

Autonomous Power Control for the Lunar Power Grid

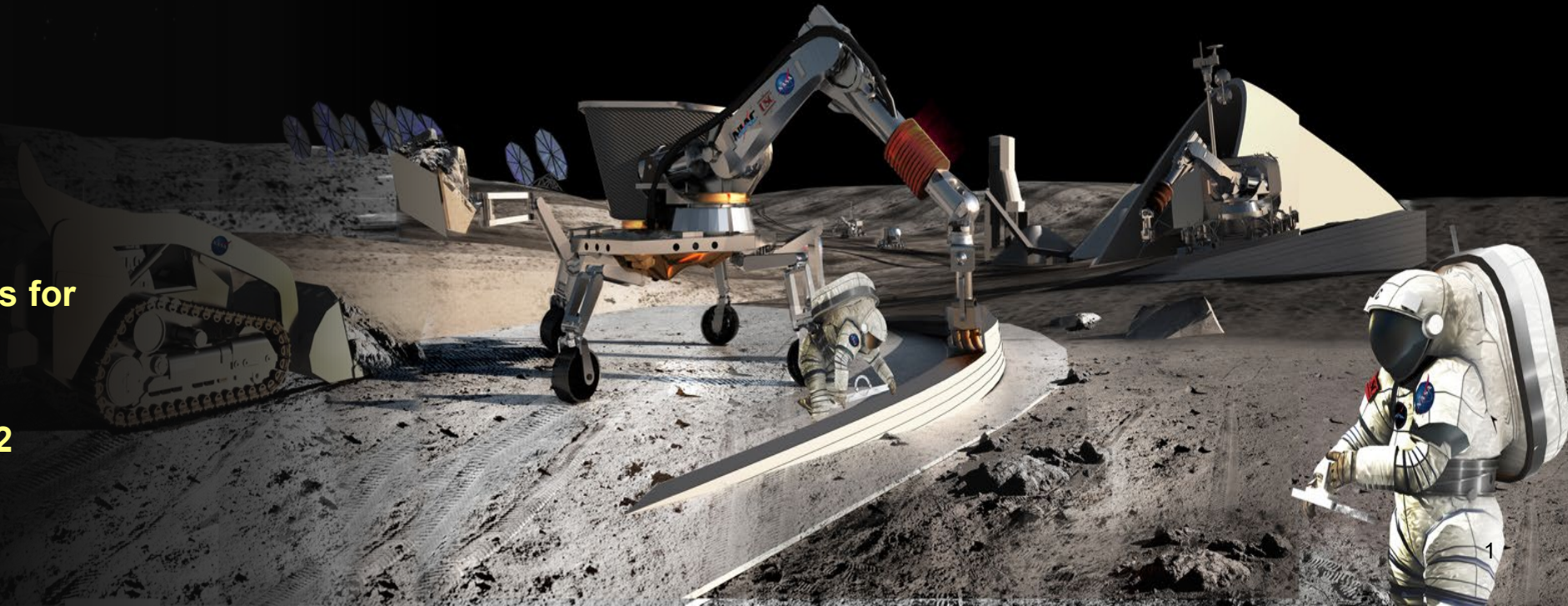
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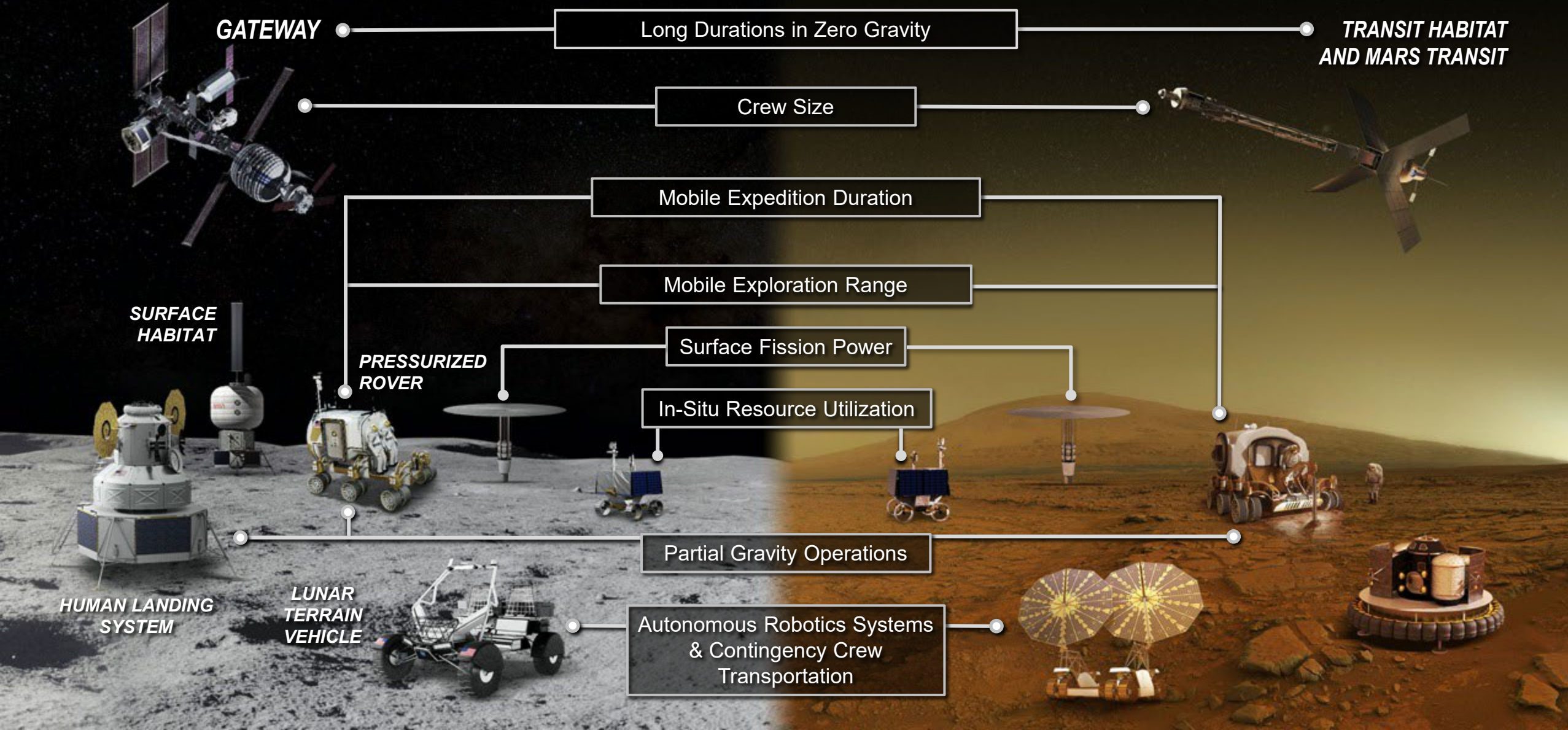
**2022 Advanced Power Systems for
Deep Space Exploration**

August 30 – September 1, 2022



Moon to Mars Exploration

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





Artemis Base Camp Buildup

First lunar surface expedition through Gateway; external robotic system added to Gateway; Lunar Terrain Vehicle delivered to the surface

Sustainable operations with crew landing services; Gateway enhancements with refueling capability, additional communications, and viewing capabilities

Pressurized rover delivered for greater exploration range on the surface; Gateway enables longer missions

Surface habitat delivered, allowing up to four crew on the surface for longer periods of time leveraging extracted resources. Mars mission simulations continue with orbital and surface assets.

Lunar Terrain Vehicle (LTV)

Crew Landing Services

Pressurized Rover

Fission Surface Power

ISRU Pilot Plant

Surface Habitat

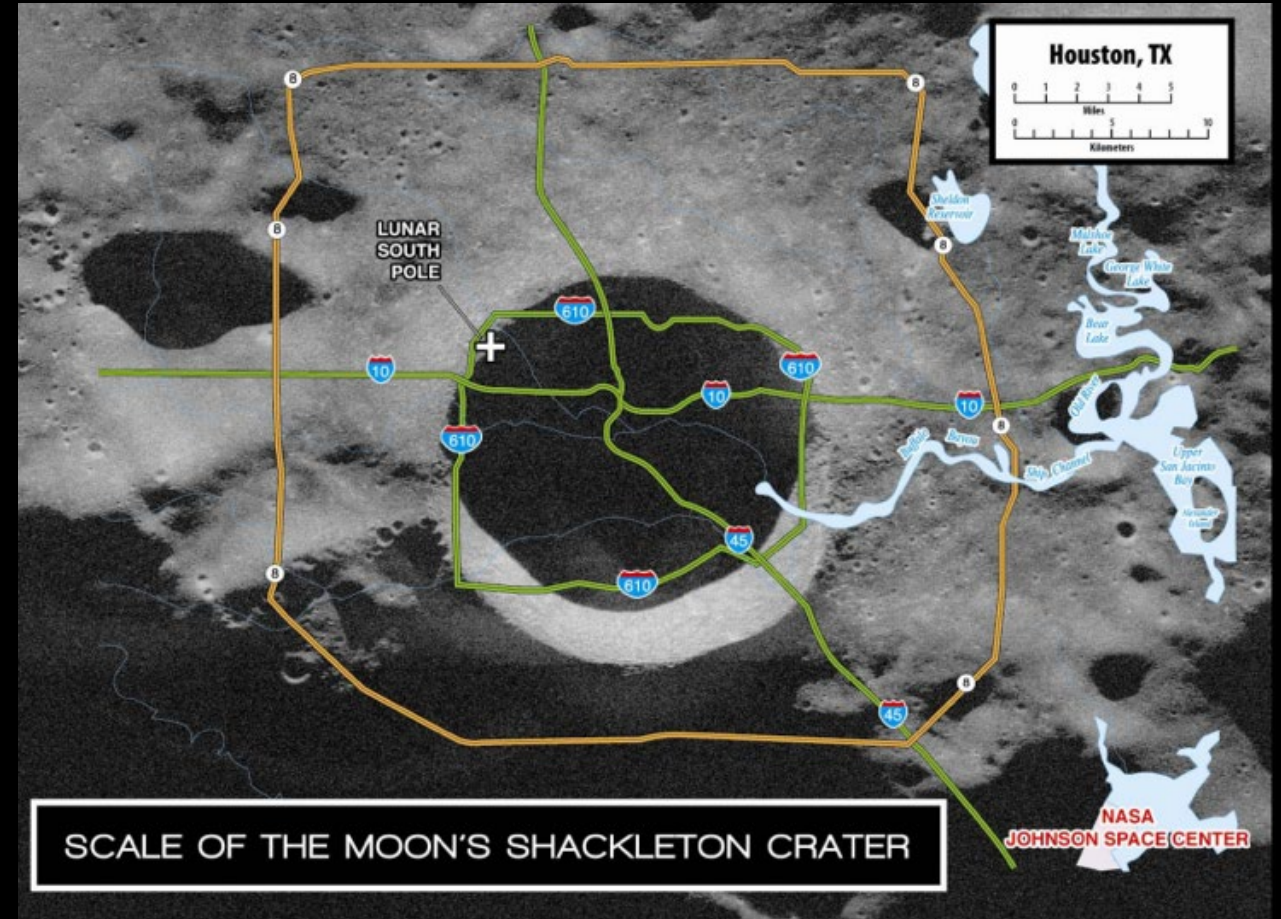
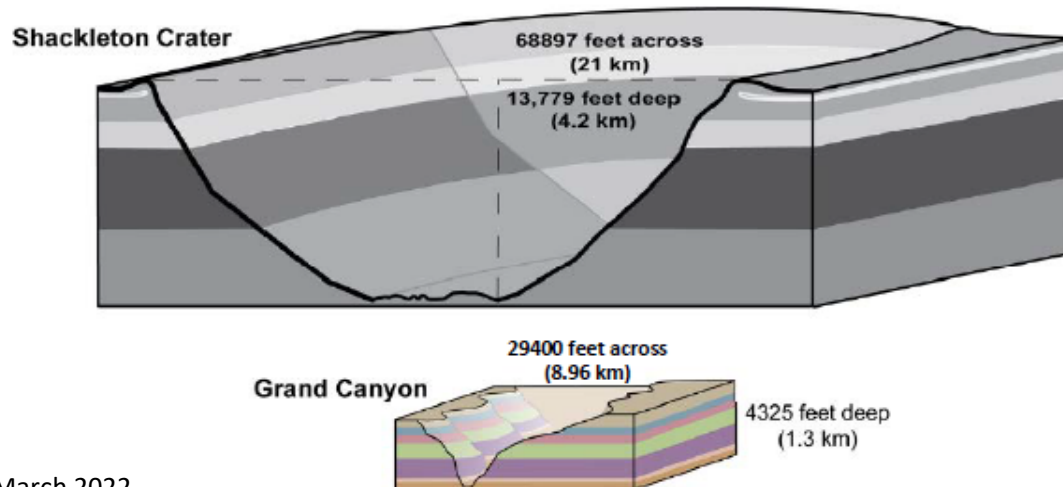
SUSTAINABLE LUNAR ORBIT STAGING CAPABILITY AND SURFACE EXPLORATION

MULTIPLE SCIENCE AND CARGO PAYLOADS | U.S. GOVERNMENT, INDUSTRY, AND INTERNATIONAL PARTNERSHIP OPPORTUNITIES | TECHNOLOGY AND OPERATIONS DEMONSTRATIONS FOR MARS

Shackleton Crater

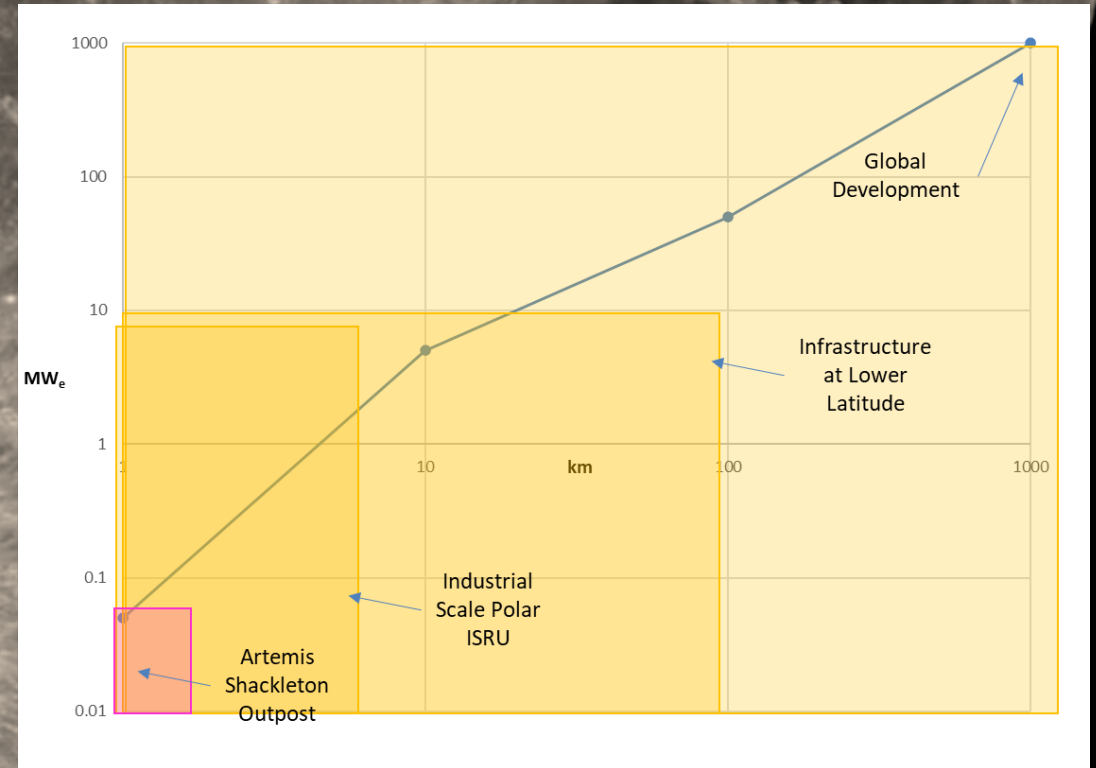
- ~20 km in diameter
- ~4 km deep and ~3x deeper and wider than the Grand Canyon at Enfilade Point
- Located at Lunar South Pole
- Rim and Connecting Ridge are primary targets for future lunar landings

SHACKLETON CRATER vs. GRAND CANYON

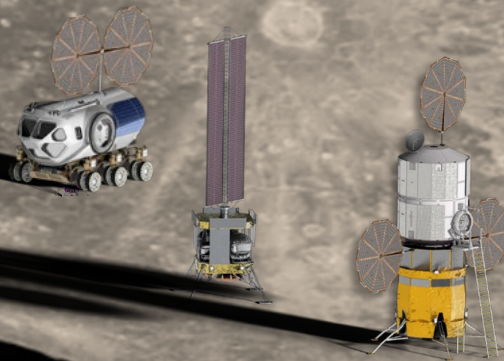


Artemis Base Camp Zone

Ultimate Global Exploitation



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



Sustainable Power for the Lunar Surface



Living beyond Earth

Testing and demonstrating technologies for sustained presence (Moon2Mars)

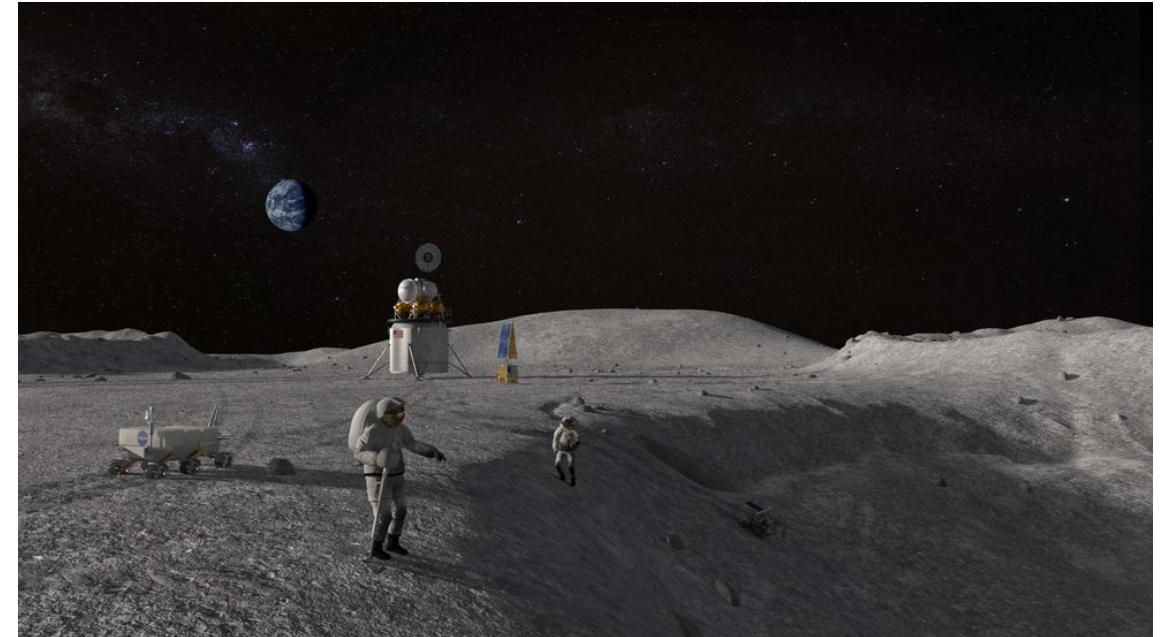
Expand beyond Artemis towards establishing a lunar economy (STMD Global Exploitation)

- **Power System Architecture**

- Complex power strategy (generation / storage)
 - Include dissimilar power sources
 - Meet peak power demand without oversizing
 - Extend daylight operations
- Distributed distribution architecture
 - Reconfigurable / expandable

- **Power System Operation**

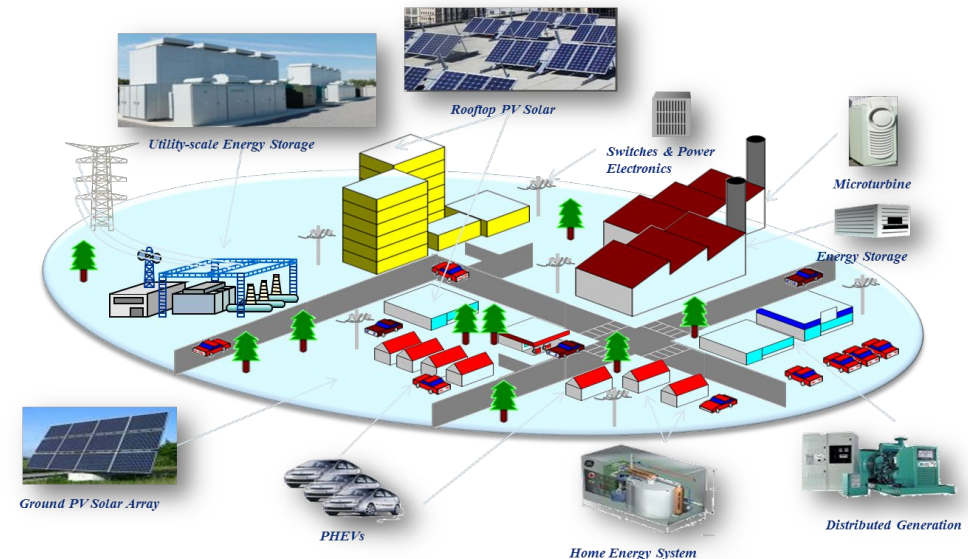
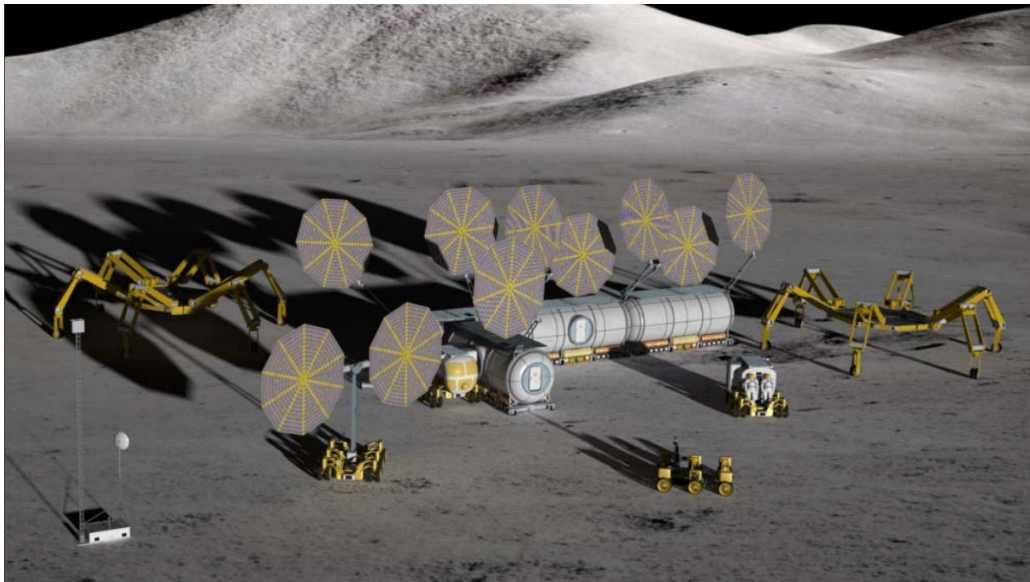
- Robotically deployable PMAD / power systems
- Autonomously operated PMAD systems



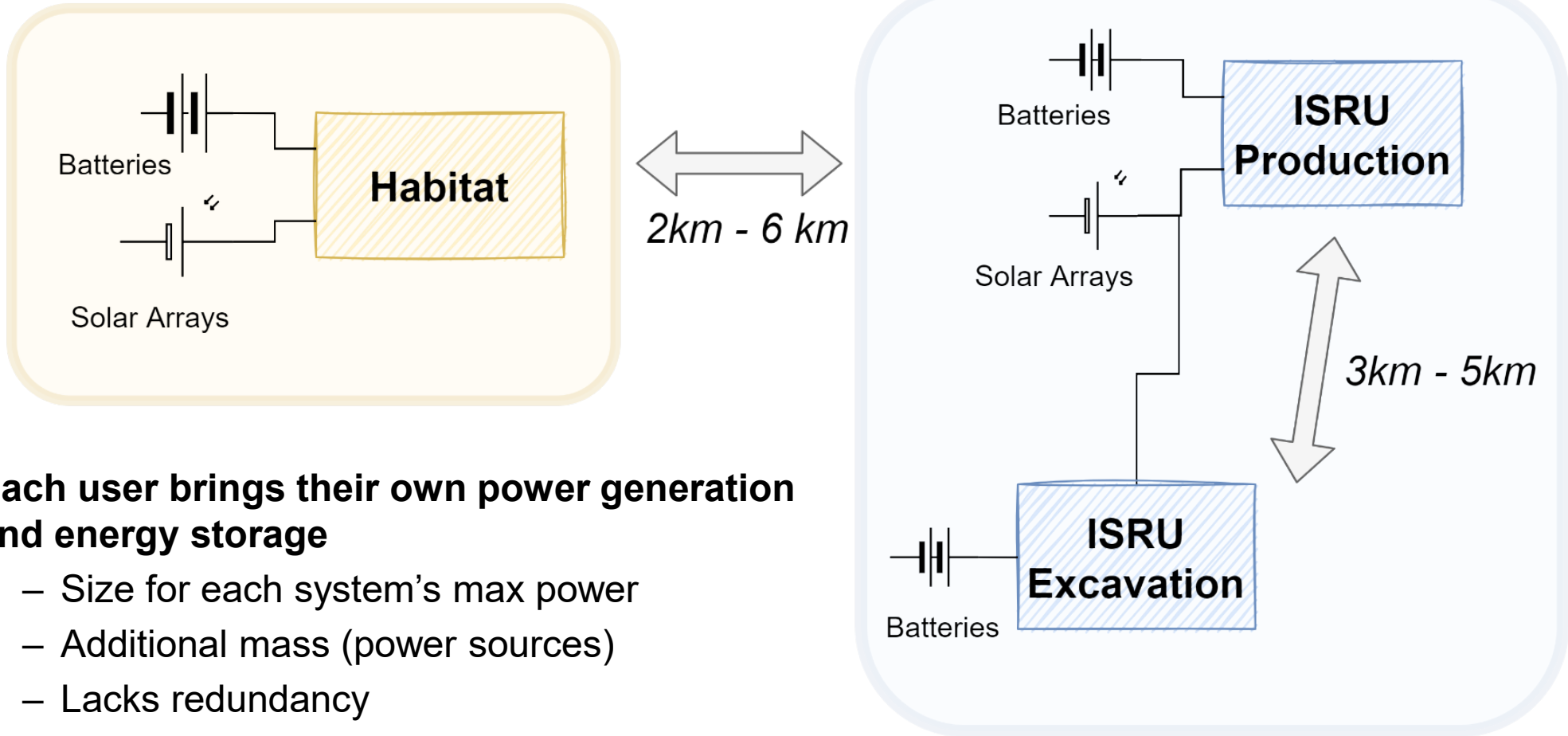
Case for a Lunar Microgrid



- **Benefits of a microgrid for lunar surface power**
 - Optimal dispatch of power sources / energy storage to service loads
 - Dissimilar source and storage methodologies to enhance reliability and availability
 - Systematic integration of new sources and loads as lunar surface activities evolve
 - Adoption of a common grid interface for source and loads facilitate growth and interchangeability
 - Deployment of future science loads that do not need to carry their own power generation

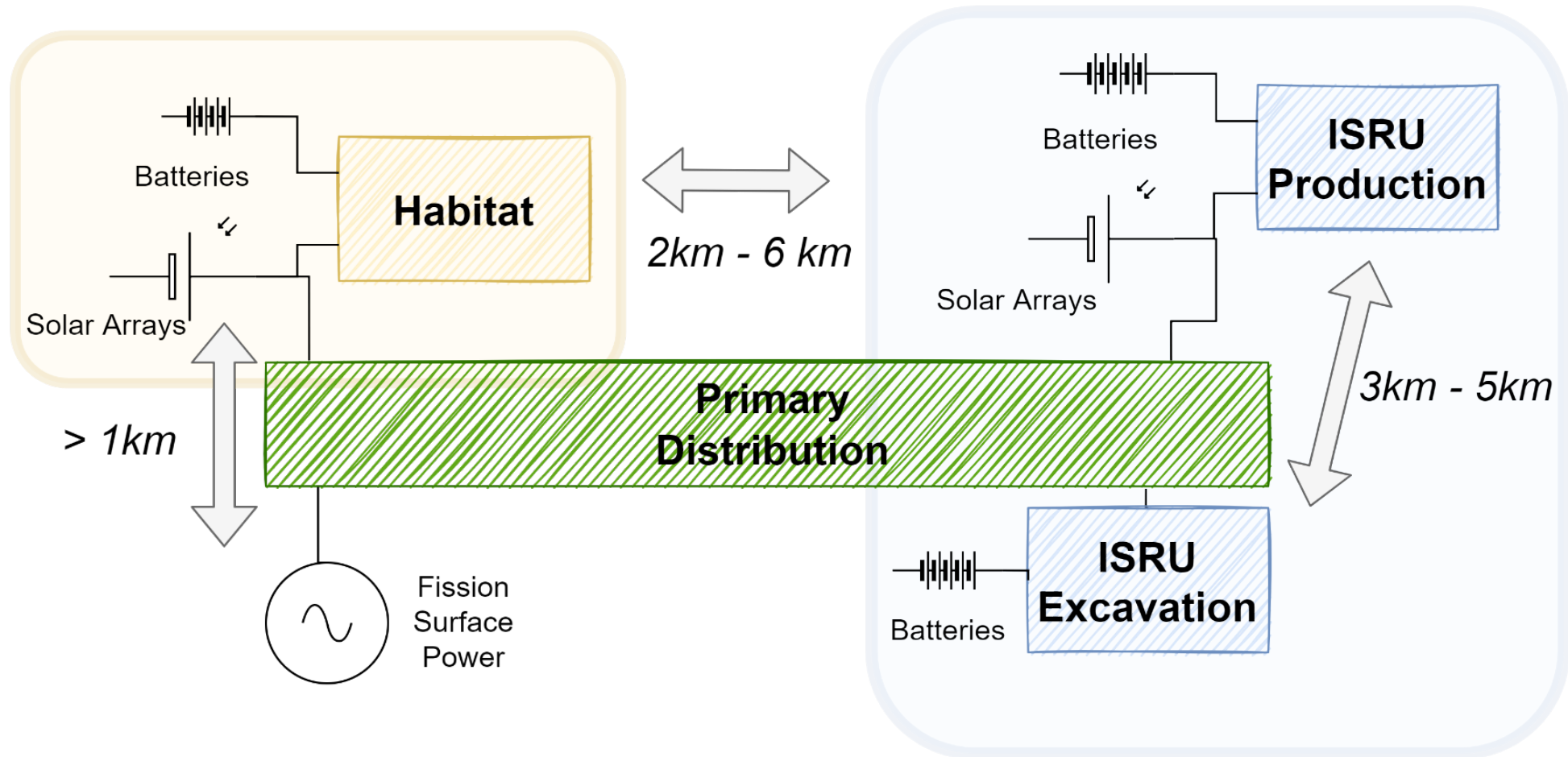


Baseline Artemis Power System



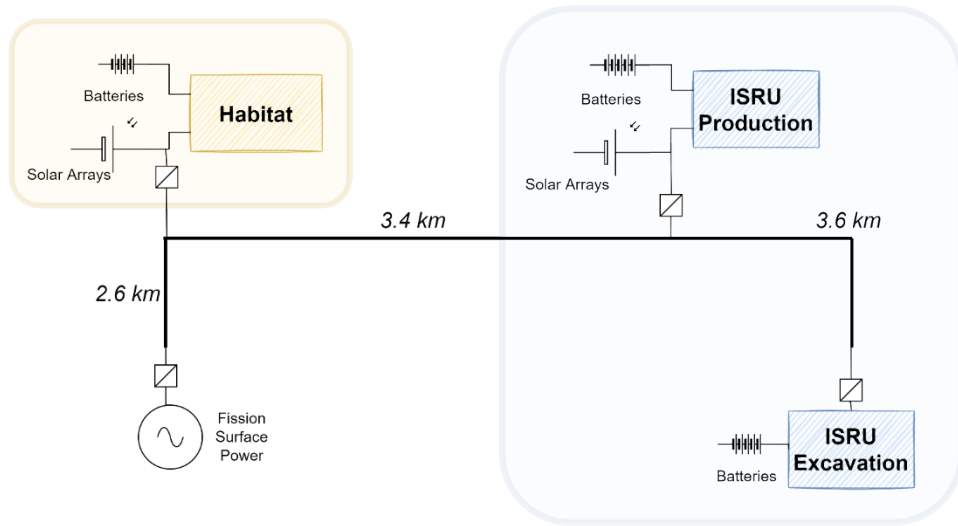
- **Each user brings their own power generation and energy storage**
 - Size for each system's max power
 - Additional mass (power sources)
 - Lacks redundancy

Artemis Power System with Primary Distribution

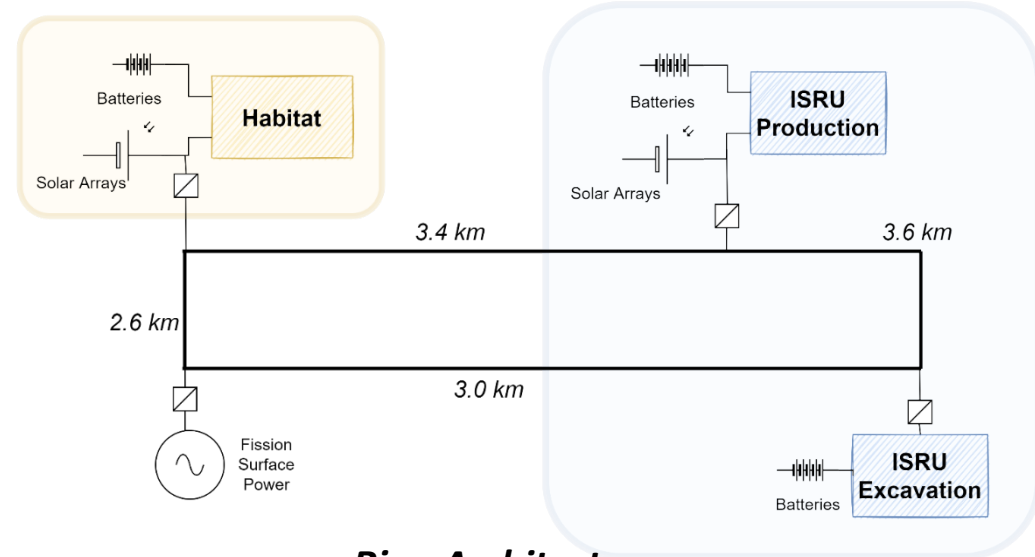


- Power from additional power source is available to all loads
- Power can be shared between sources (increases redundancy)

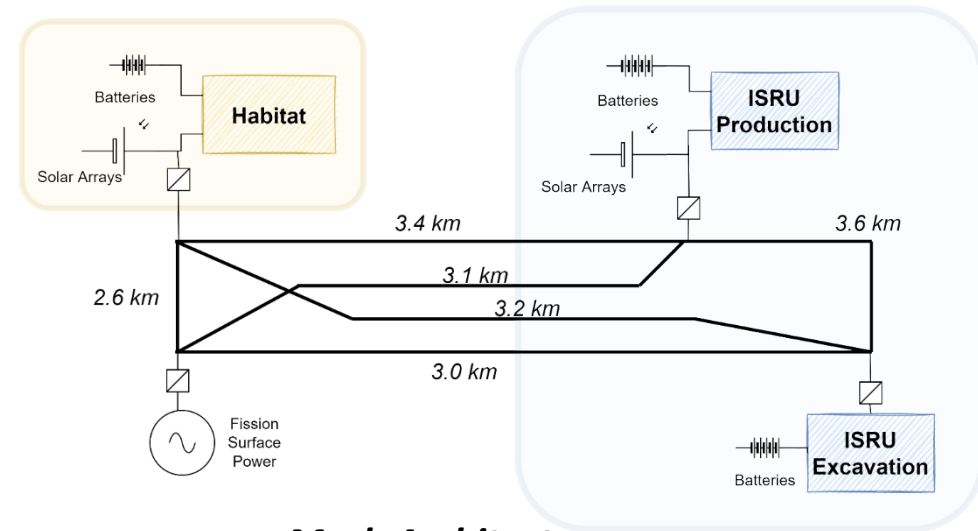
Power System Architectures



Radial Architecture



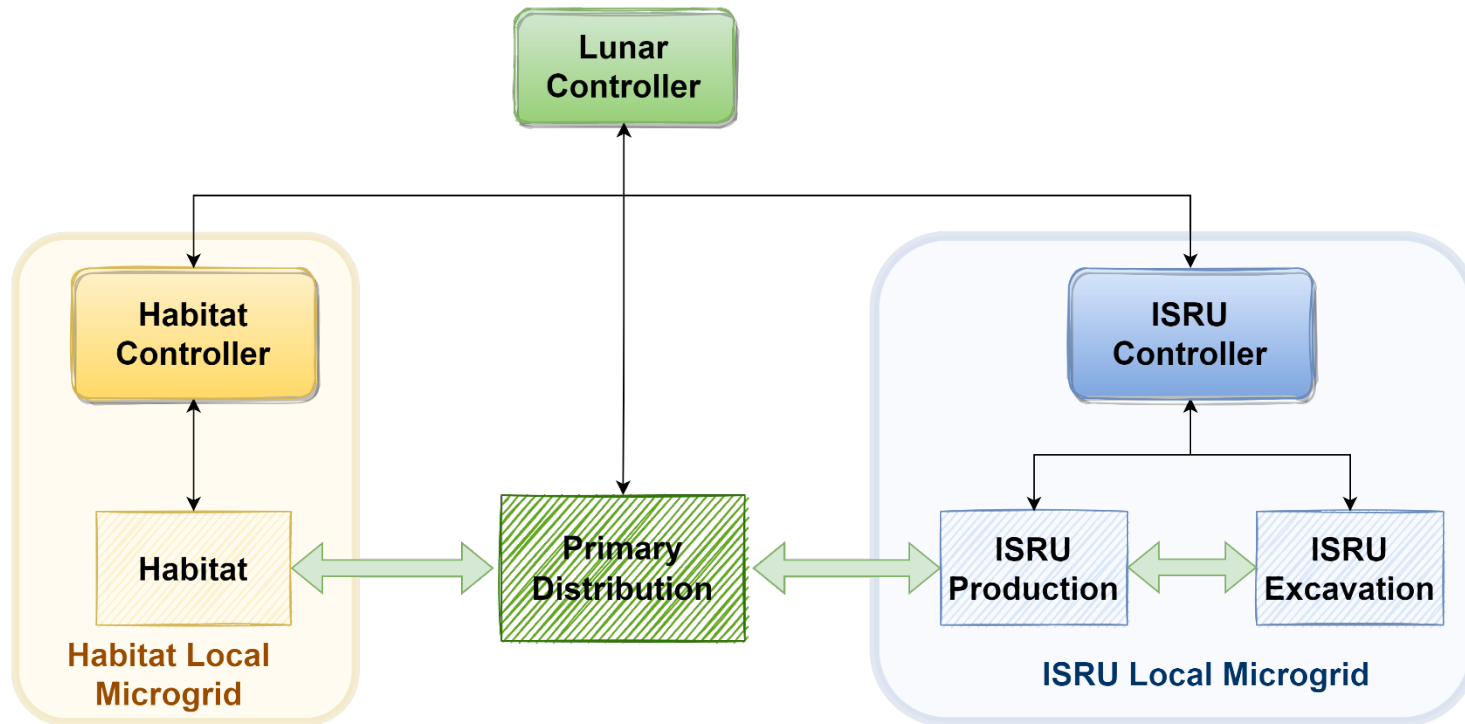
Ring Architecture



Mesh Architecture

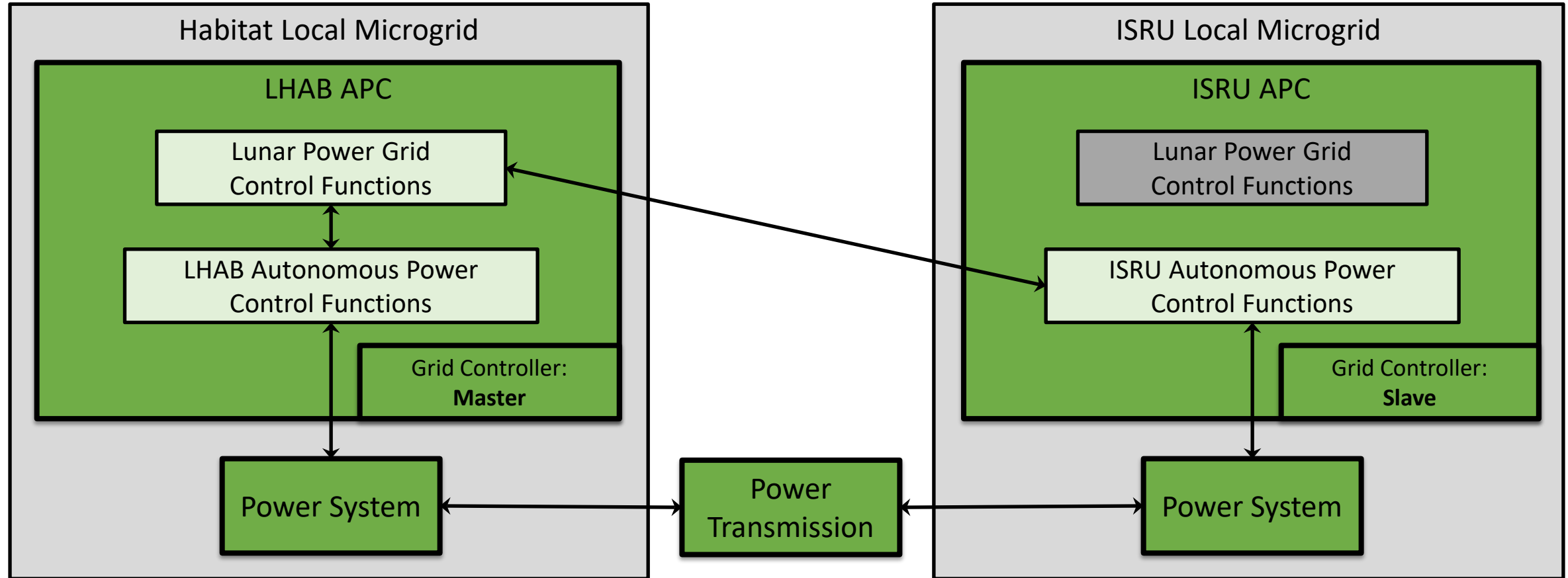
- **Architecture chosen based on tradeoff between redundancy and mass**
 - Increase redundancy = increased mass

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

Power Sharing Architecture



- **One Local Microgrid Controller is the master (Master APC)**

- Responsible for executing the Lunar Power Grid Controller Functions

- All other Local Microgrid Controllers are slaves (Slave APC)

- Lunar Power Grid Controller Functions are disabled

Secondary & Tertiary Controller



- **Secondary Controller**

- Power Generation Forecast

- Given predicted PV capability and battery capacity
 - Computes available power to the loads using Newton-Raphson load flow
 - Accounts for losses in lines and power electronics

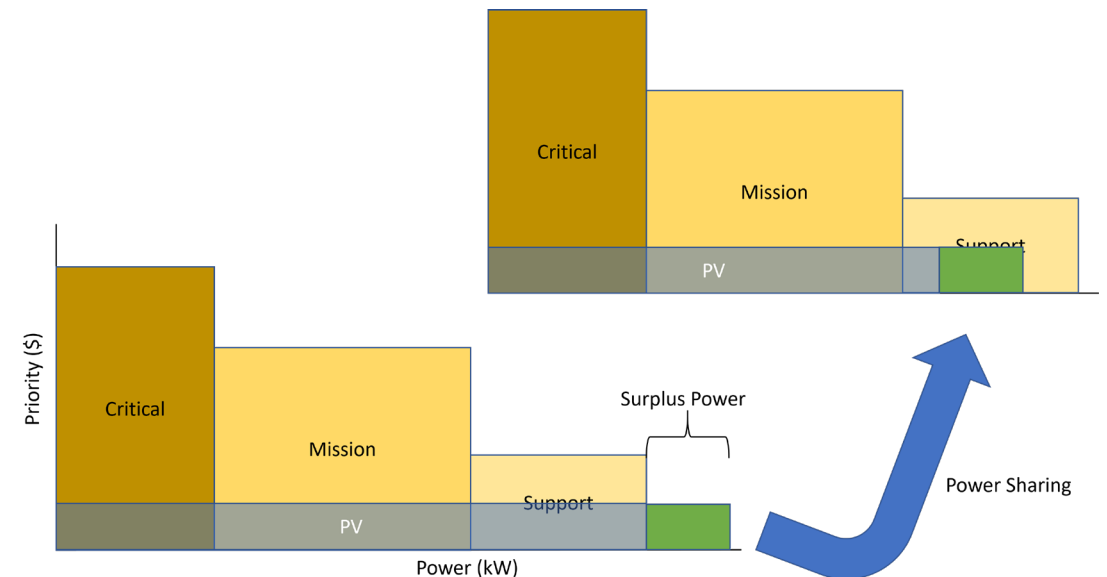
- Predicted Load Demand

- Given upcoming load schedule for future time window
 - Each load is given a unique priority and classification
 1. Critical
 2. Mission
 3. Support

- **Tertiary Controller:**

- Cost function analysis

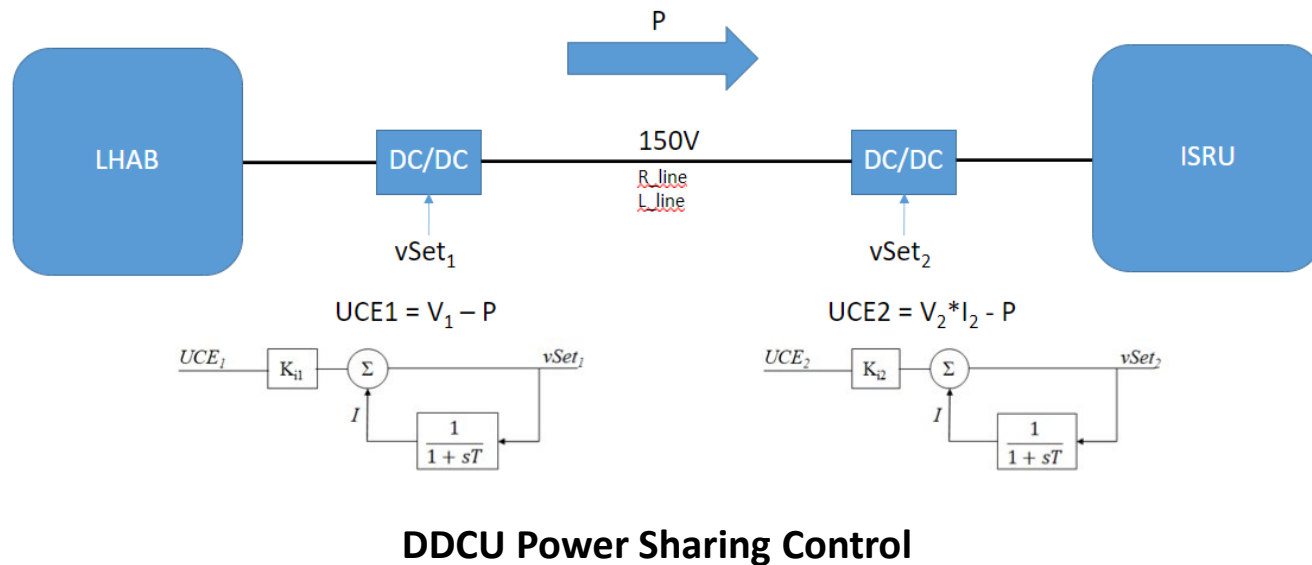
- Determines the surplus/deficit of each MG
 - Computes power sharing capability when needed
 - Allocates power in order of priority



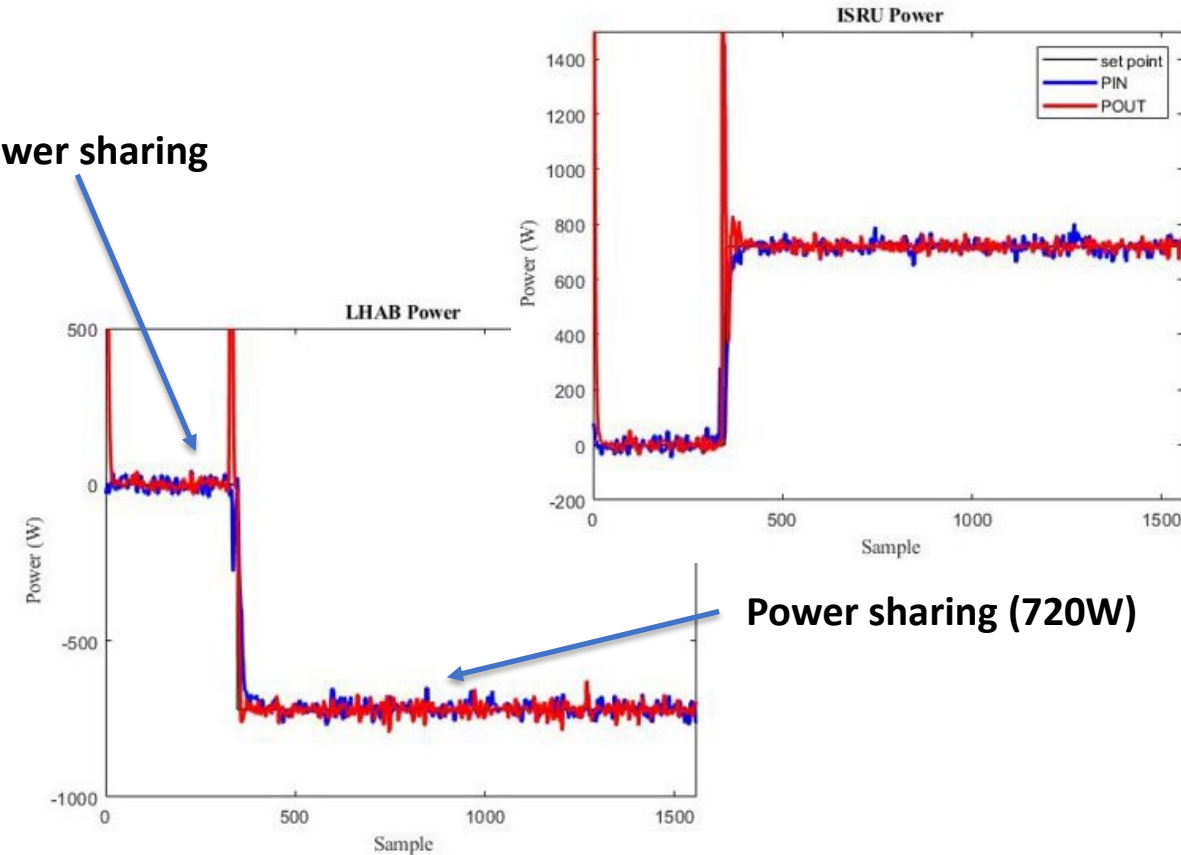
Primary Controller



- **Lower-level control for DDCU implementation**
 - Regulates voltage setpoint to achieve constant power transfer
- **Two use-case scenarios tested**
 - Normal Operation No Power Sharing
 - Normal Operation Power Sharing



No power sharing

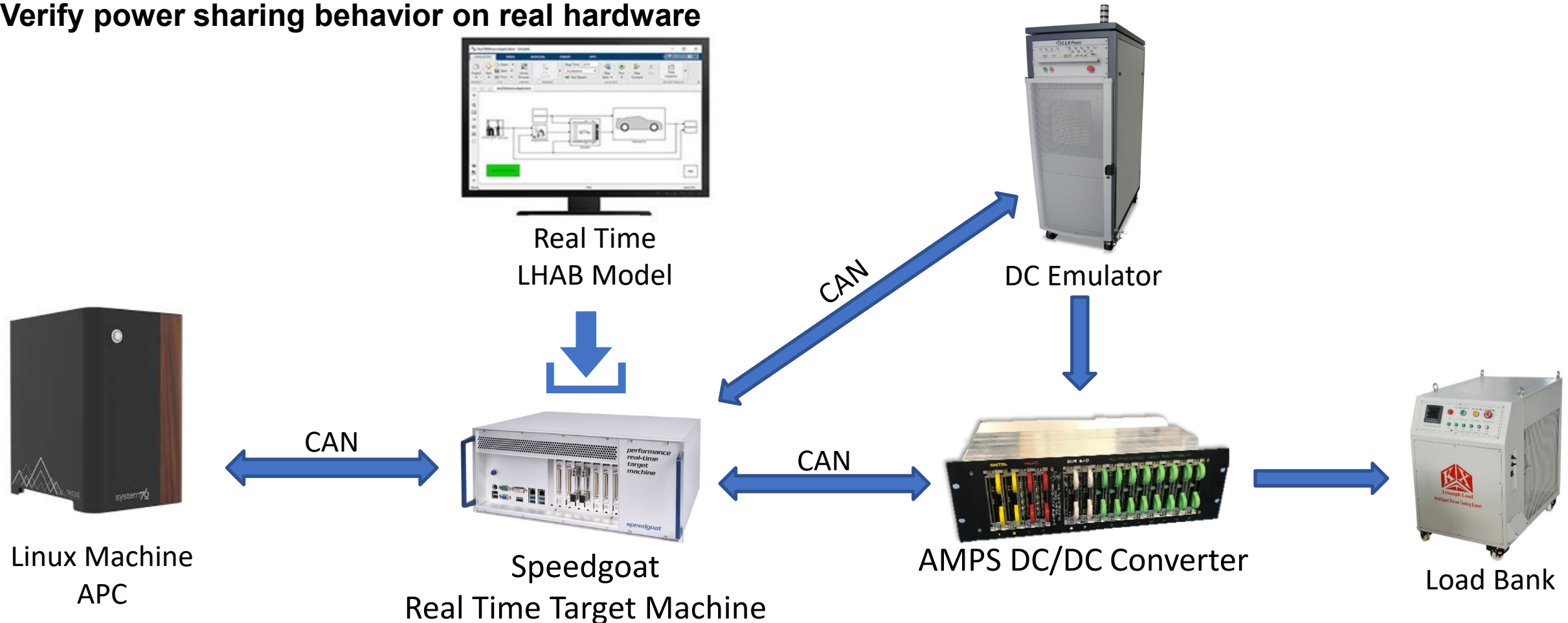


Use-Case Simulation Results

Testing with Hardware-in-the-Loop



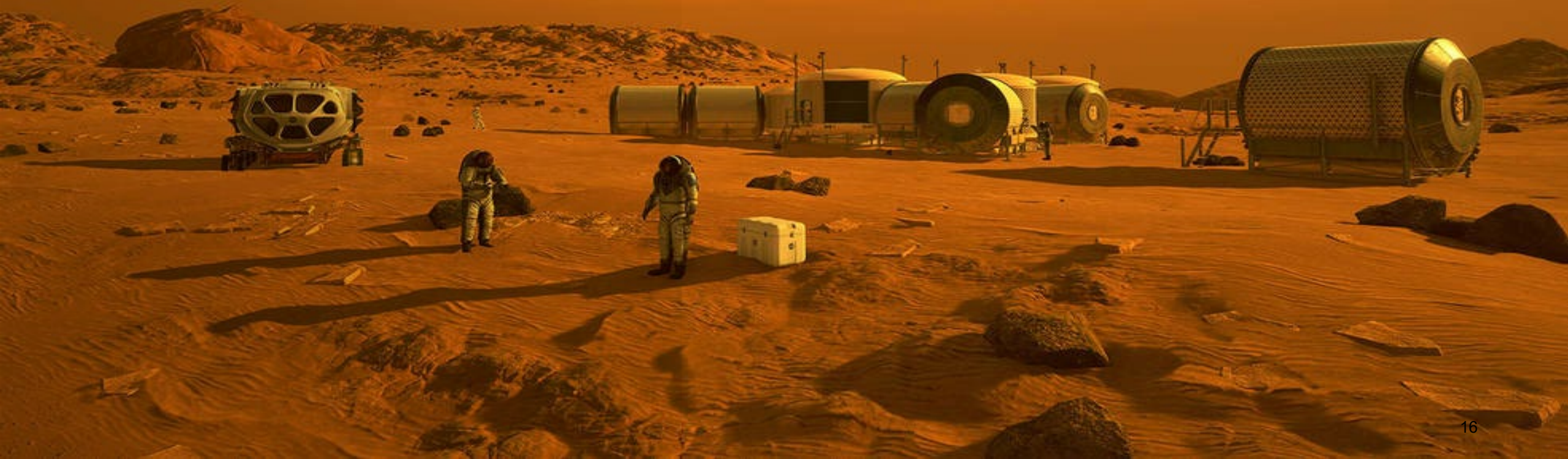
- Exercise the power sharing controller with real AMPS hardware (DC/DC converter) using Speedgoat
- Run real-time Simulink model power system in parallel with HiL
- APC runs from Linux CPU
- Verify power sharing behavior on real hardware



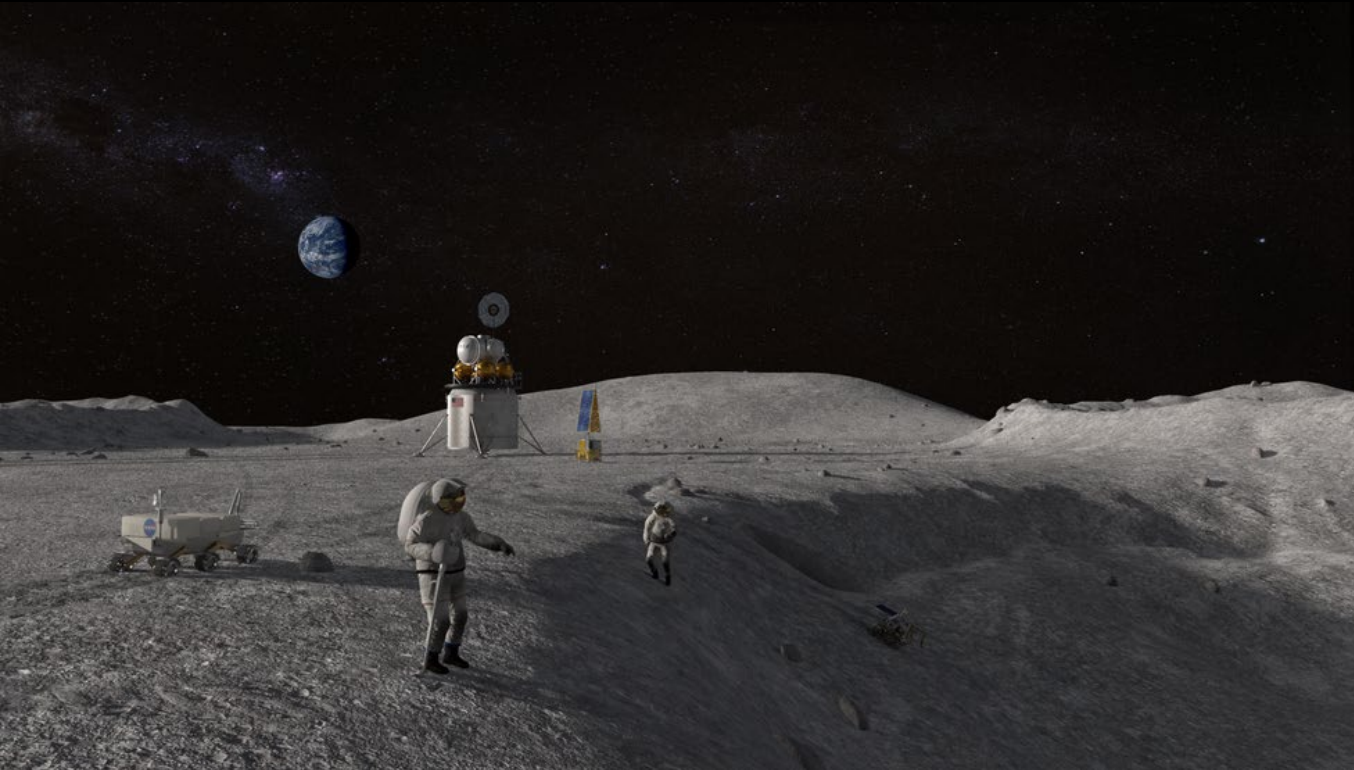
Future Power Architectures



- **Flexible mission-driven architectures**
 - Modular, adaptable, and scalable
 - Highly reliable and mobile power
 - Flexible power strategy
 - Integrate “any source” power
 - Convenience and availability
 - Mixed power types (AC & DC)



NASA / Army Collaboration Opportunity: Universal Power



“In the future fight, soldiers engaged in battle will likely be cut off from outside resources and support. They might as well be on the moon.”

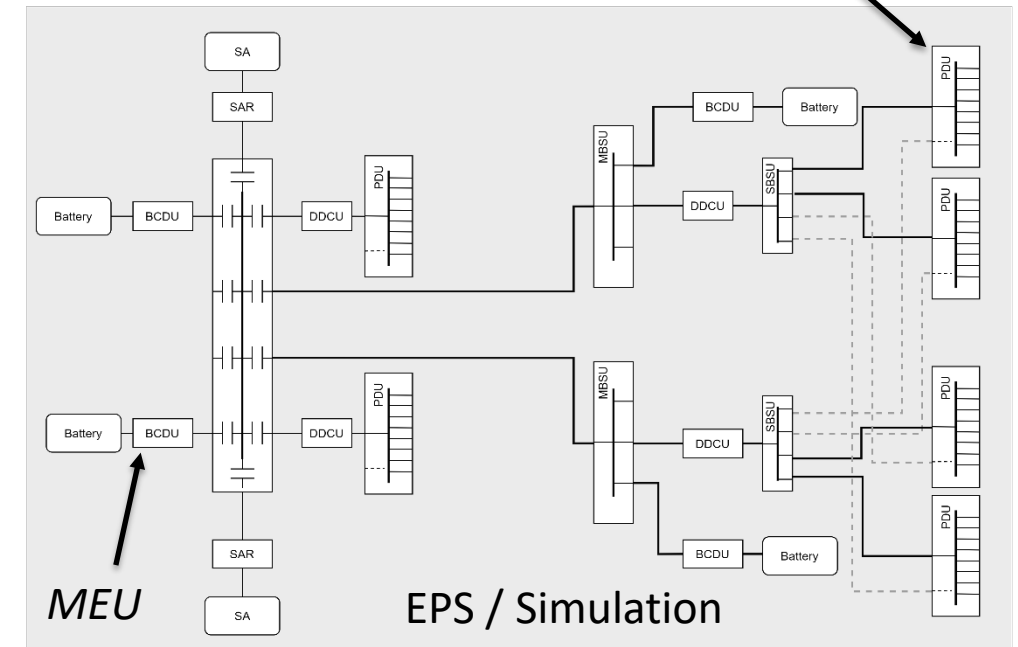
-Tom Bozada on the similarities of Army and NASA interest in future power needs

- **TMS is a government (DoD) developed open interoperability standard for Intelligent Power Systems**
 - TMS uses Data Distribution Service (DDS) as a messaging system
 - DDS Topics contain message content
 - Hardware information
 - Telemetry (Operational Data)
 - Commands
 - Replies
 - Enables interoperable power system components to form a microgrid
 - Ensures interoperability in communications between intelligent power equipment
 - Management and monitoring of power system devices
- **Benefits of a TMS Architecture**
 - Vendor agnostic and prevents proprietary solutions
 - Power system device discovery
 - Enables a plug and play solution
 - Scalable

- Evaluate the Tactical Microgrid Standard (TMS) Open Standard for Space Power Systems
- Project Tasks
 - Understand TMS and how best to implement
 - Implement & demonstrate TMS on MEU
 - Power Distribution Unit
 - Document initial findings of TMS for space power systems
 - Implement & demonstrate TMS for complete electrical power system in software/simulation
 - Develop further plan for PnP Capability
 - Updates to control software to allow for autonomous operation



Power Distribution Unit



- **Collaborations / Partnerships can improve overall technology development**
 - Develop solutions faster and more cost effective
 - Benefit from broader set of expertise and experience
 - US Government - Leverage existing investments (DOD, NASA, etc.)
- **Terrestrial, Tactical, and Lunar Microgrids have similar challenges**
 - Integration of dissimilar power sources (renewables)
 - Highly distributed power system architectures
 - Ensure performance (stability, interoperability, etc.)
 - Need for highly automated and autonomous power systems
 - Terrestrial: Difficult for human operator to take full economic advantage of renewables
 - Tactical: Operators may not have sufficient time/resources
 - Lunar: Operations continue while systems are un-crewed
 - Deep Space Exploration: Communication latency times force on-board control

- **Moon2Mars Mission & Lunar Surface Power offers an opportunity for technology development:**
 - Common power system components
 - Modular, adaptable, scalable, and reconfigurable power systems
 - Intelligent power systems
 - Flexible power strategy (“any source power”)
 - Highly reliable power
 - Reducing human interaction towards fully autonomous operation
 - Standards
 - High Voltage Standards and AC Power Quality Standards for Space
 - Interface Standards

Thank you

