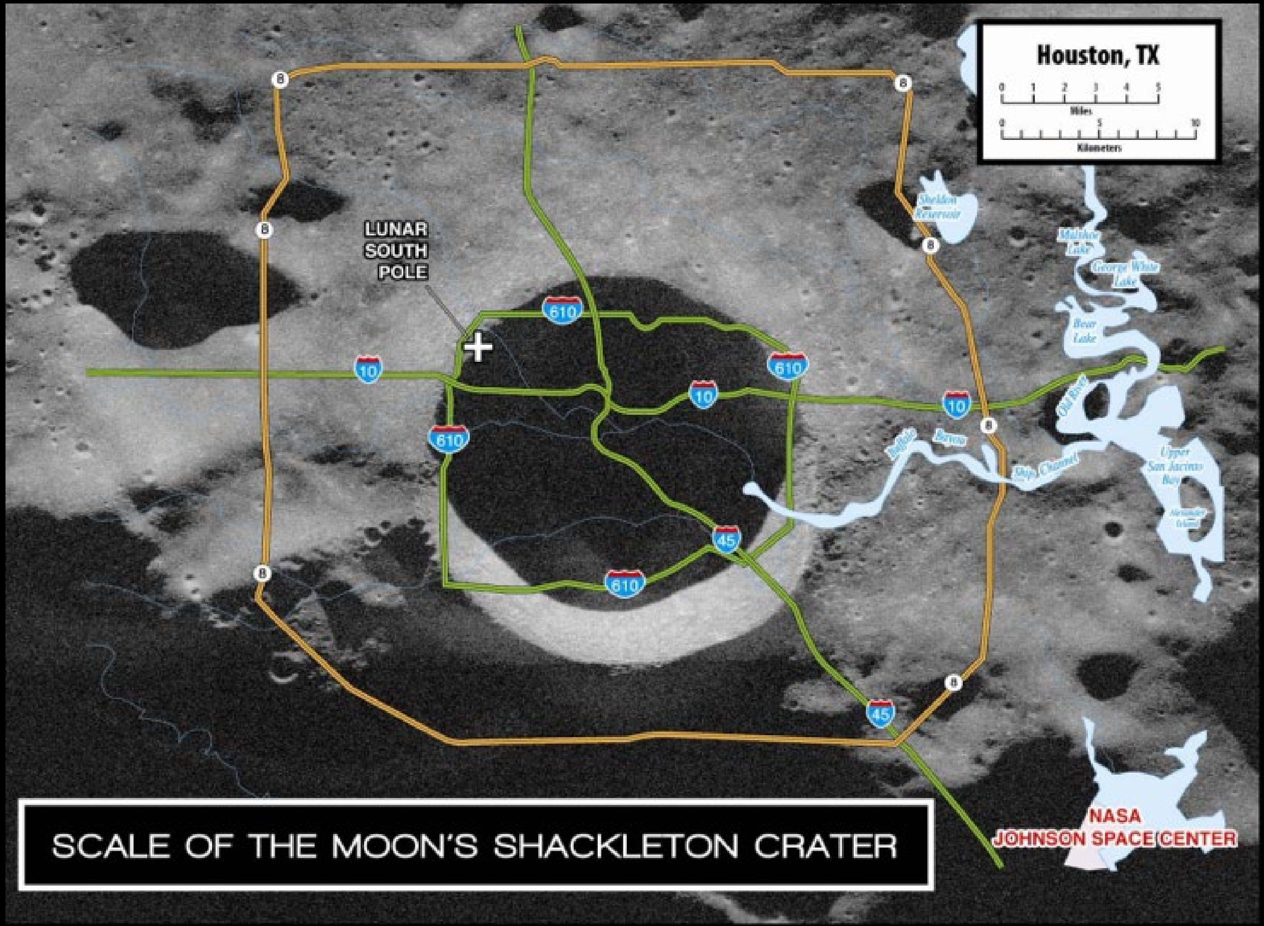
Polar Illumination Limits

- Intermittent with up to 100 hours darkness
- Highly dependent on location/elevation

Shackleton Crater

- ~20 km in diameter
- ~4 km deep and ~3x deeper and wider than the Grand Canyon at Enfilade Point
- Located at Lunar South Pole
- Rim and Connecting Ridge are primary targets for future lunar landings





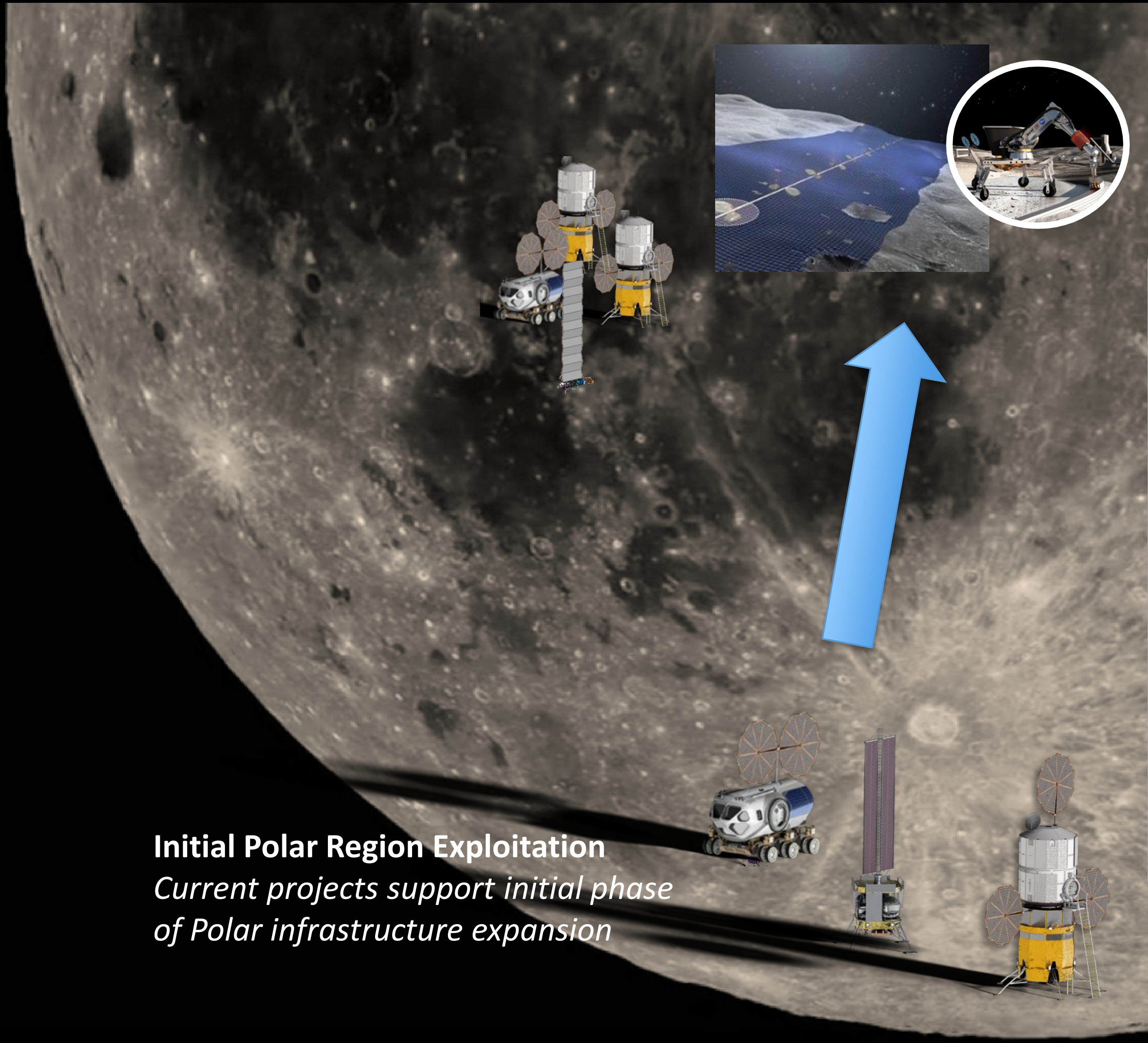
Artemis Base Camp Zone

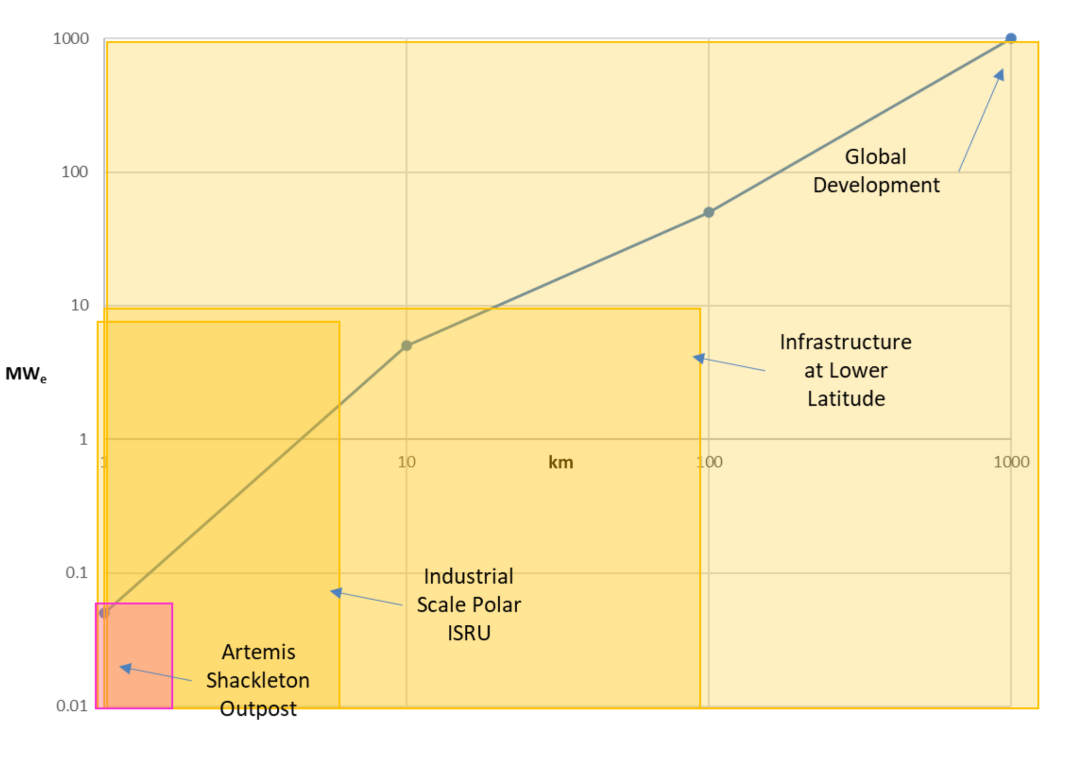
Power Related Infrastructure Objectives for Lunar and Mars

Lunar Infrastructure (LI) Goal: Create an interoperable global lunar utilization infrastructure where U.S. industry and international partners can maintain continuous robotic and human presence on the lunar surface for a robust lunar economy without NASA as the sole user, while accomplishing science objectives and testing for Mars.	
LI-1	Develop an incremental lunar power generation and distribution system that is evolvable to support continuous robotic/human operation and is capable of scaling to global power utilization and industrial power levels.
LI-4	Demonstrate advanced manufacturing and autonomous construction capabilities in support of continuous human lunar presence and a robust lunar economy.
LI-7	Demonstrate industrial scale ISRU capabilities in support of continuous human lunar presence and a robust lunar economy.
LI-8	Demonstrate technologies supporting cislunar orbital/surface depts, construction and manufacturing maximizing the use of in-situ resources, and support systems needed for continuous human/robotic presence.

Mars Infrastructure (MI) Goal: Create essential infrastructure to support initial human Mars exploration campaign.	
MI-1	Develop Mars surface power sufficient for an initial human Mars exploration campaign.
MI-4	Demonstrate Mars ISRU capabilities to support an initial human Mars exploration campaign.

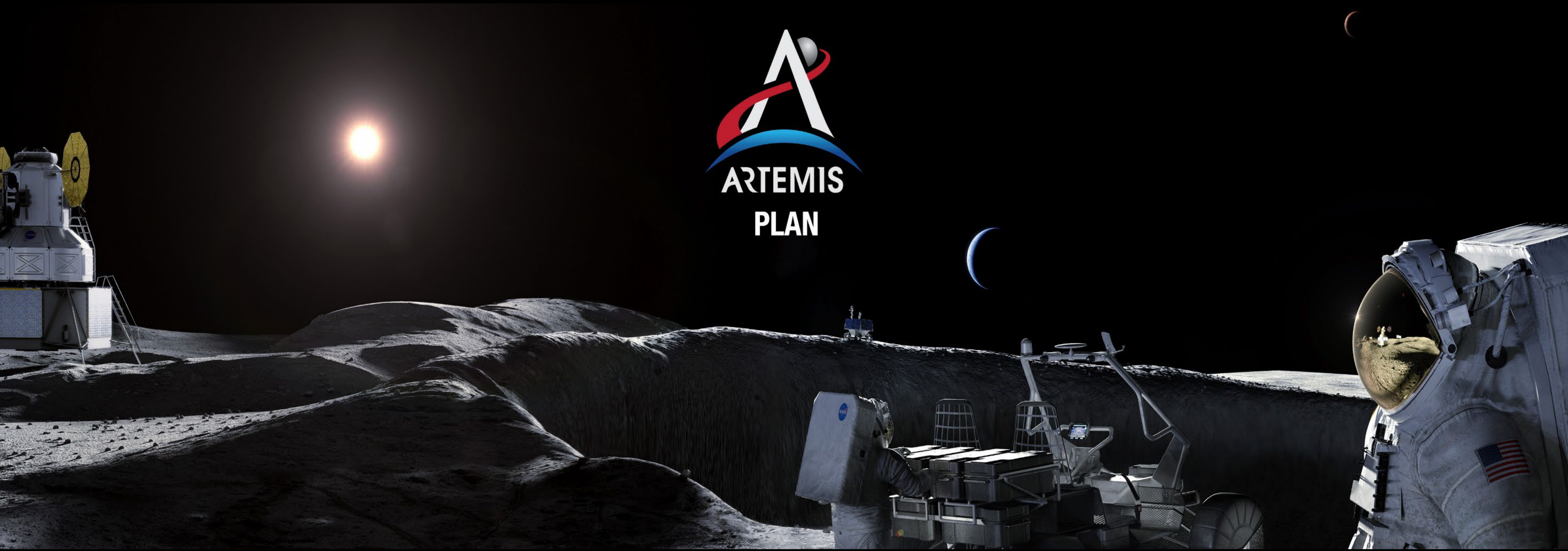
Ultimate Global Exploitation



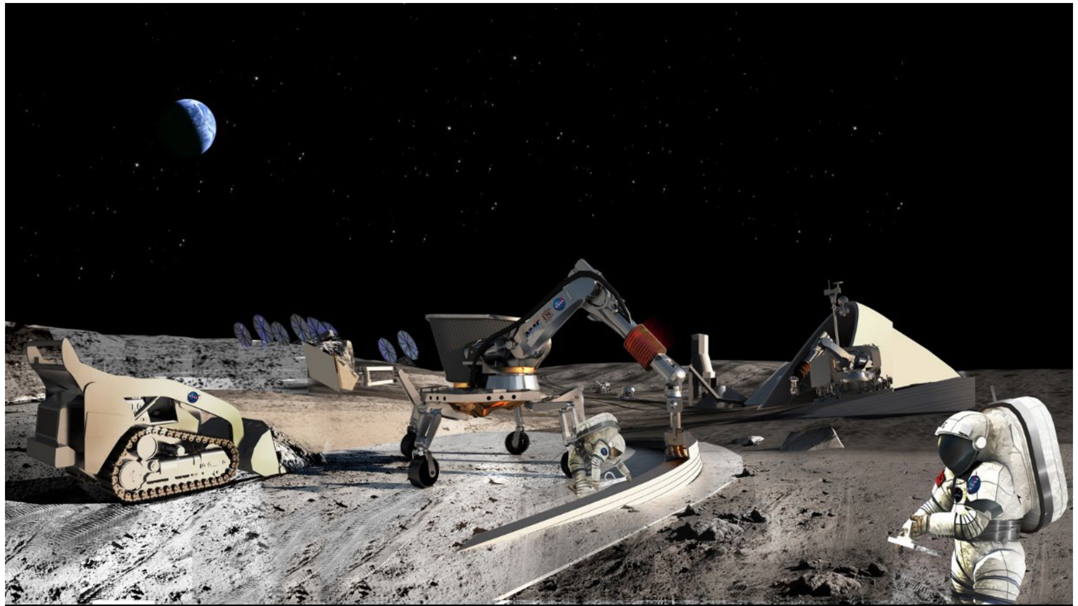


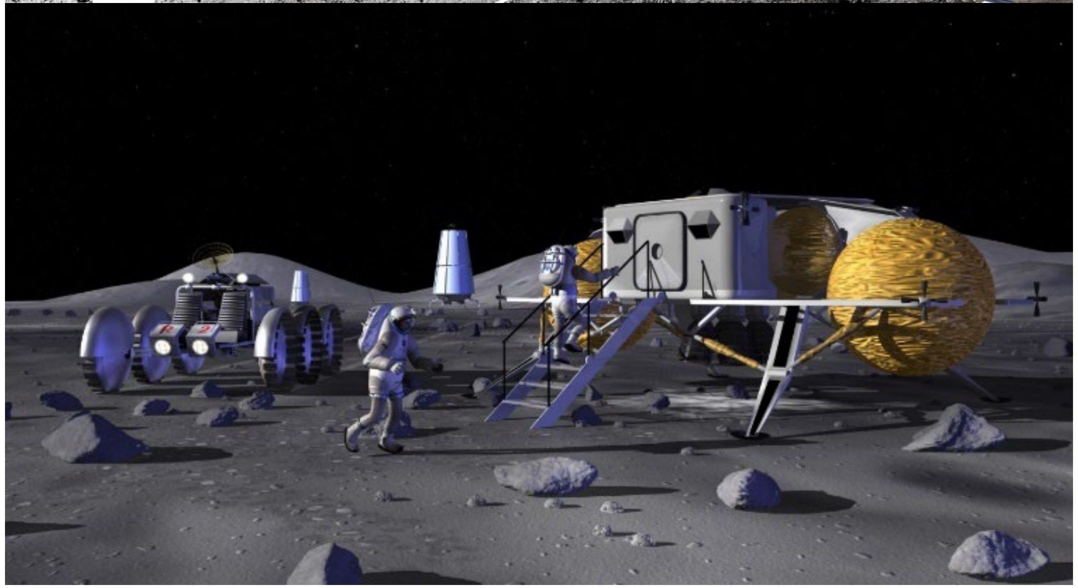
Initial Polar Region Exploitation
Current projects support initial phase of Polar infrastructure expansion

Artemis Lunar Surface Power System



Early Lunar Surface Power Users



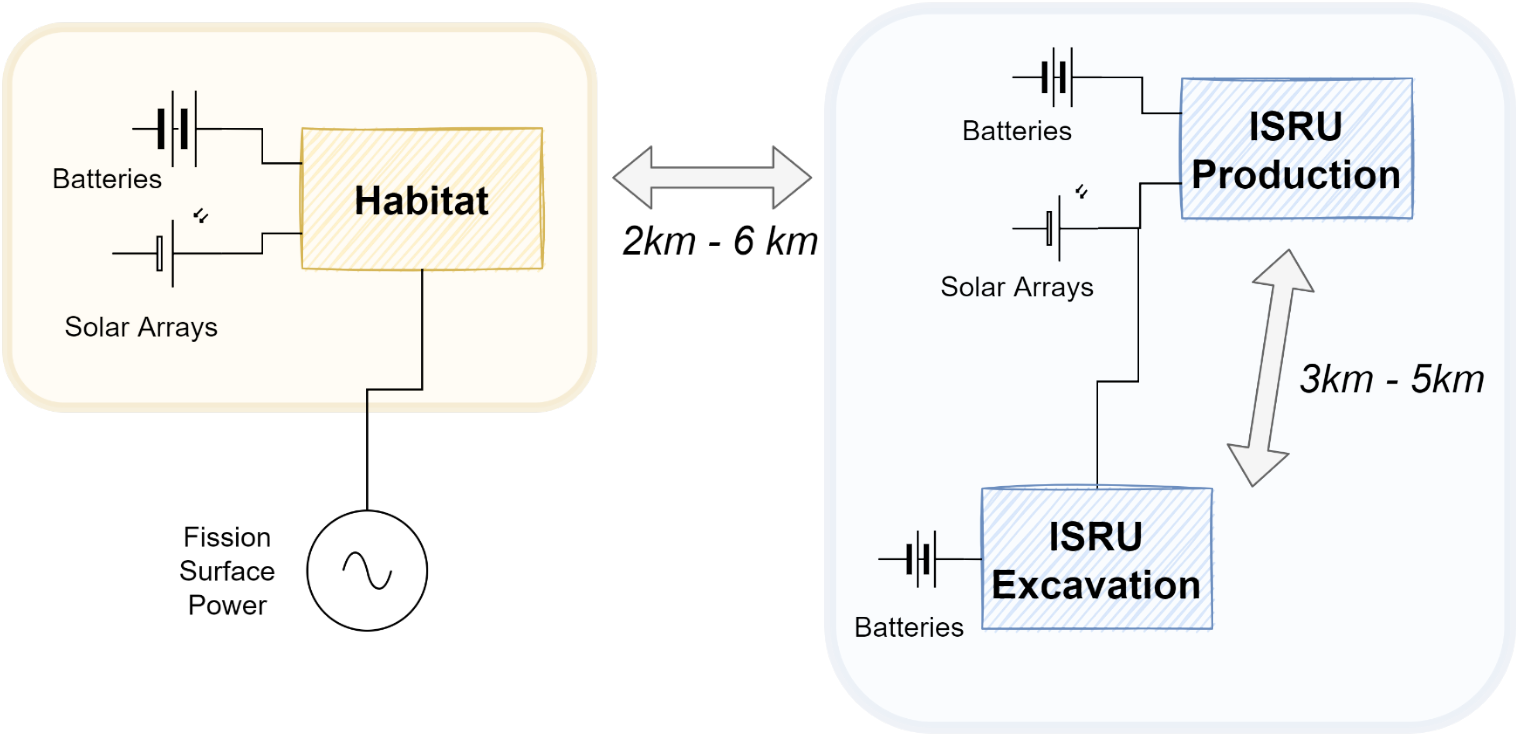


- **In-Situ Resource Utilization (ISRU)**
  - Largest power user 60+ kW
  - Power is needed over long distances (3-5 km)
    - Mine water ice in crater, transport to crater rim, process into H_2, O_2
  - Restricted to operate during periods of heavy insolation

- **Habitat**
  - Second larger power user during habitation
    - 20 – 50 kW
  - Crew of 4 for 30+ days – 4 times per year
  - Habitation restricted to periods of heavy insolation

- **Lunar science / Exploration**
  - Various rovers @ 500 W each
  - Power beaming @ TBD power

Baseline Artemis Power System

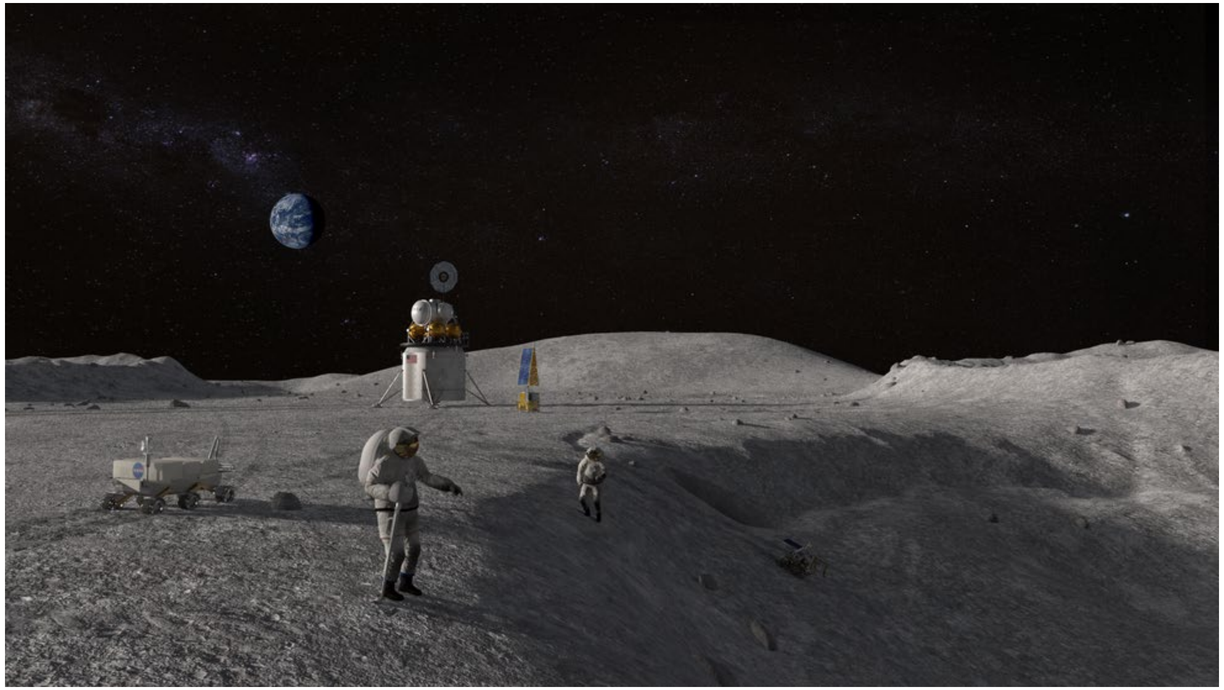


- **Each user has their own power (power generation and energy storage)**
- **Independently manage their own power**

Lunar Surface Sustainable Power Challenges

Lunar surface activities and the power system will continue to grow and evolve over time

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

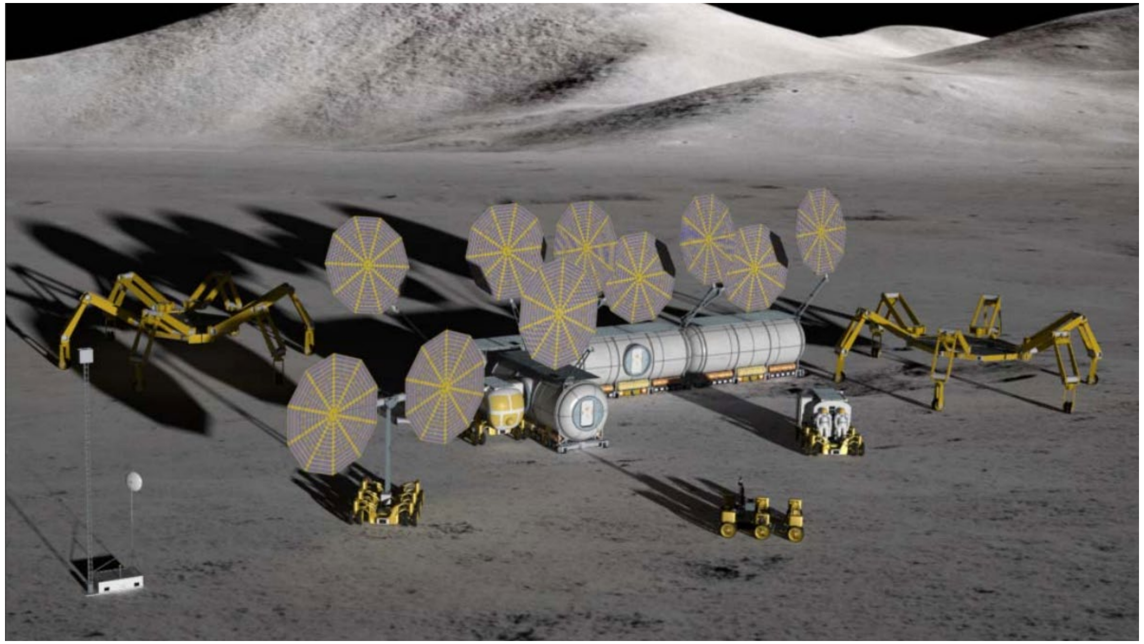


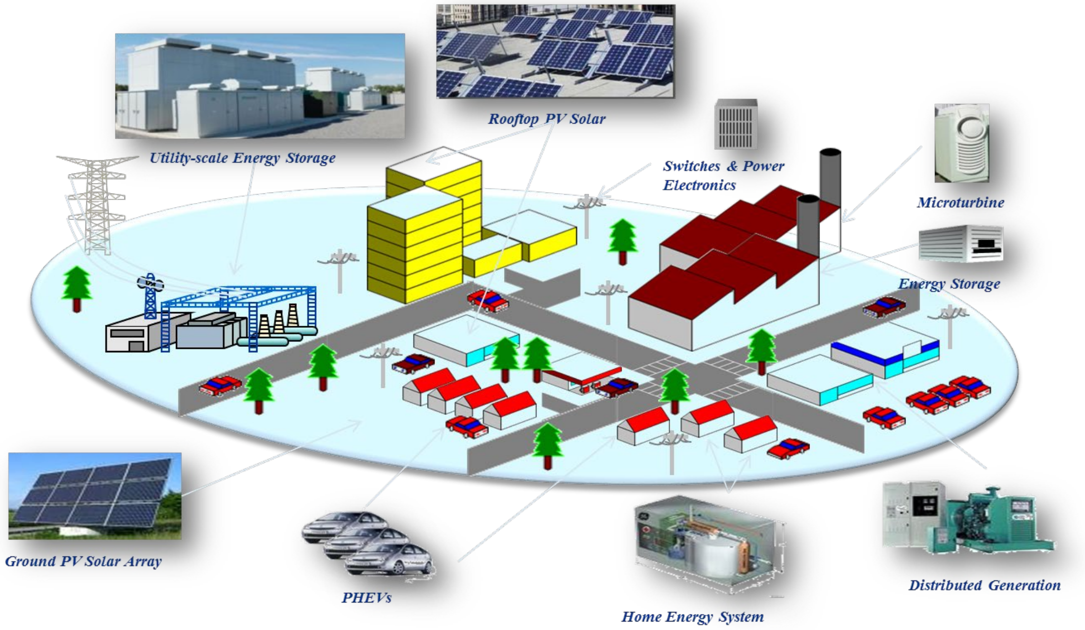
- **Power Availability Challenges**
  - Night-time power demand
    - Extend daylight operations

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

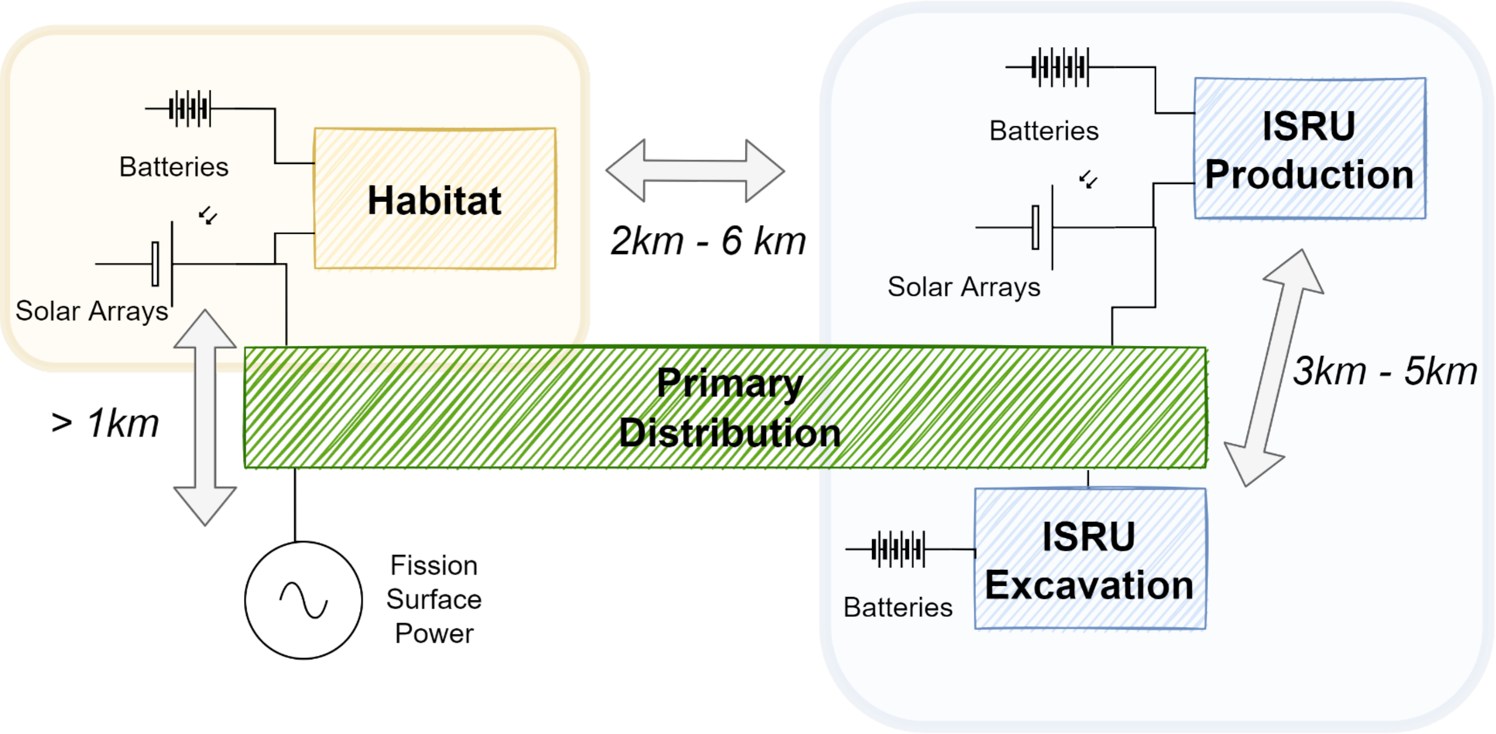
Case for a Microgrid

- **Lunar microgrid 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 science loads that do not need to carry their own power generation**





Notional Artemis Base Camp Microgrid



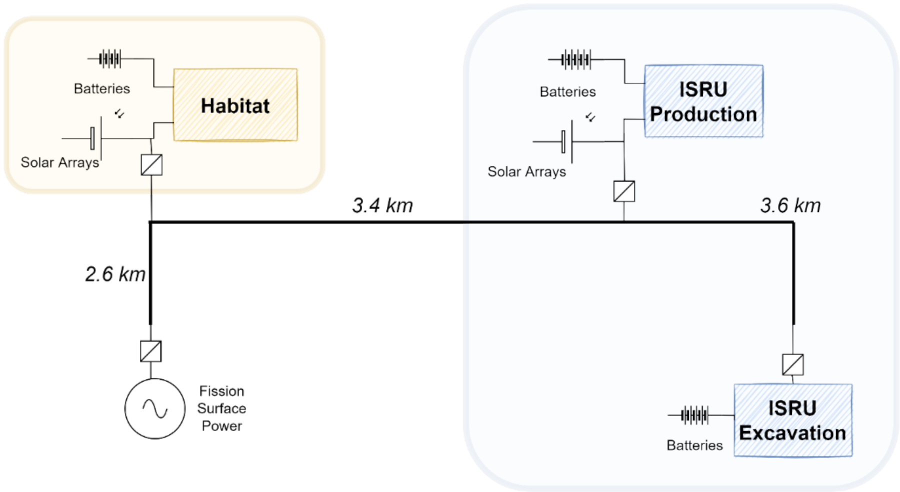
- **Lunar surface south microgrid**
  - Create local microgrids that can manage their own power
  - Primary distribution system to enable power sharing between local microgrids
  - Additional power sources (such as FSP) that can be utilized by and local microgrids
  - Additional power loads can connect to primary power distribution system

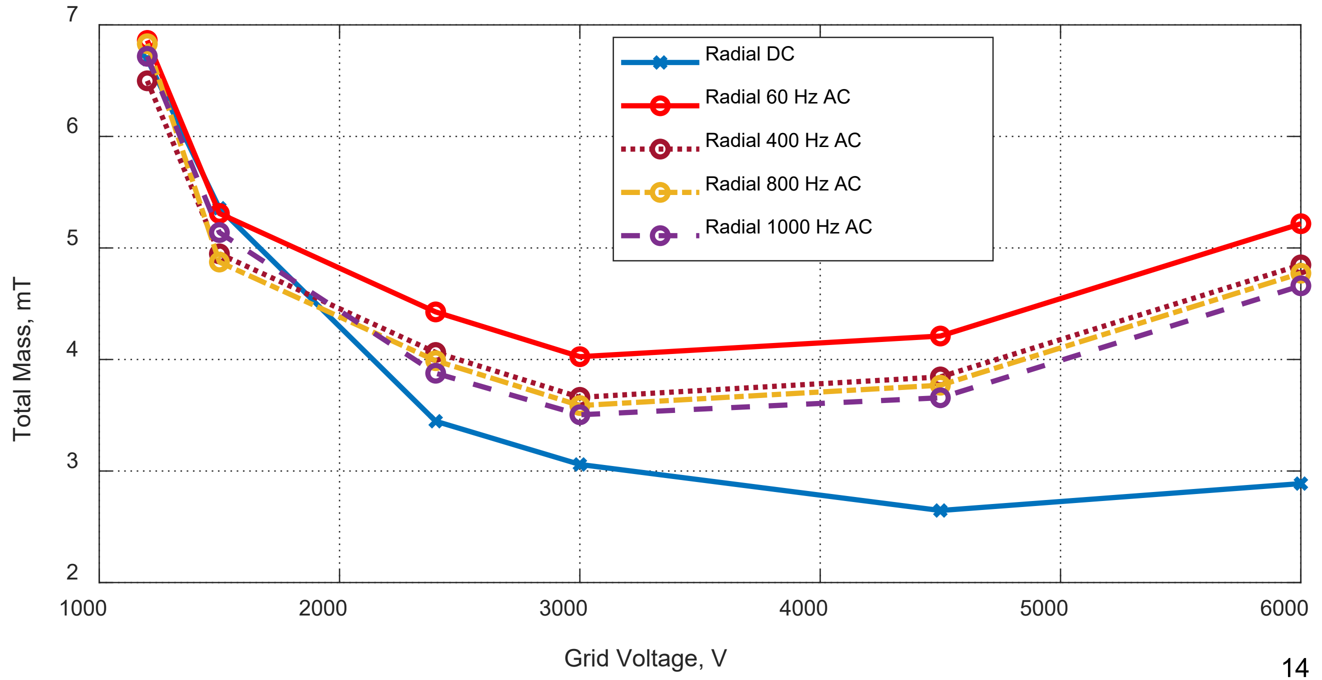
Radial Architecture

- **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

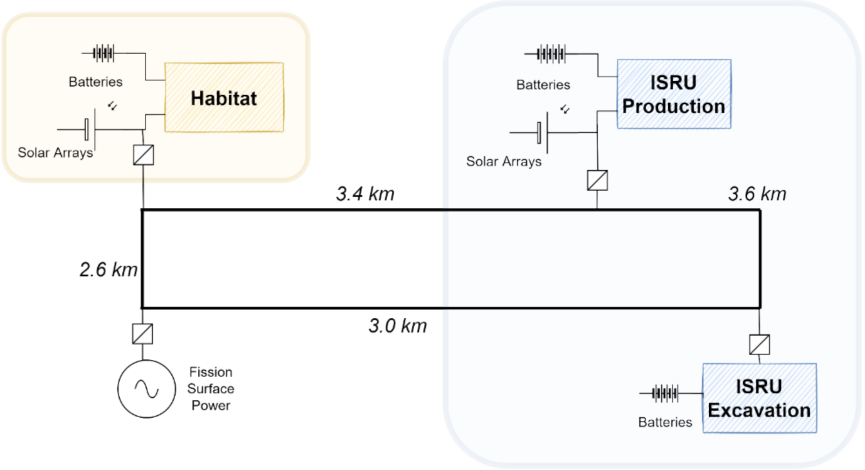
- **Radial Disadvantages**
  - Lack protection / redundancy during failure

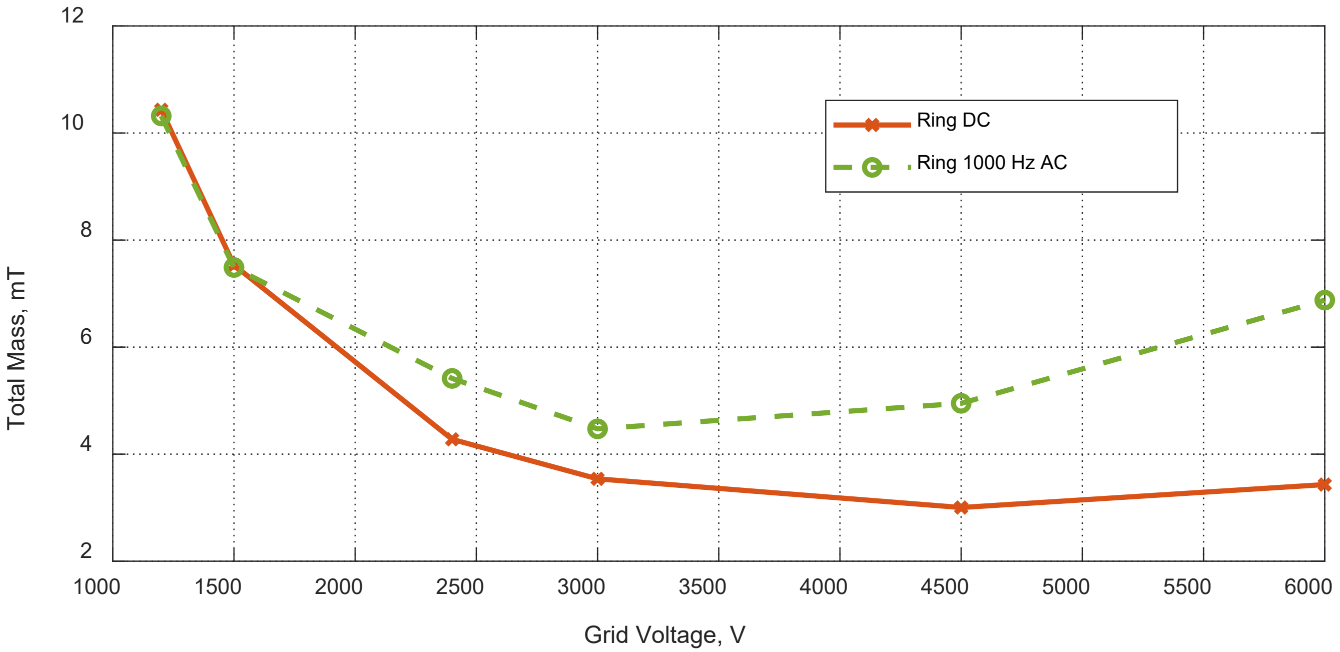




Ring Architecture

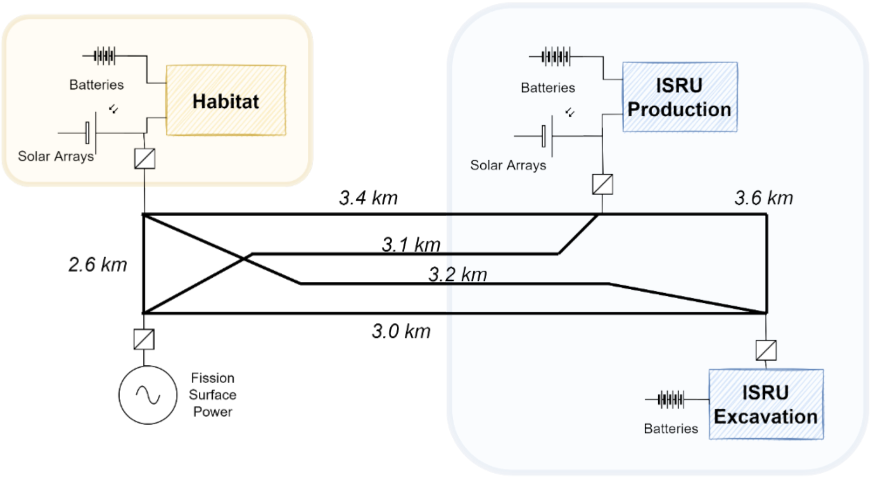
- **Ring architecture adds a second tie line between FSP and ISRU**
  - Assume FSP to Habitat line matches overall grid power type
- **Ring Advantages**
  - Adds single line tolerance for only one more tie line
  - Adds more efficient path for FSP power to get to ISRU mining which has no power of its own
- **Ring Disadvantages**
  - ~50% heavier than radial network
  - Can only lose one line and maintain ability to transmit power between any two assets

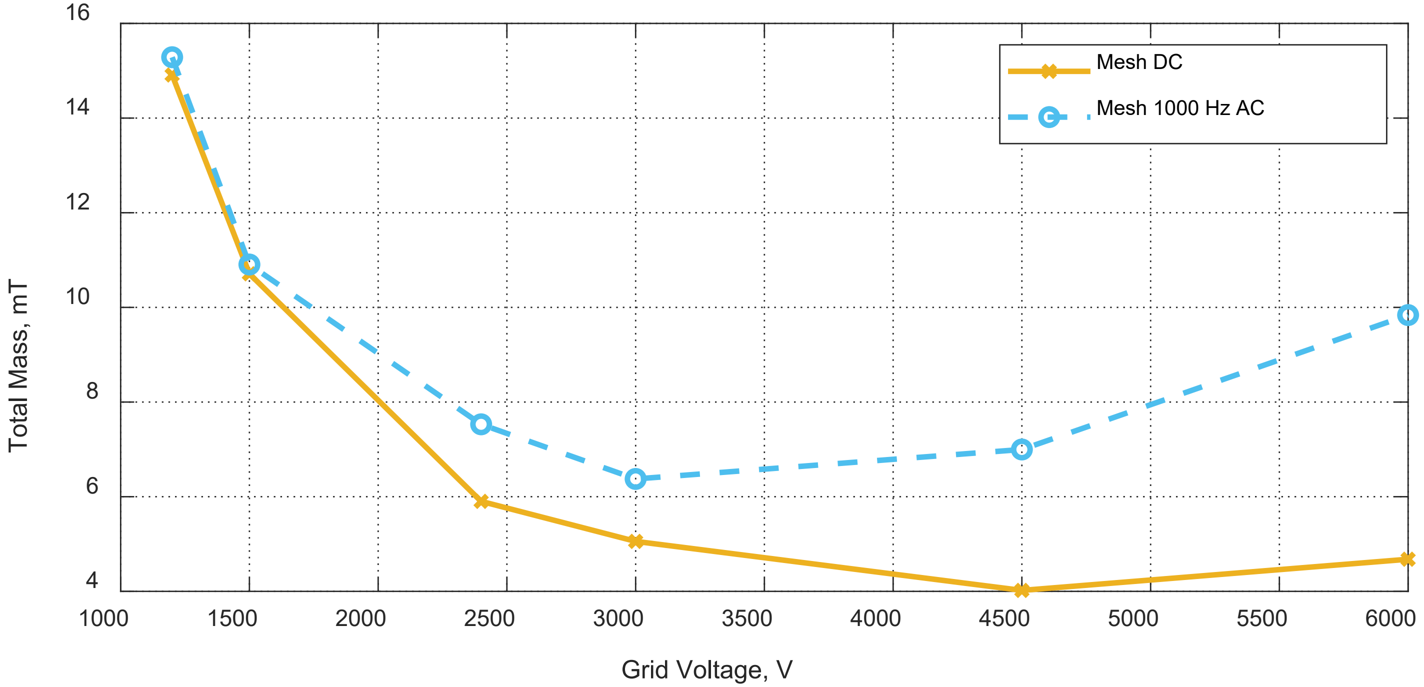




Mesh Architecture

- **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

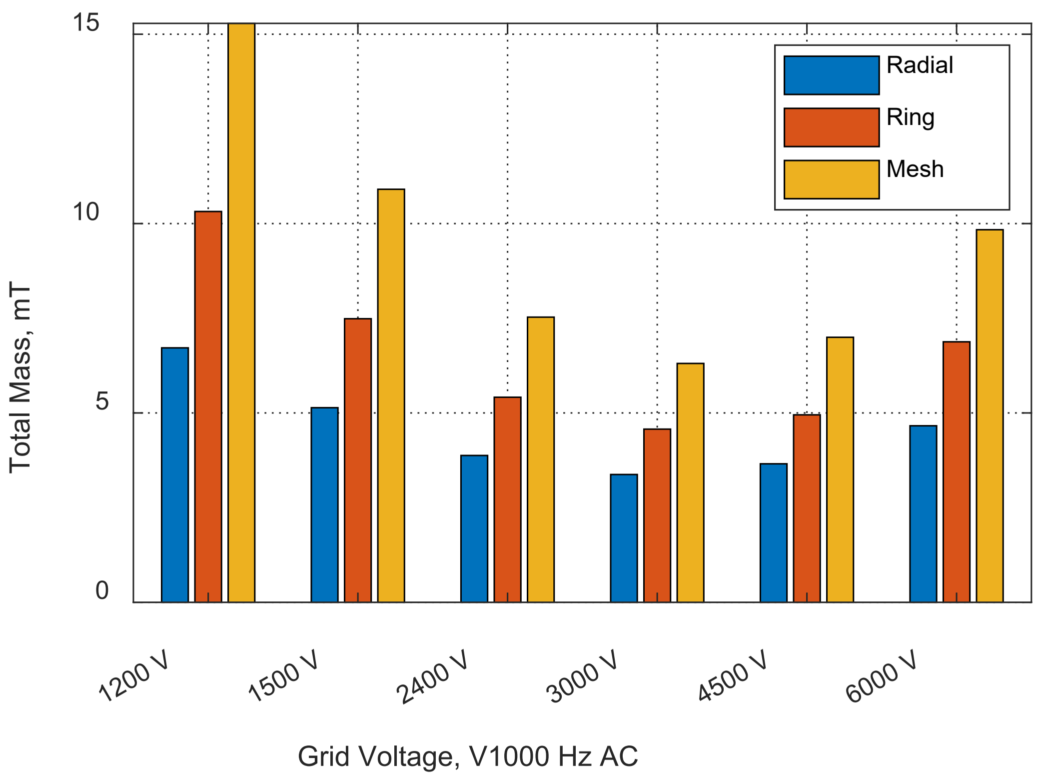




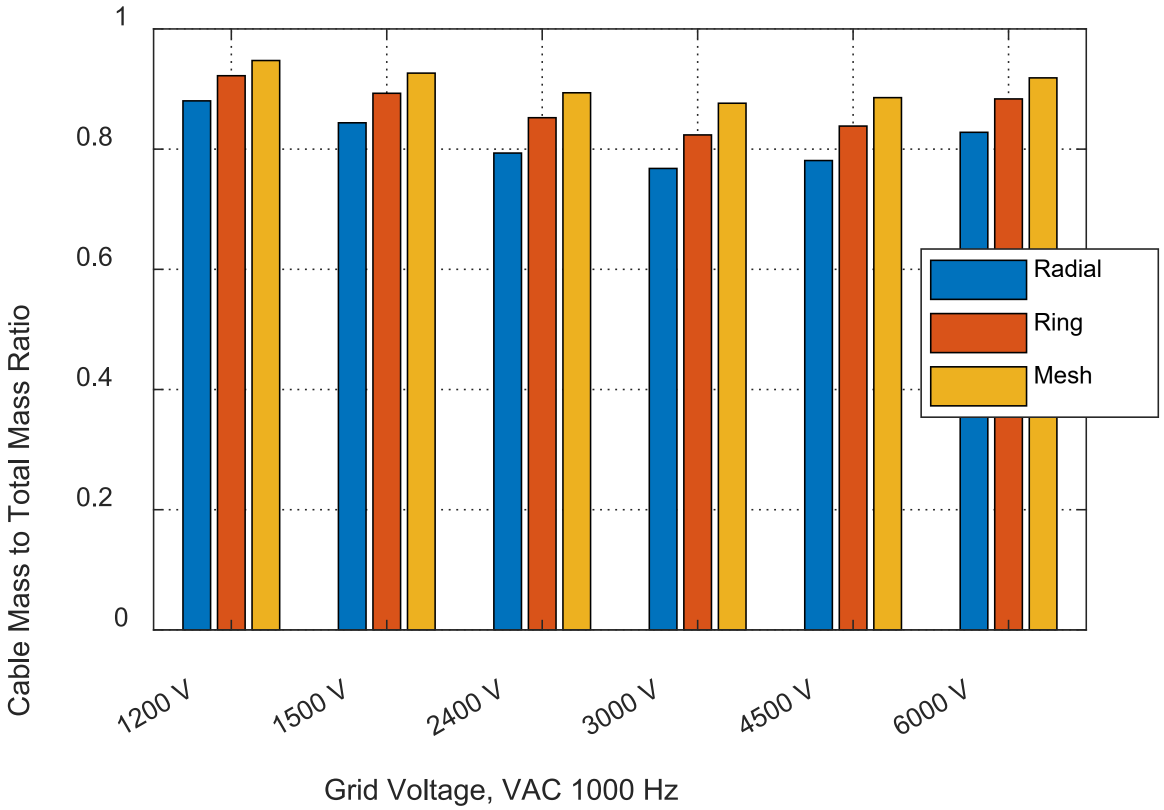
Architecture Comparison

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

Mass vs voltage and architecture



Cable-to-total mass ratio vs voltage/architecture



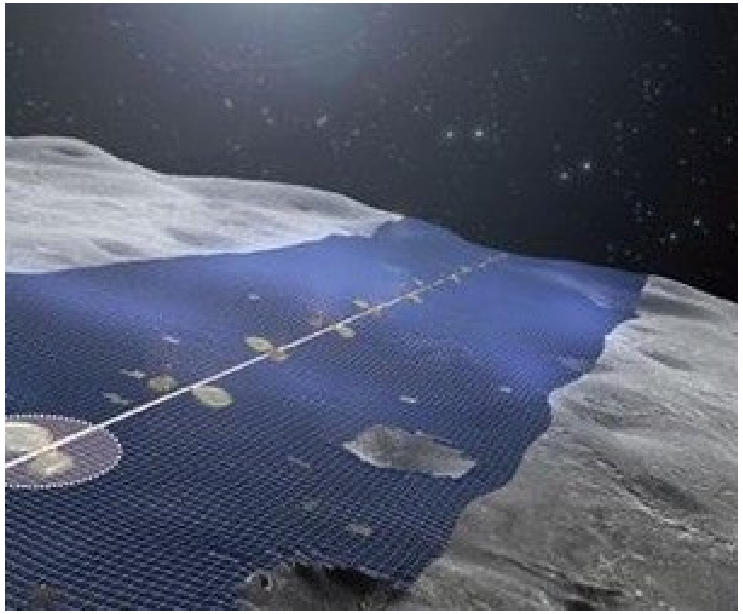
Overall Analysis Results

- **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

Towards a Commercial Lunar Economy

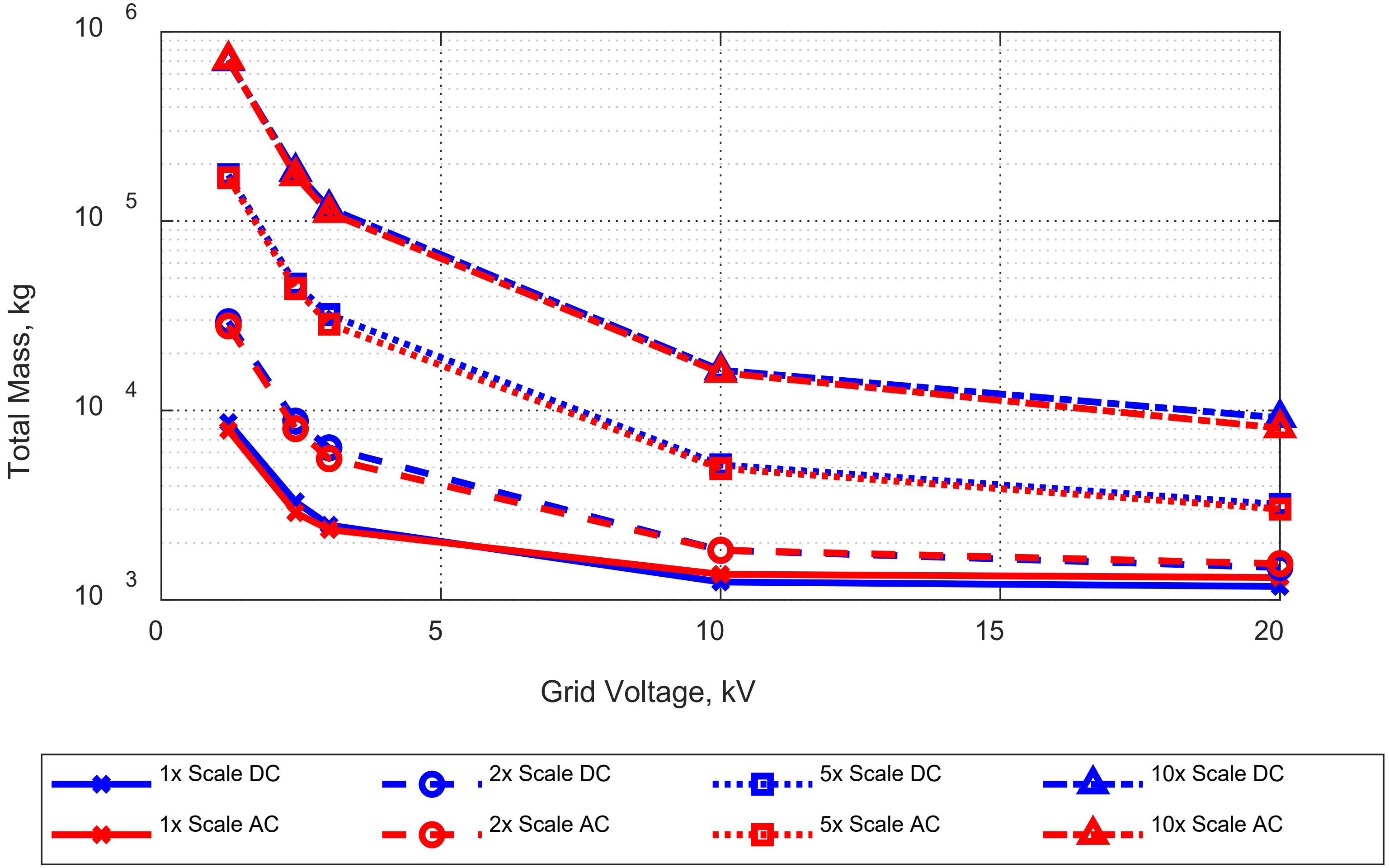
Beyond Artemis

- **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



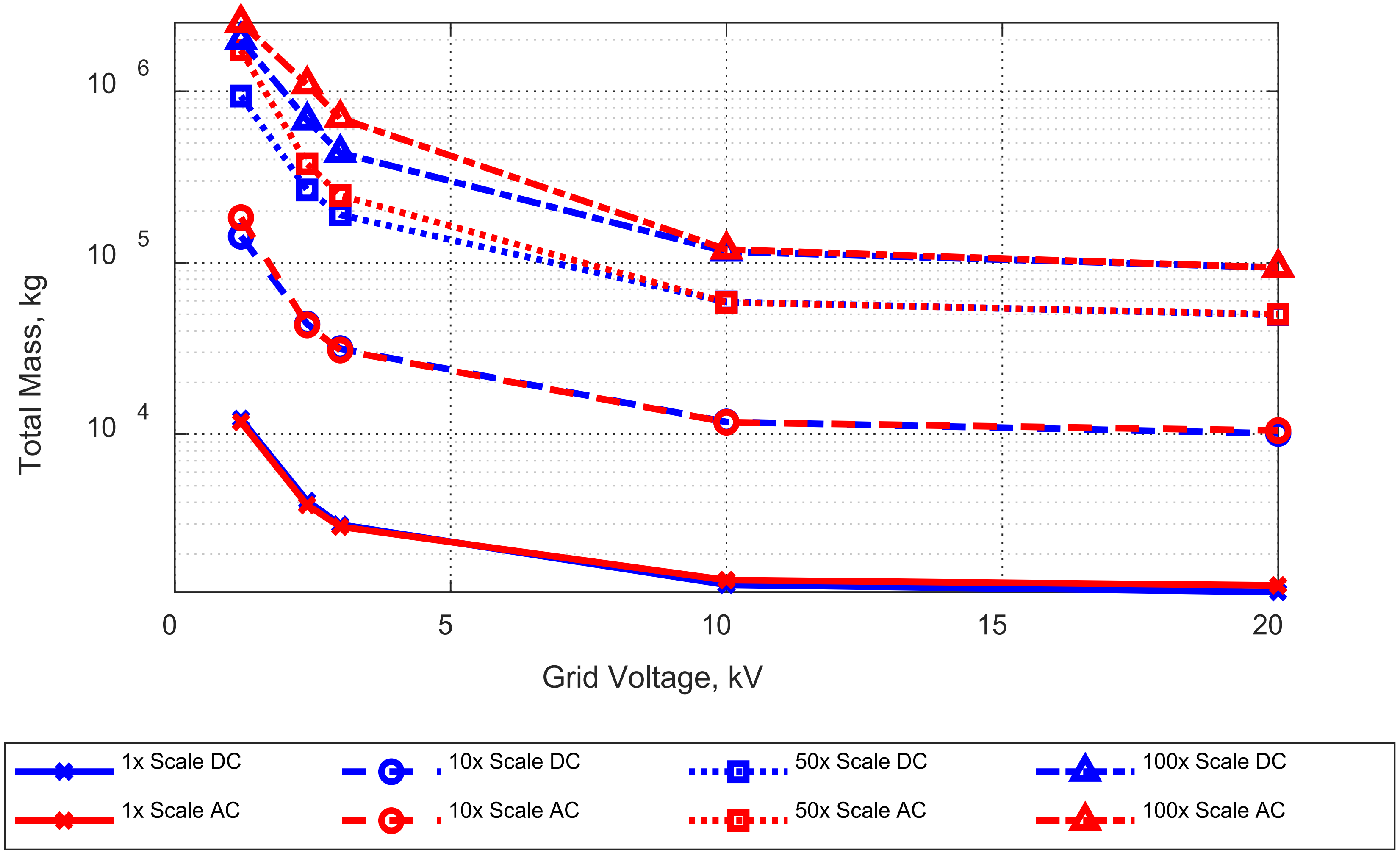
Radial Architecture Mass for Increased Distance

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



Radial Architecture Mass for Increased Power Demand

- **Total Mass for increased power demand up to 100x (10 MW)**



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
    - Rad-hard limits DC voltages
  - AC has benefit in stepping up/down voltages (transformers)
    - Long distance transmission (20 kV)
    - Regional transmission (3 kV)
    - Secondary Distribution (120 V)

Working with NASA

ARTEMIS SURFACE TECHNOLOGY OBJECTIVES

The Lunar Surface Innovative Initiative works across industry, academia and government through in-house efforts and public-private partnerships to develop transformative capabilities for lunar surface exploration.

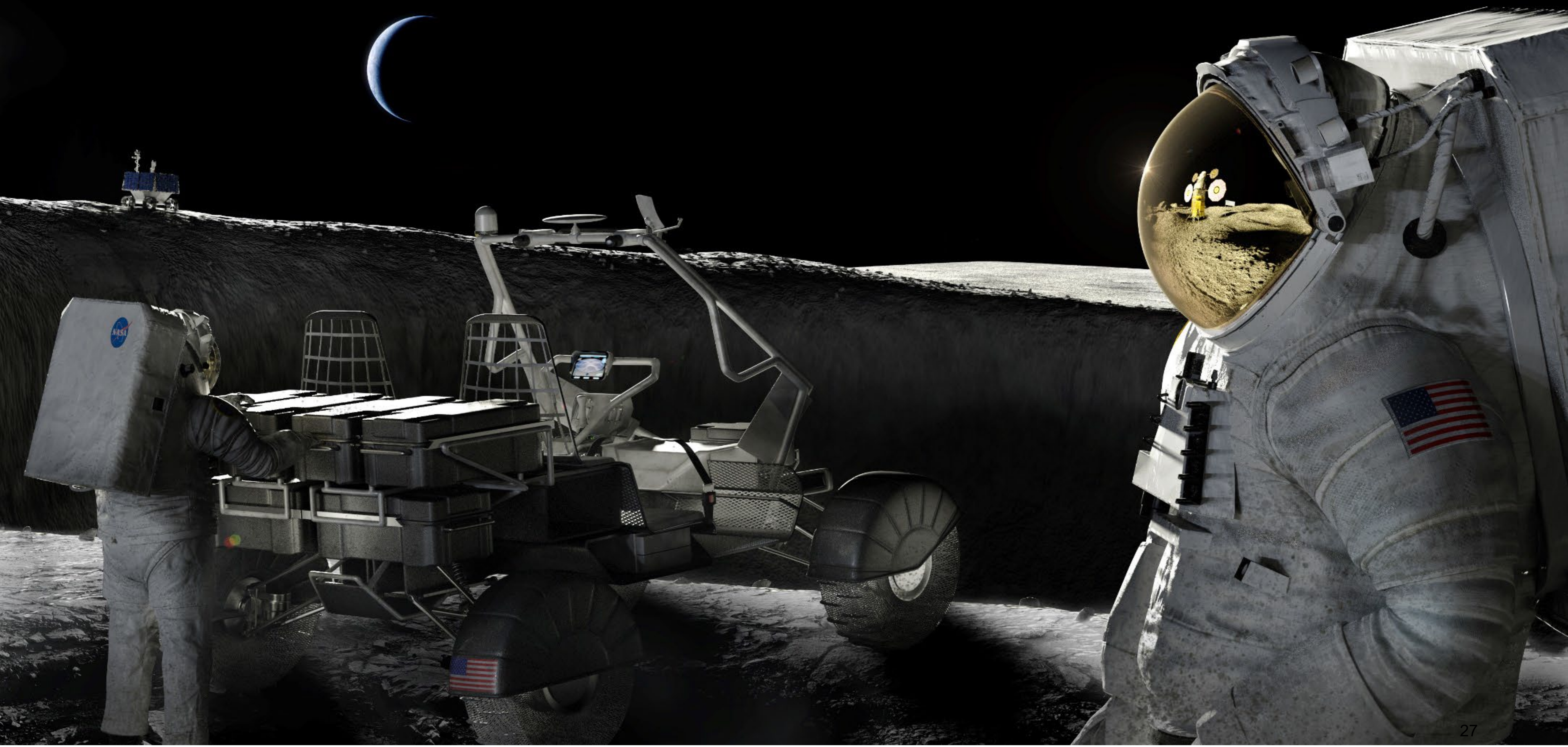
- **In-situ resource utilization** technologies for collecting, processing, storing, and using material found or manufactured on the Moon or other planetary bodies
- **Surface power technologies** that provide the capability for sustainable, continuous power throughout the lunar day and night
- **Dust mitigation technologies** that diminish dust hazards on lunar surface systems such as cameras, solar panels, space suits, and instrumentation
- **Extreme environment technologies** that enable systems to operate throughout the range of lunar surface temperatures
- **Extreme access technologies** that enable humans or robots to efficiently access, navigate, and explore previously inaccessible lunar surface or subsurface areas
- **Excavation and construction technologies** that enable affordable, autonomous manufacturing or construction

Funding Opportunities

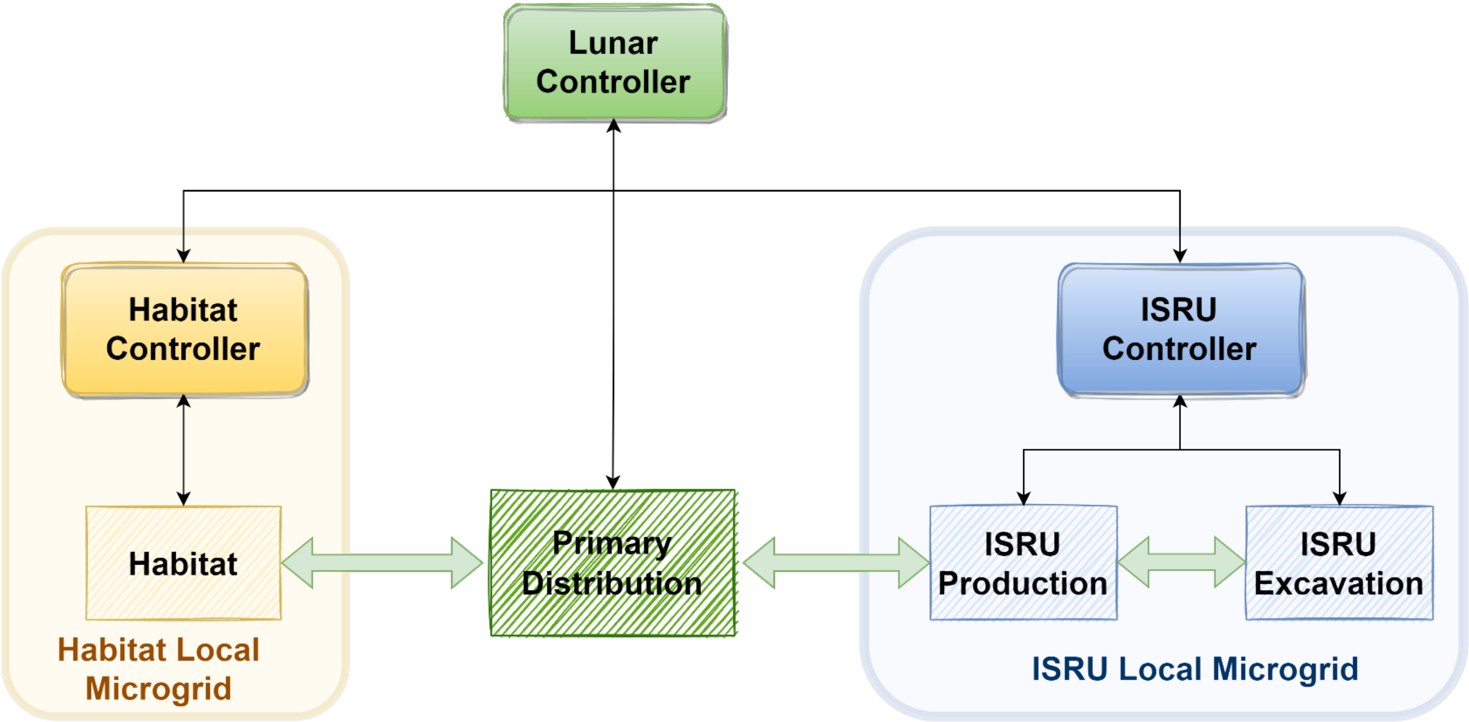
- **Strategic partnerships with academia and industry**
  - Small Business Innovation Research (SBIR) / Small Business Technology Transfer (STTR)
  - NASA Innovative Advanced Concepts (NIAC)
  - Space Technology Research Institutes (STRI) Grants
  - NASA Space Technology Graduate Research Opportunities (NSTGRO)
  - https://www.nasa.gov/directorates/spacetech/solicitations
  - https://nspires.nasaprs.com/external/

- **For more information regarding NASA PMAD technologies / partnerships / collaborations**
  - Jeffrey Csank – Electrical Engineer
    - jeffrey.t.csank@nasa.gov

Thank you



Distributed Hierarchical Control Architecture



- **Local microgrids fully control their power**
- **Lunar (regional) controller enable/force power sharing to highest priority loads**
  - E.g., when habited, habitat and power to support Astronauts have highest priority
  - E.g, when un-habited, habitat and FSP power is available for other uses

Lunar and Martian Infrastructure Objectives

Lunar Infrastructure (LI) Goal: Create Global Lunar Utilization infrastructure where U.S. industry and international partners can maintain continuous robotic and human presence on the lunar surface for a robust lunar economy without NASA as the sole user, while accomplishing Mars testing and science objectives.

LI-1: Develop an incremental lunar power grid that is evolvable to support continuous human/robotic operation and is capable of scaling to global power utilization and industrial power levels.

LI-2: Develop Lunar surface, orbital, & Lunar to Earth communications, position, navigation and timing architecture capable of scaling to support long term science, exploration, and industrial needs.

LI-3: Demonstrate autonomous construction, precision landing, surface transportation, industrial scale ISRU and Advanced Manufacturing capabilities in support of future continuous human lunar presence and a robust lunar economy.

LI-4: Demonstrate technologies supporting cislunar orbital/surface depots, construction and manufacturing maximizing the use of in-situ materials, and support systems needed for continuous human/robotic presence.

Martian Infrastructure (MI) Goal: Create essential infrastructure to support initial human Mars demonstration.

MI-1: Develop Mars Surface Power sufficient for the initial human Mars demonstration mission.

MI-2: Develop Mars surface, orbital, & Mars to Earth communications to support the initial human Mars demonstration mission.

MI-3: Develop and demonstrate entry, descent, and landing (EDL) systems capable of delivering crew and large cargo to the Martian surface.