Power and Energy for the Lunar Surface

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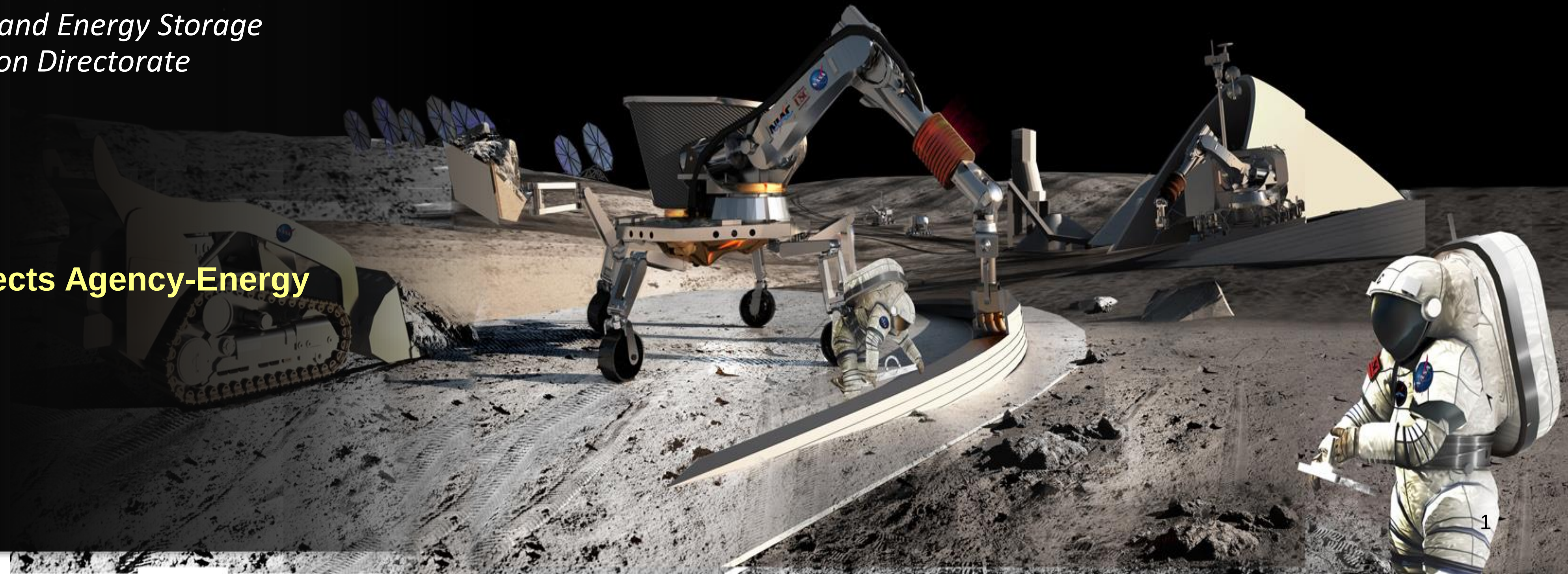
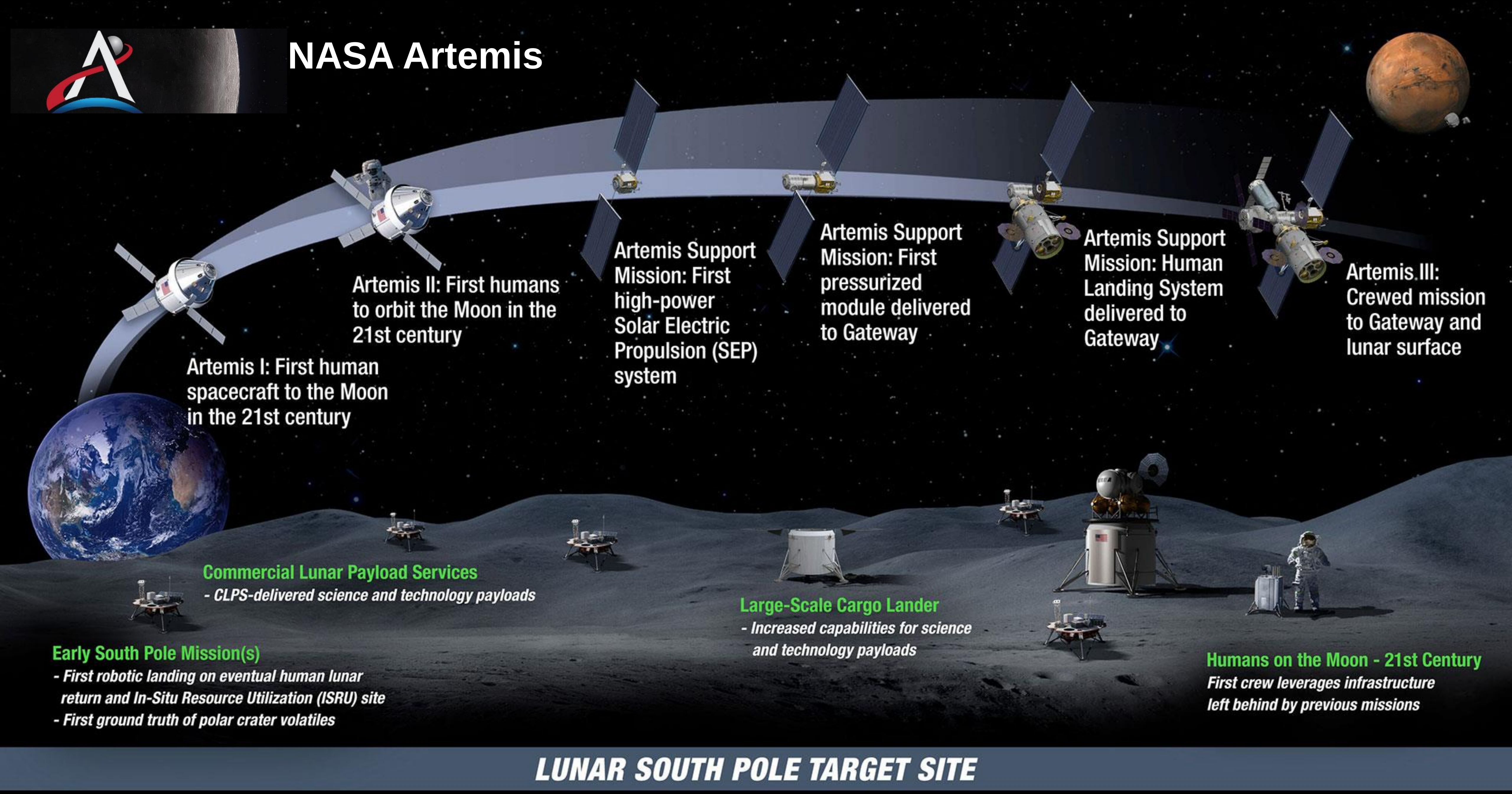
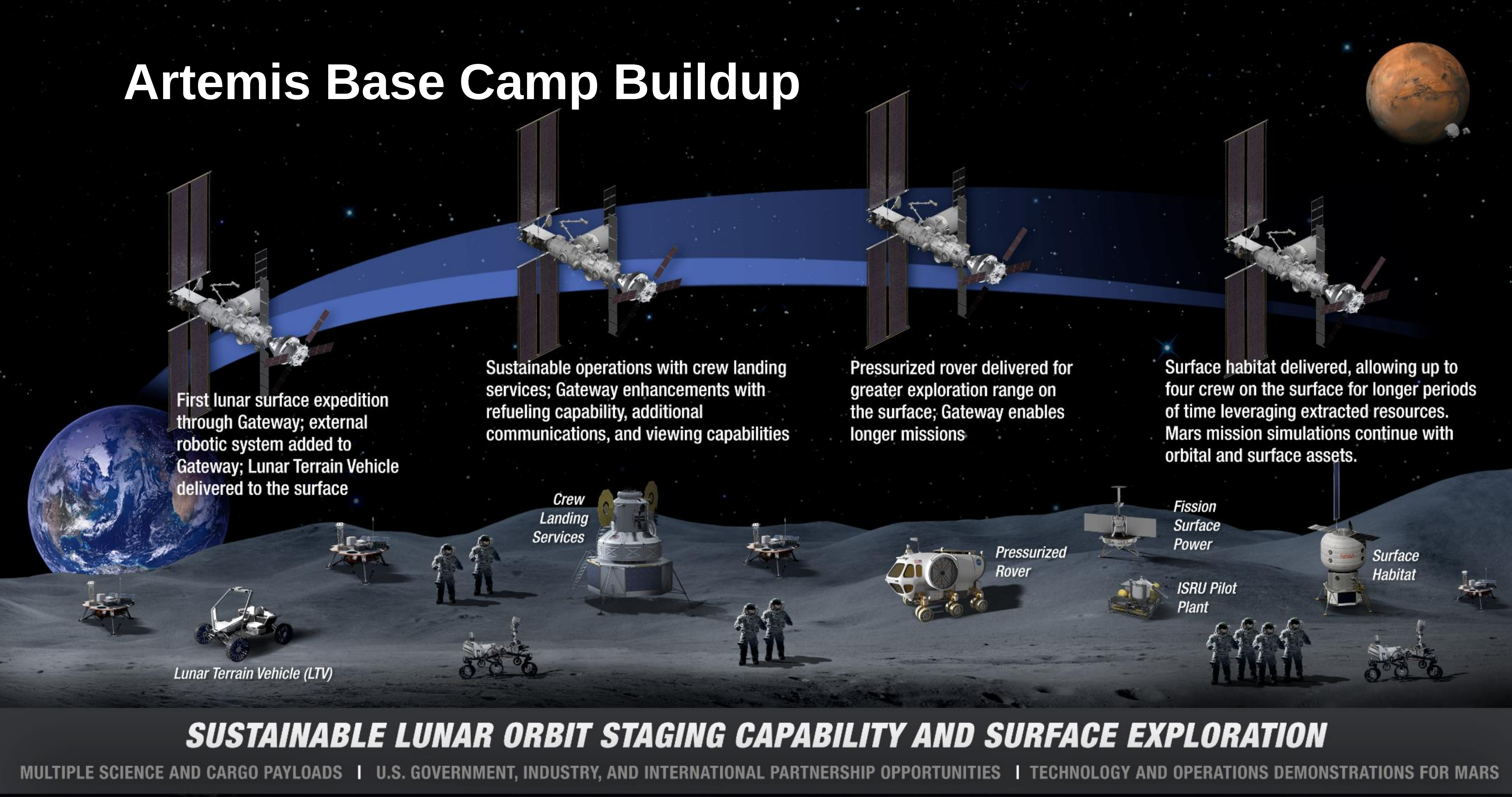


Advanced Research Projects Agency-Energy (ARPA-e)
Tech-to-Market Briefing
April 29, 2022

NASA Artemis



Artemis Base Camp Buildup



POWER

The key commodity needed to exploit the Lunar Surface

Equatorial Illumination Limits

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

Illumination

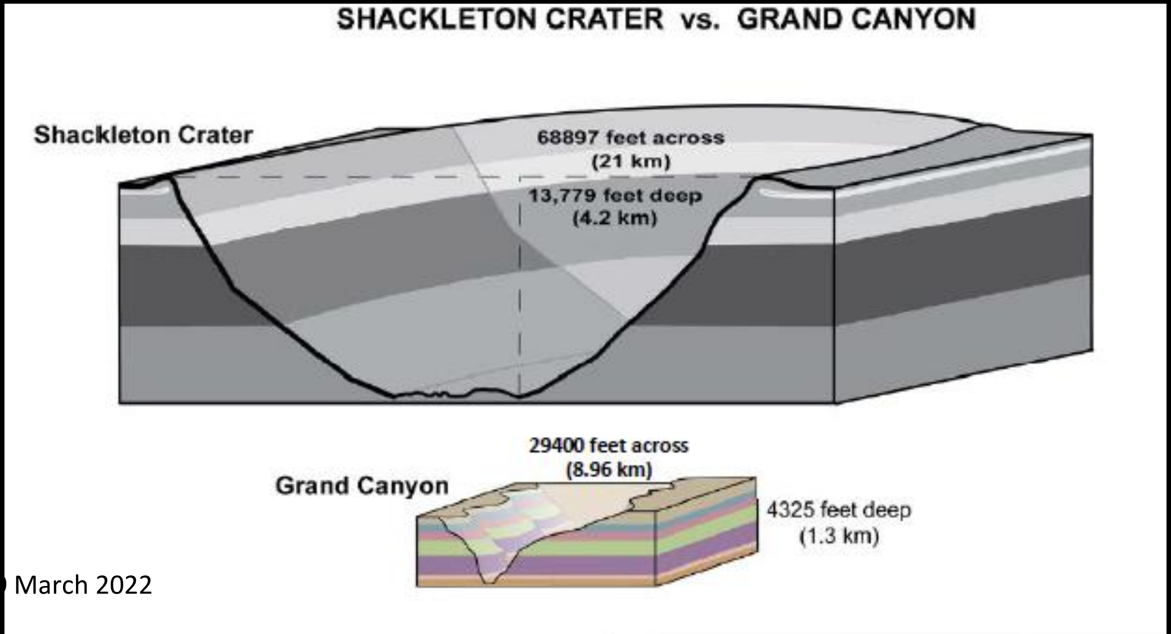
The scarce resource needed to produce power

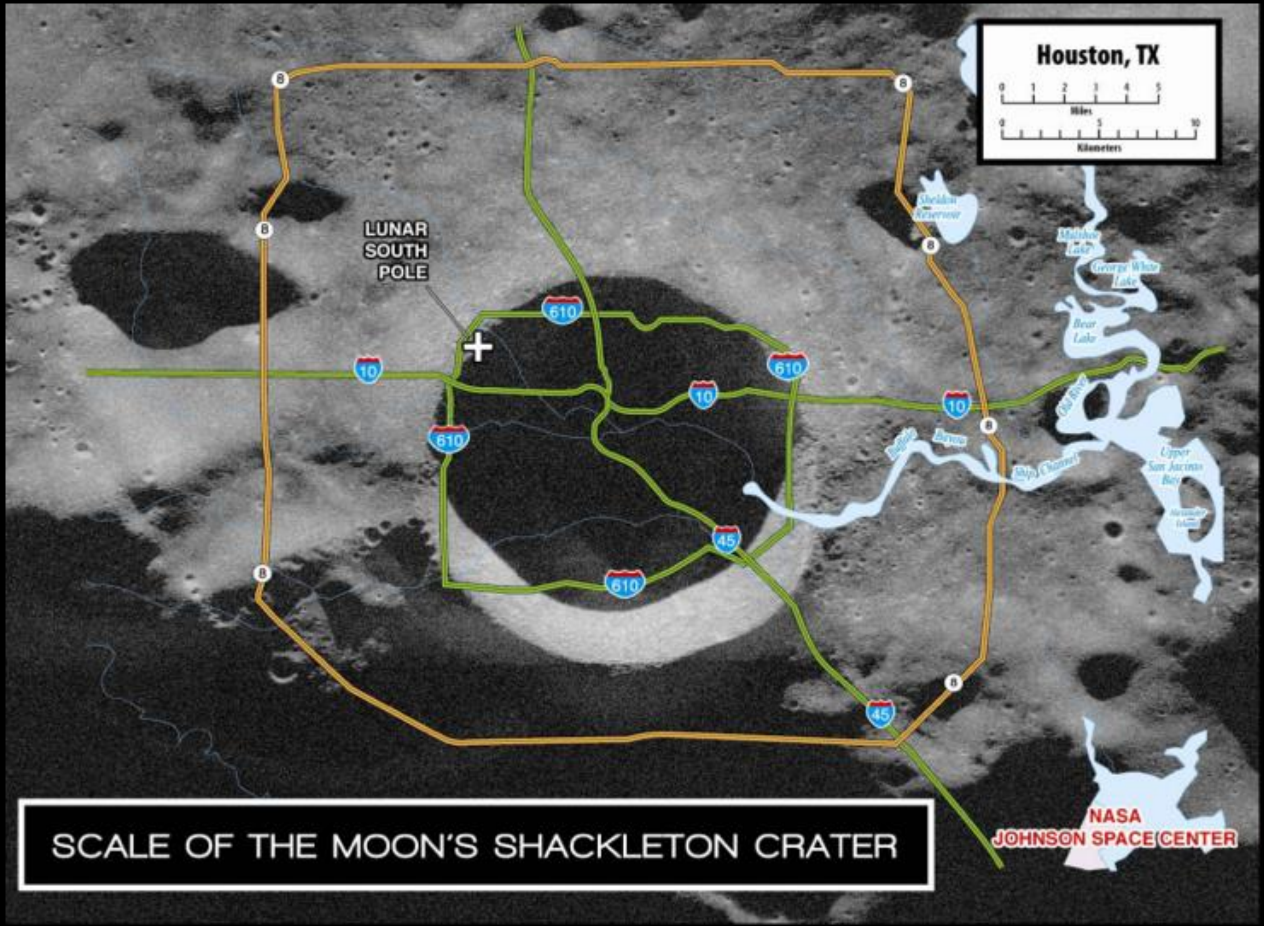
Polar Illumination Limits

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

Shackleton Crater

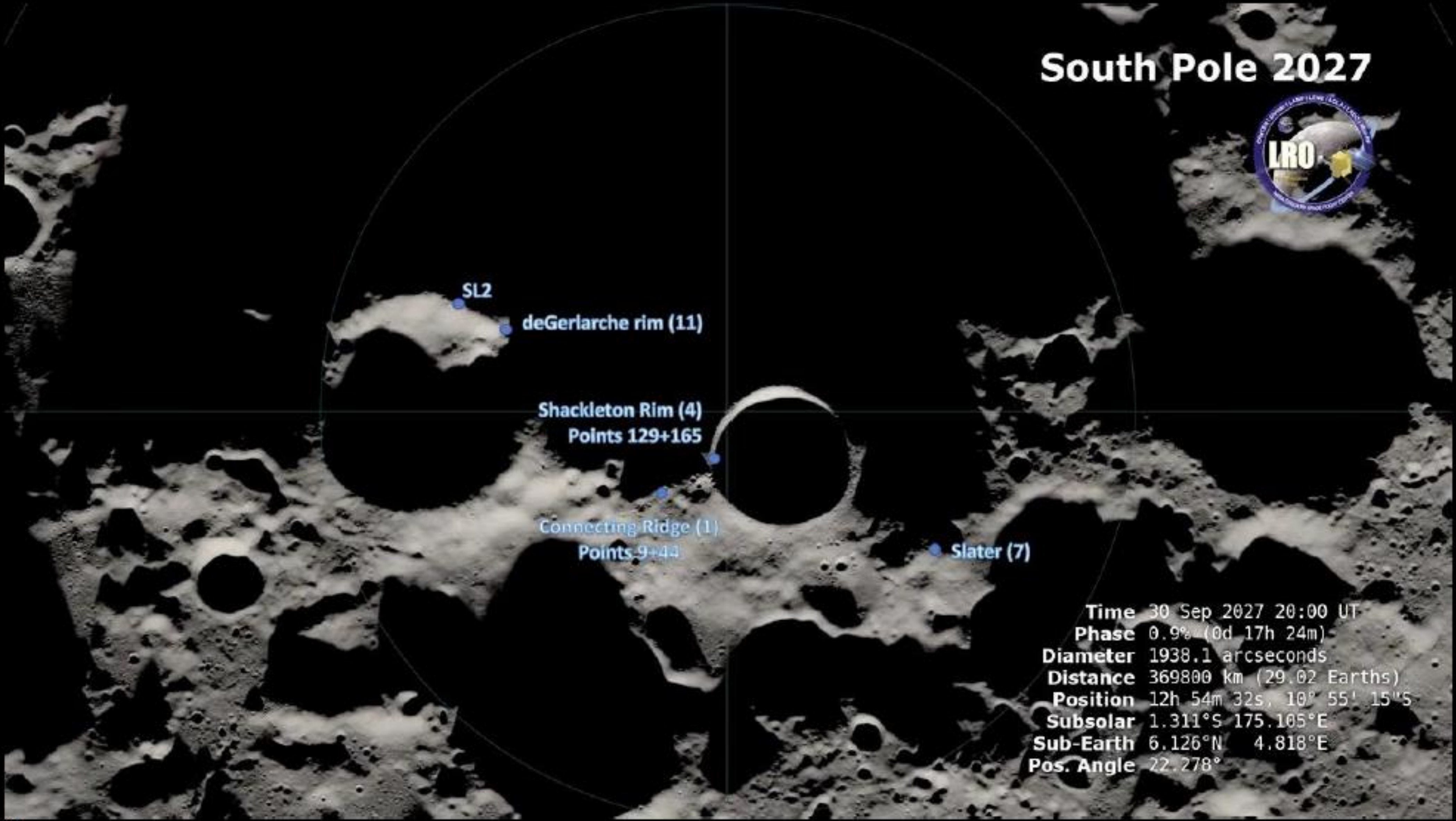
- ~20 km in diameter
- ~4 km deep and ~3x deeper and wider than the Grand Canyon at Enfilade Point
- Located at Lunar South Pole
- Rim and Connecting Ridge are primary targets for future lunar landings





Artemis Base Camp Zone

90-Day Illumination Cycle at South Pole



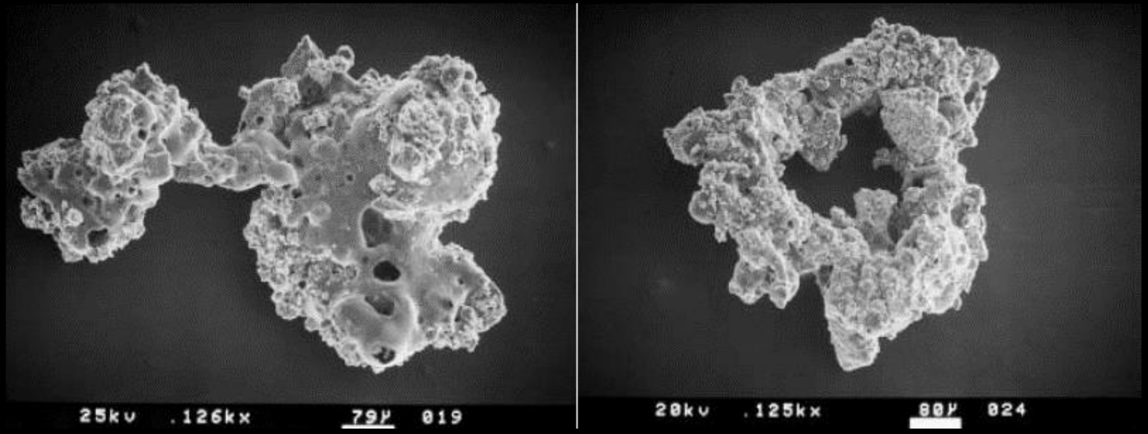
Lunar Surface Environment

Dust and Thermal Extremes are challenges in general.

Lunar Surface Temperatures

-173 C to 130 C
(-250 C in Permanently Shadowed Regions)

Lunar regolith (incl. lunar dust) is angular, abrasive, irregular in shape, small in particle size, and adheres to surfaces

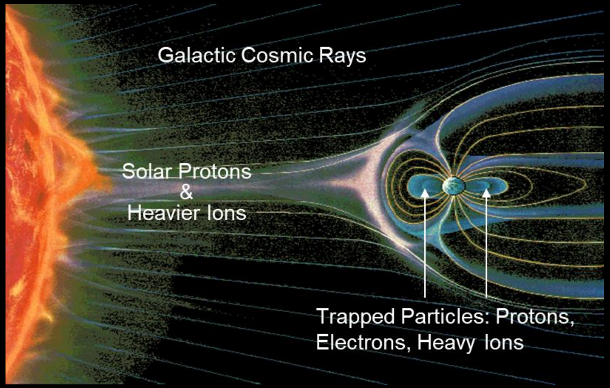


Lunar Surface Environment

RADIATION is the more difficult problem, particularly for semiconductors

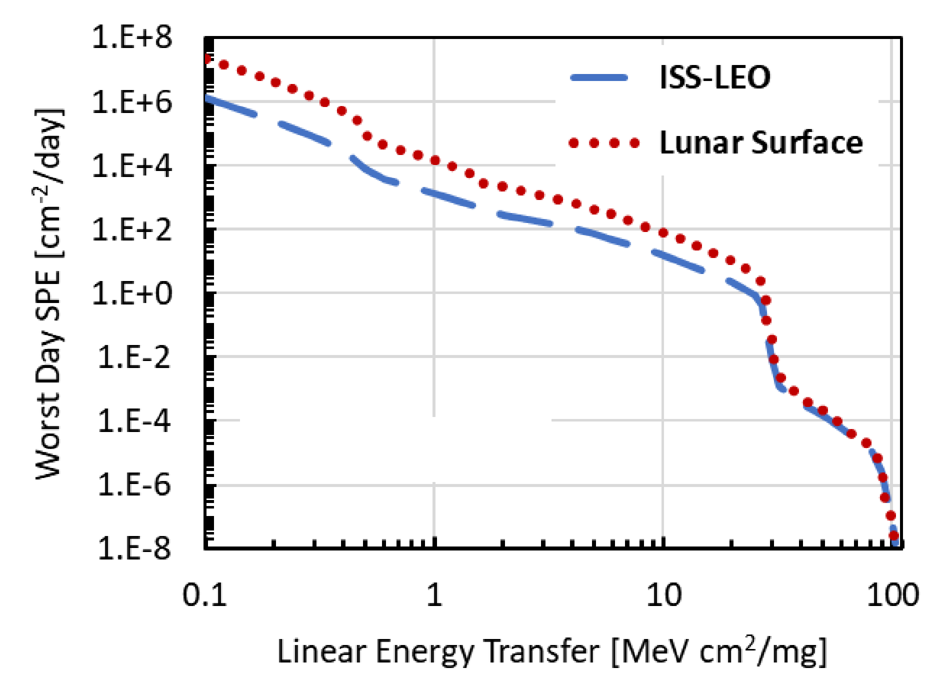
Total Ionizing Dose

Orbit	~1-year TID (2.5 mm Al) krad(Si)
Jovian	1000
GEO	150
Lunar Orbit	4
Lunar Surface	2
ISS LEO	2
Earth Surface	< 0.001



Single Event Effects

"Achilles' Heel" of Wide Band Gap Materials



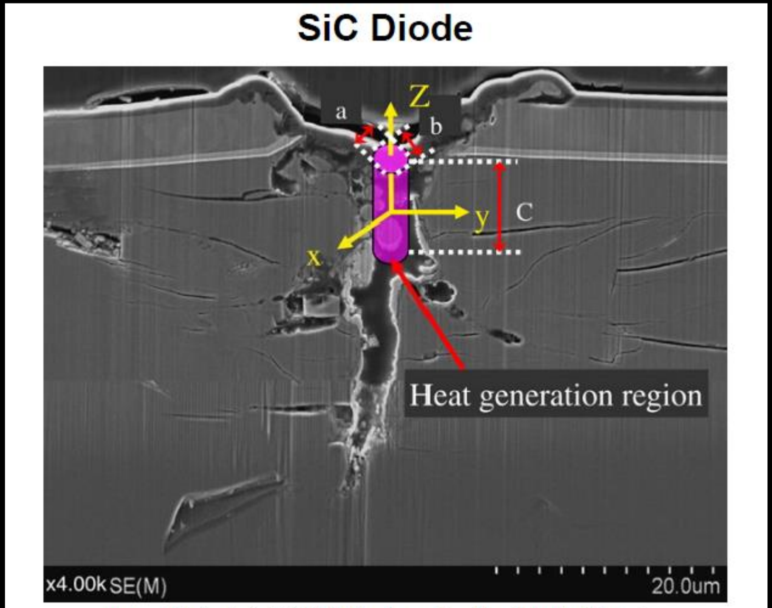
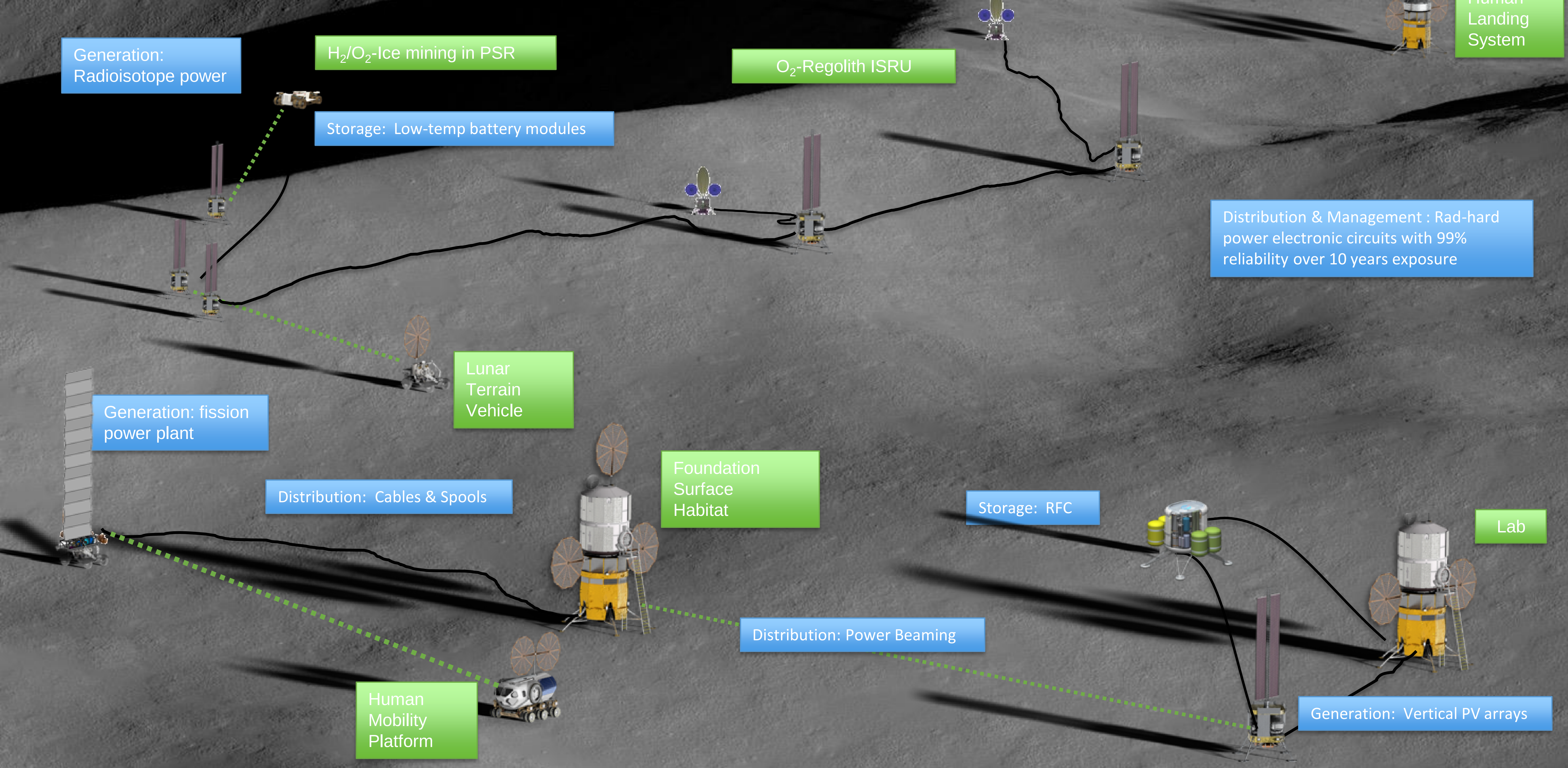


Image: Shoji, et al., © (2014) The Japan Society of Applied Physics, used with permission.

Building Block Power Technology Options for Initial Artemis South Pole “Outpost” (2030+)



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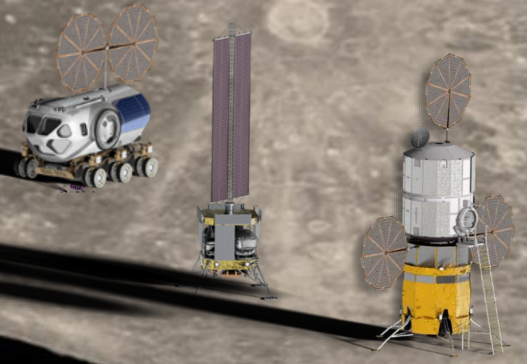
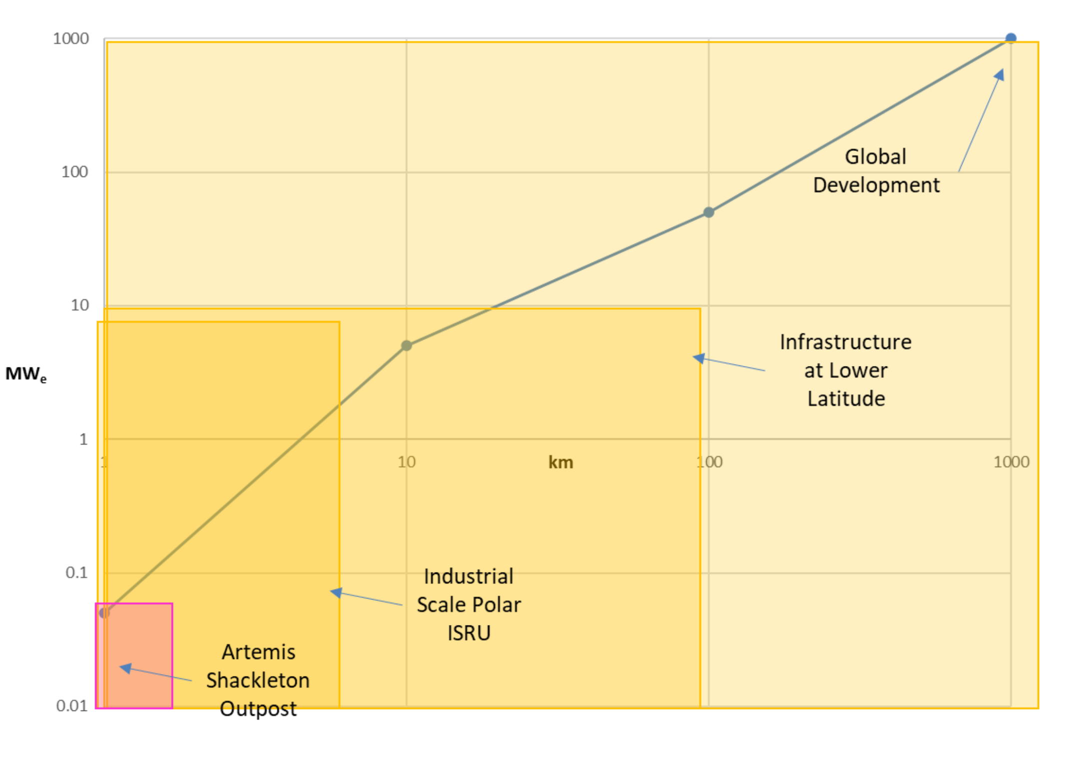
Ultimate Global Exploitation



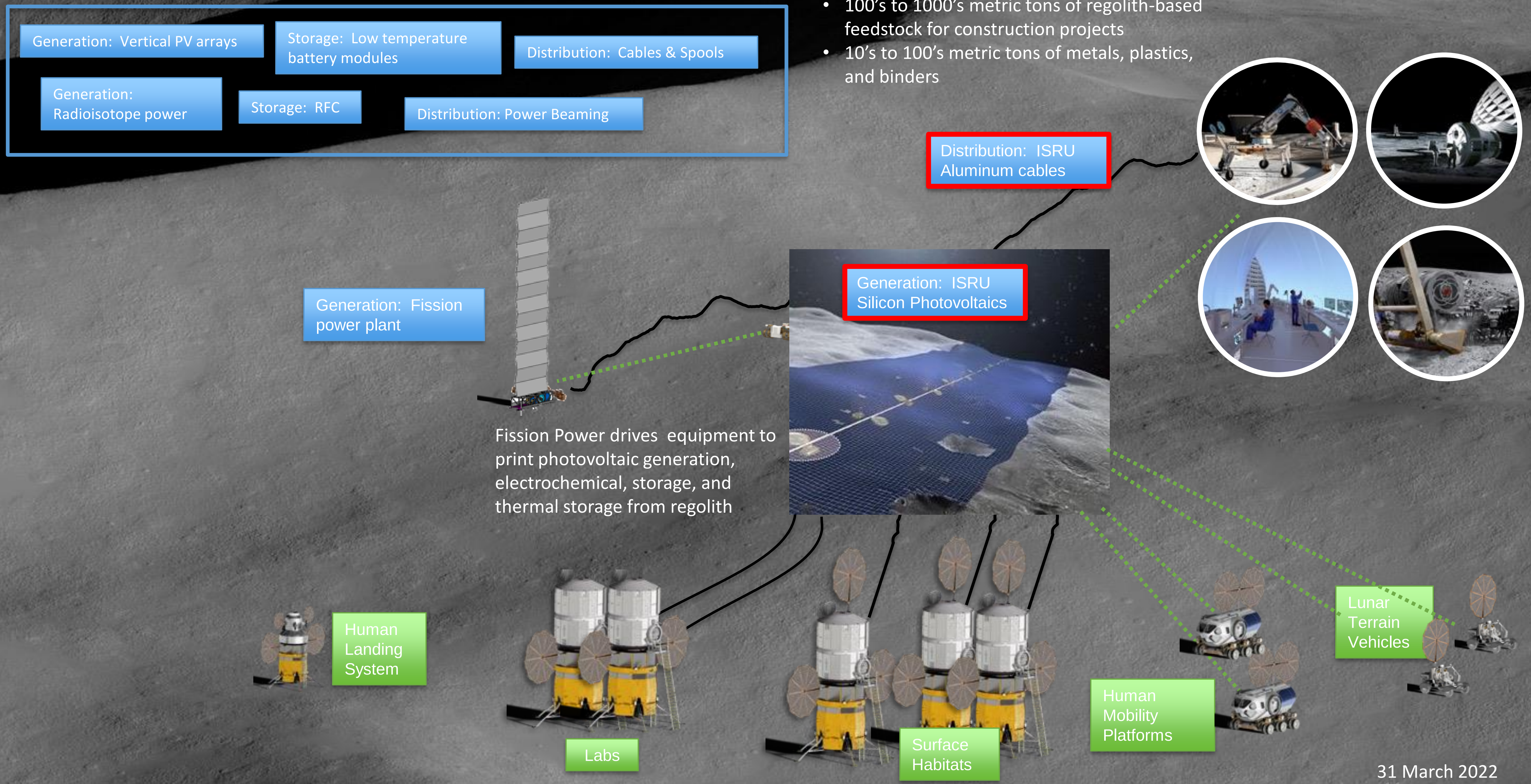


Initial Polar Region Exploitation

Current projects support initial phase of Polar infrastructure expansion

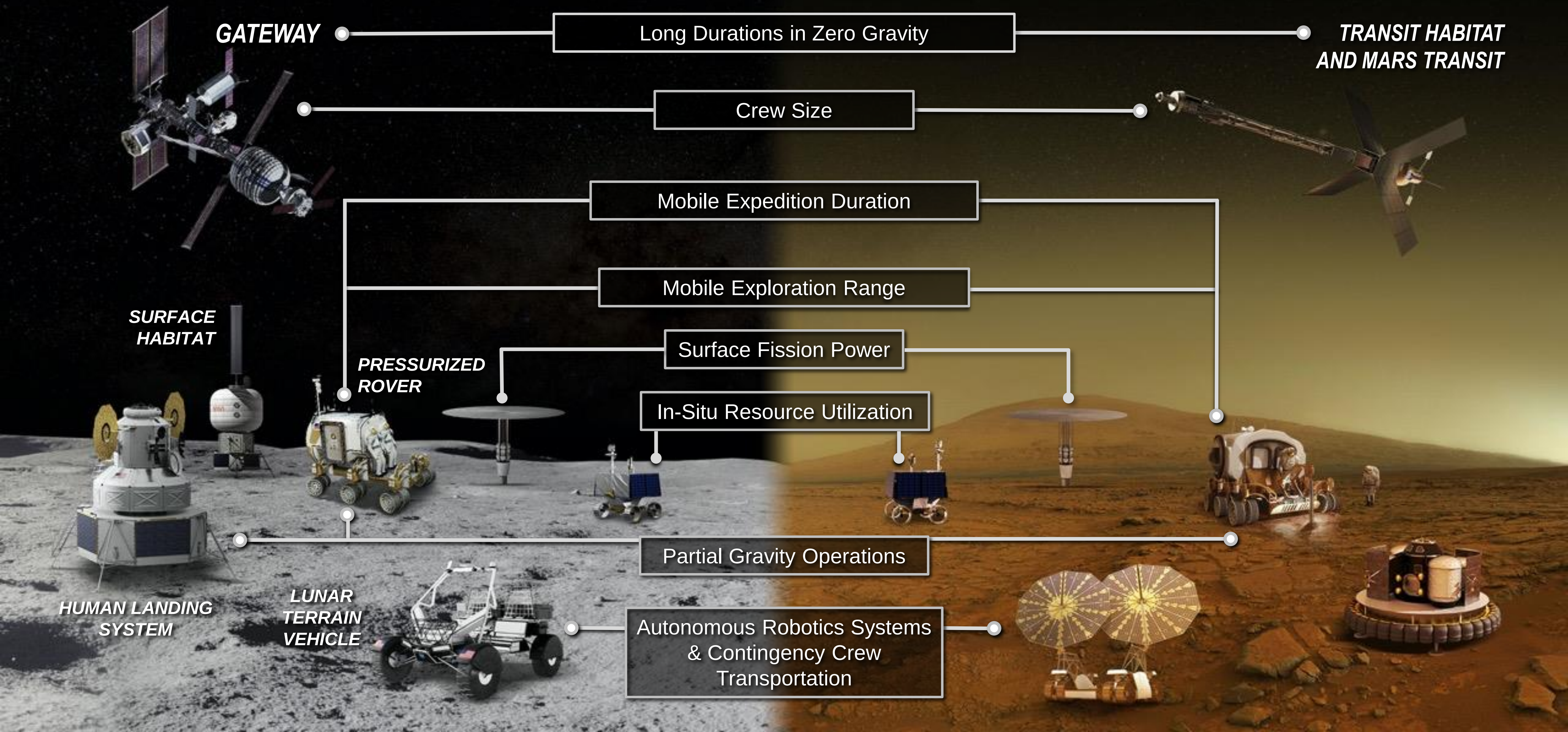
Polar Building Block Power Technologies Can Bootstrap Generation, Storage and Distribution at Lower Latitudes (2040+)

- Landing pads and protective structures
- 100’s to 1000’s metric tons of regolith-based feedstock for construction projects
- 10’s to 100’s metric tons of metals, plastics, and binders

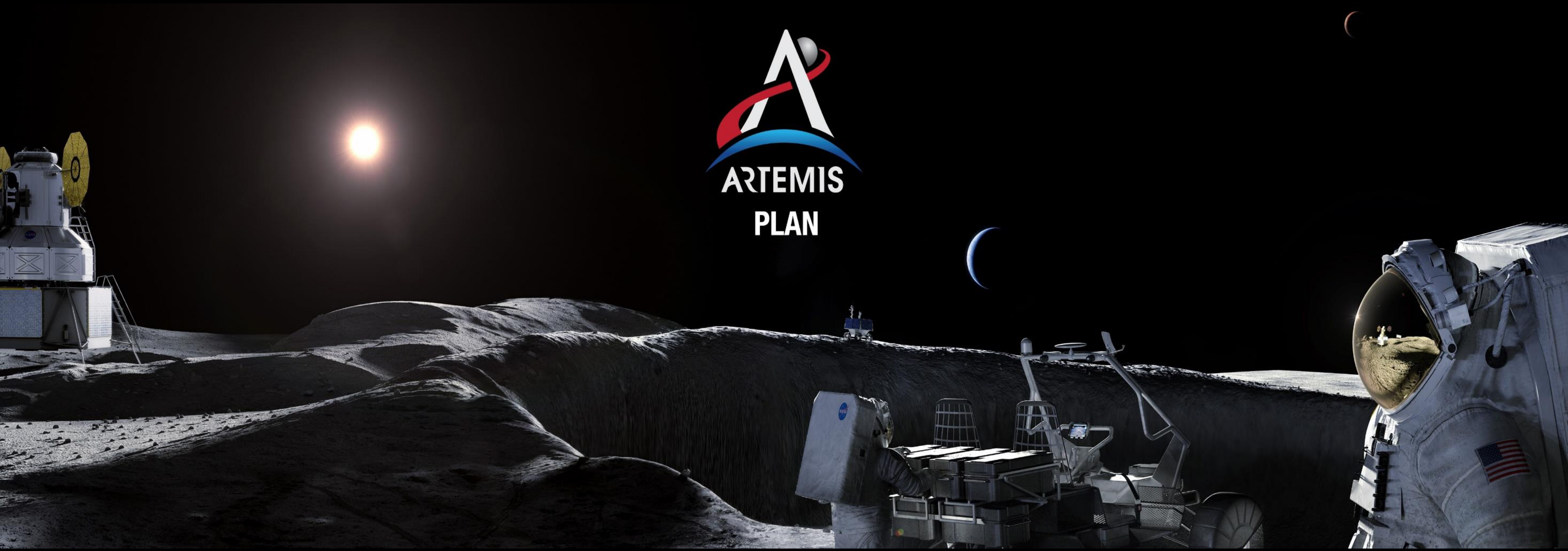


Moon to Mars Exploration

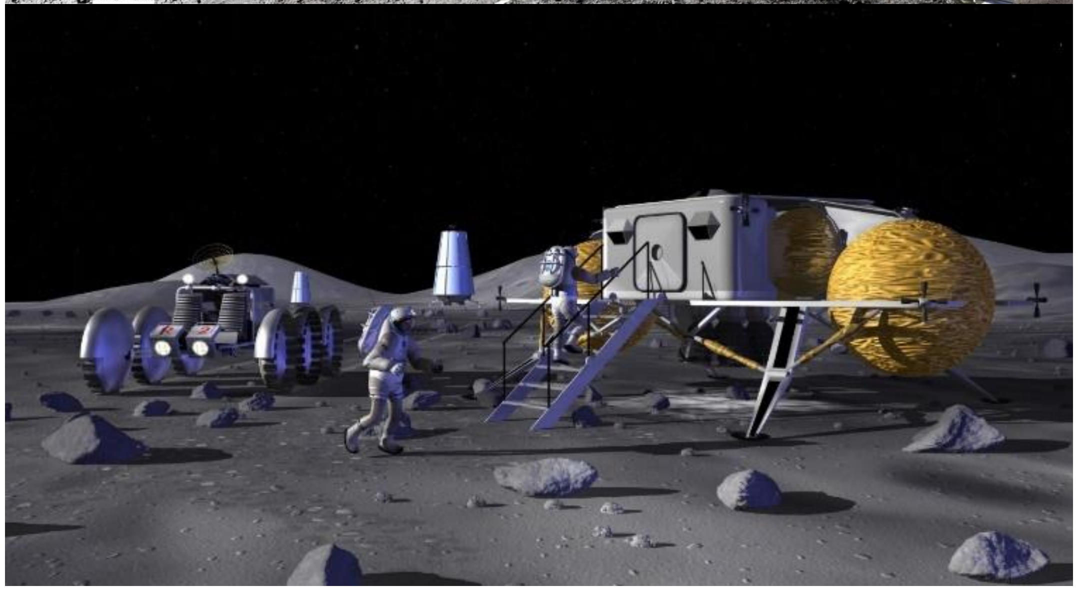
Operations on and around the Moon will help prepare for the first human mission to Mars



Sustainable Lunar Surface Power



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

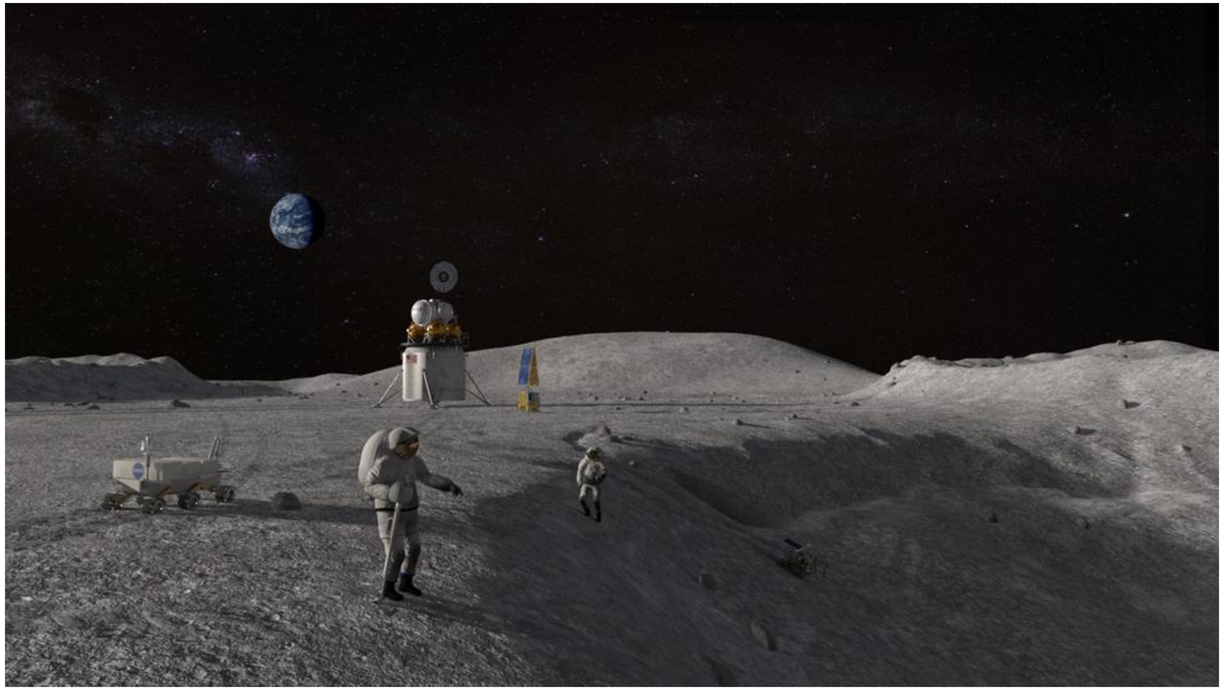
Lunar Surface Sustainable Power Challenges

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

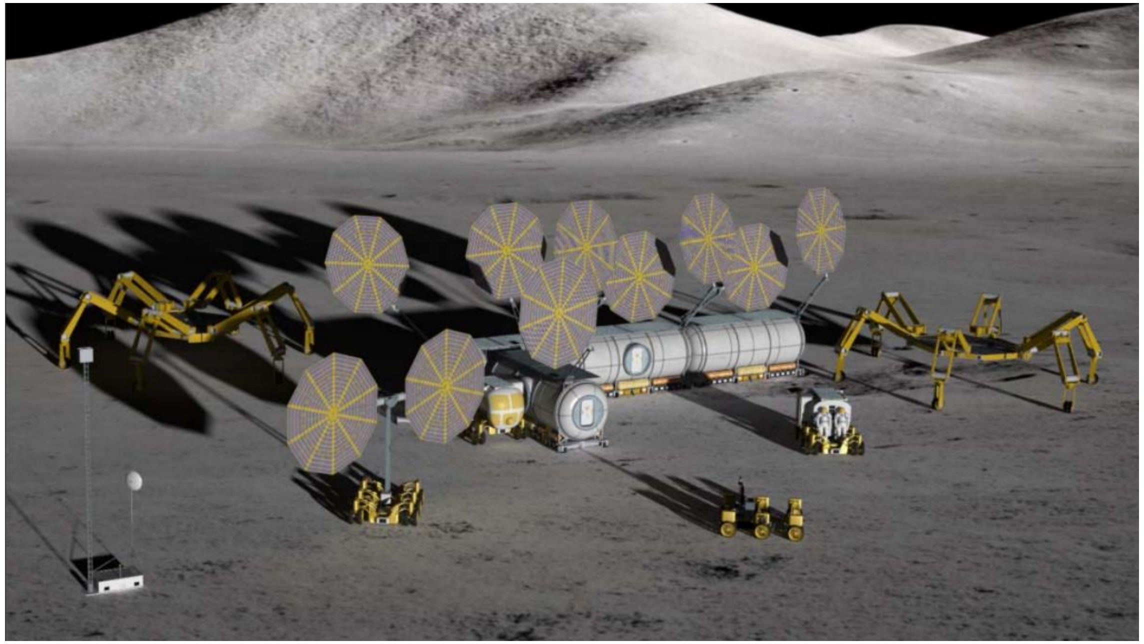
- **Power Availability Challenges**
  - Night-time power demand
    - Extend daylight operations

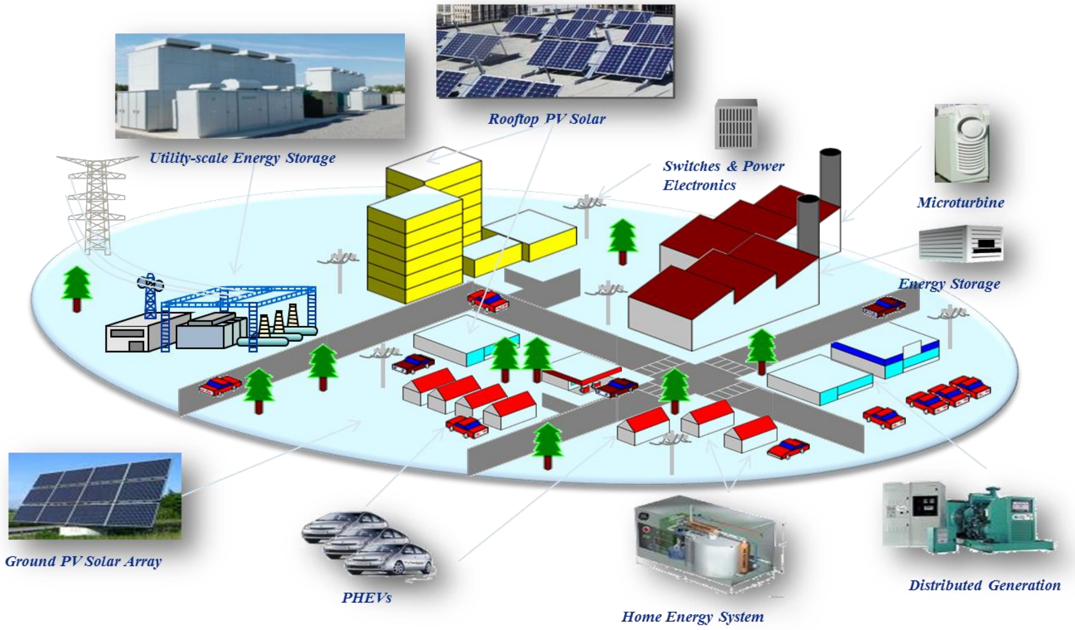
- **Operational Challenges**
  - Robotically deployable PMAD / power systems
  - Autonomously operated PMAD systems



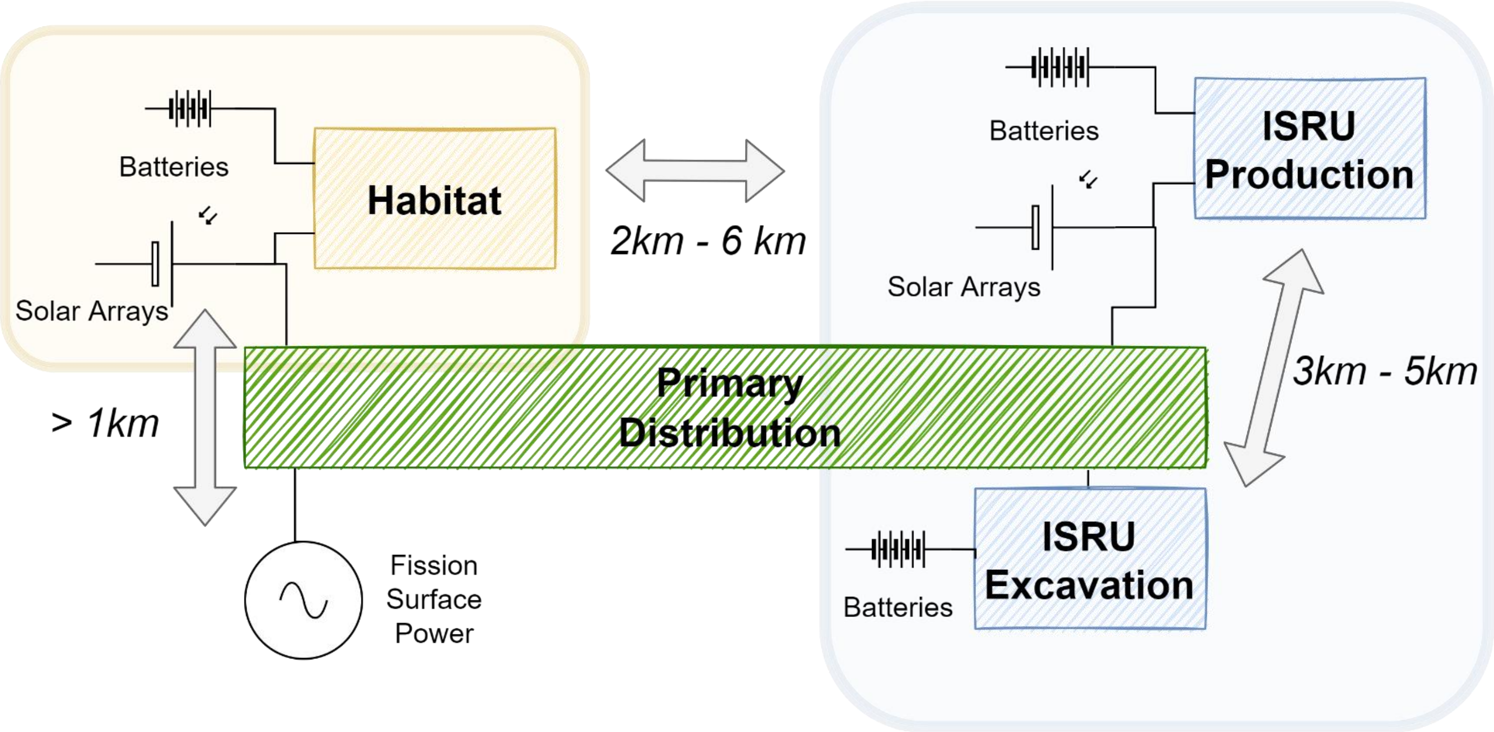
Case for a Microgrid

- **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**





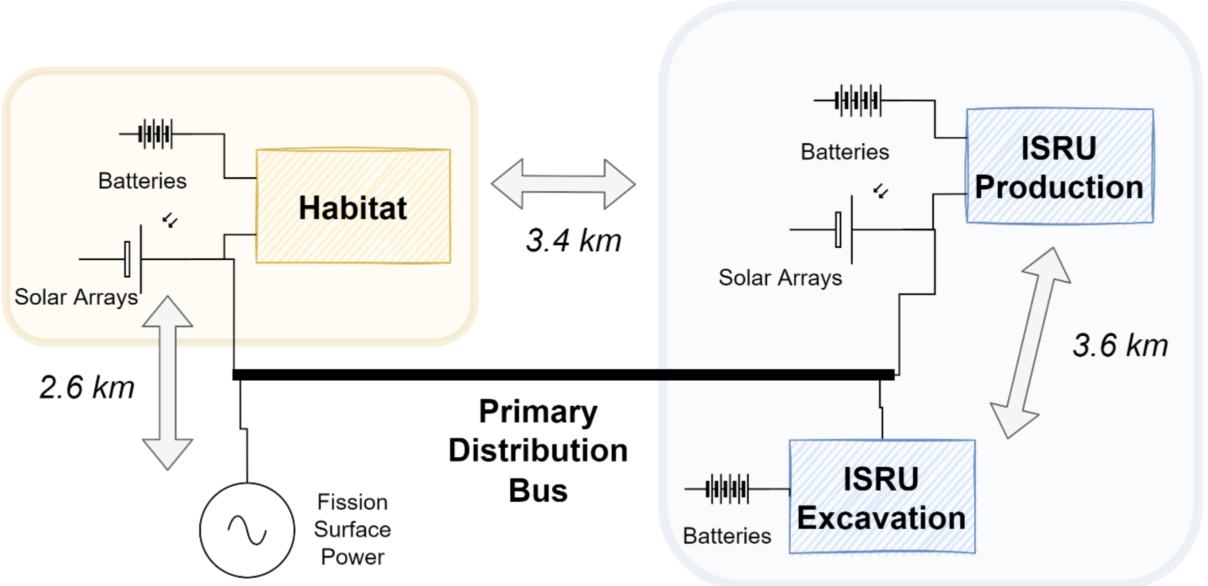
Notional Artemis Base Camp Microgrid



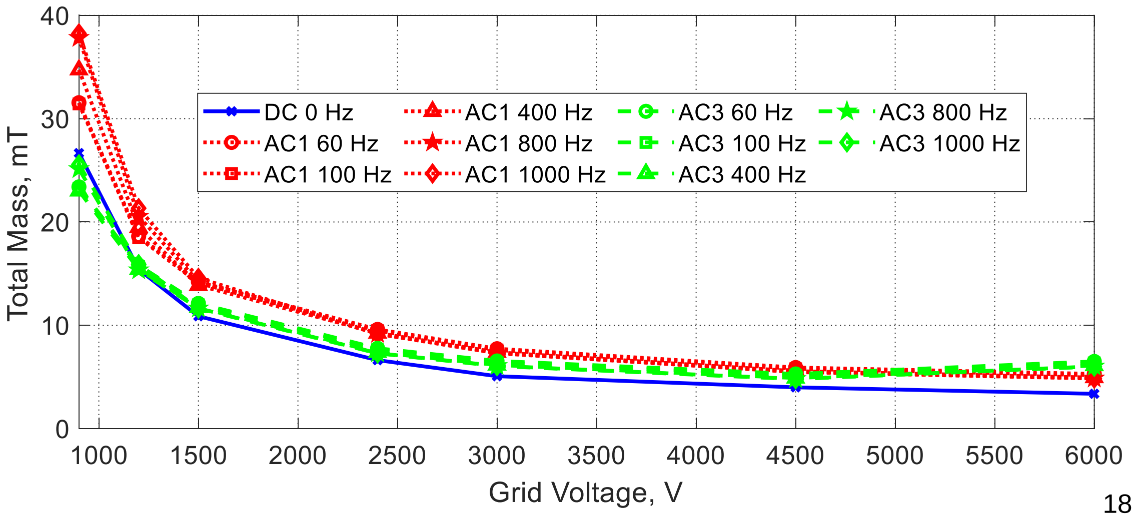
- **Lunar surface south microgrid**
  - Create local microgrids that can manage their own power
  - Primary distribution system to enable power sharing between local microgrids
  - Additional power sources (such as FSP) that can be utilized by and local microgrids
  - Additional power loads can connect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

Notional Artemis Base Camp Microgrid

- **Trade studies focused on primary power distribution system**
  - Architecture (radial, ring, mesh)
  - Power type (AC vs DC)
  - Voltage: (600V – 6 kV)
  - Data contains estimated mass of converters + cables
- **Results**
  - Increasing voltage up to 3 kV has large mass advantages
  - AC vs DC at a single voltage is marginal
    - Especially higher voltages
  - Technology limitations need to considered
    - Max DC: 1.5 kV
      - Rad hard limitations
    - Max AC: none known



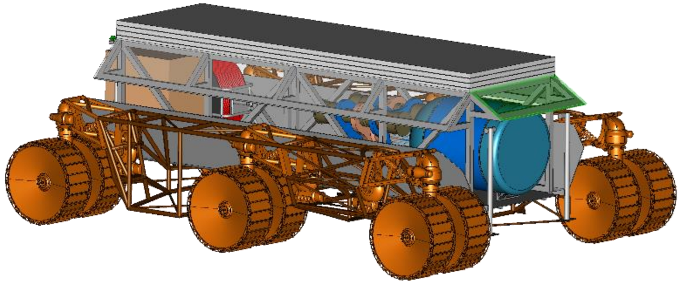
Radial Architecture



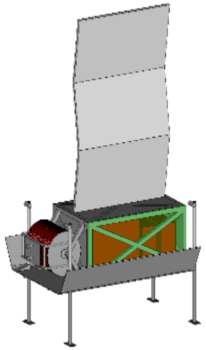
NASA Technology Development Projects

Fission Surface Power (FSP)

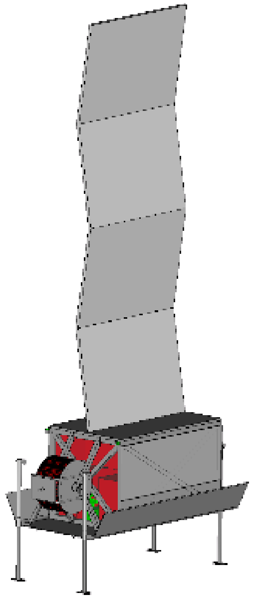
- **NASA and DOE are collaborating on the development of a 40 kWe fission surface power system for a demonstration on the moon by late 2020s with extensibility to Mars missions**
  - DOE has designated Idaho National Laboratory to manage development contracts. Los Alamos National Laboratory will provide subject matter expertise for reactor design
- **Develop the system for a 10-year life, support sustainable lunar operations**
- **Government reference design technical specs**
  - 10,000 kg mass estimate, 250-270 kg/kw
  - System is separated into 3 packages: power system, controllers, and load converter
  - Power conversion: Four - 6 kWe Stirling pairs, sodium heat pipes
  - 1-3 km power transmission to users. Elevated voltage (2 kV+) proposed. Assessing risks.
  - Nominal thermal power: 250 kWth
  - Heat transfer: sodium vaper heat pipe



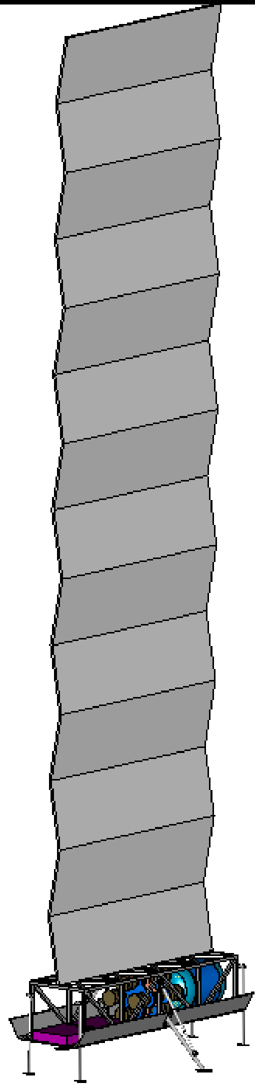
40 kW power system on lunar rover



User I/F



Control electronics

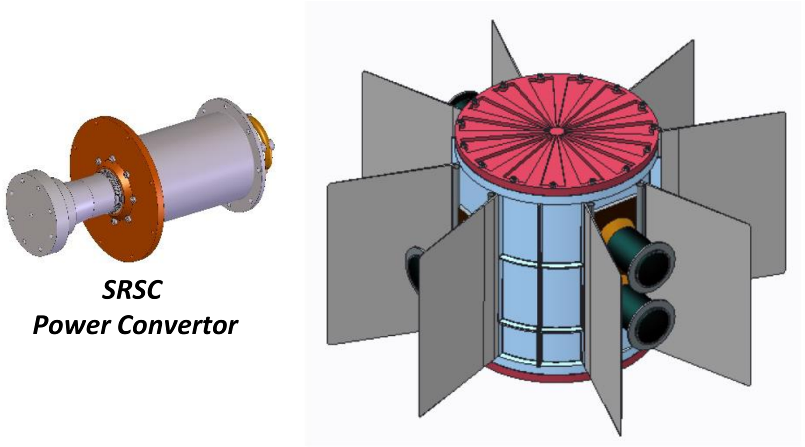


Power system

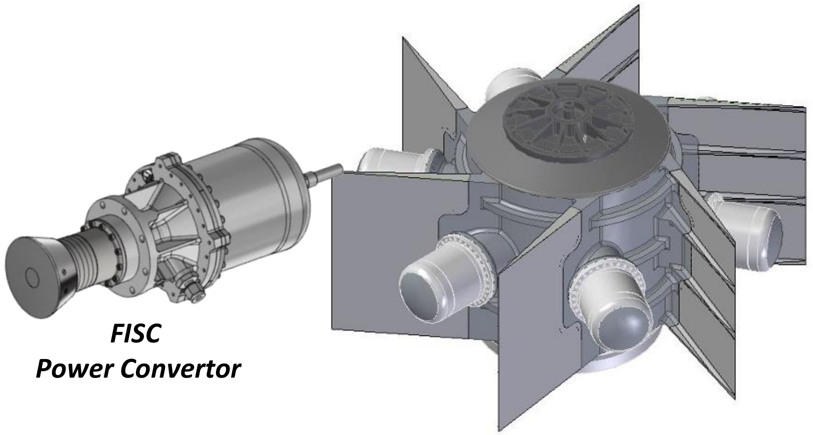
1) Oleson, Steven et al. *"A Deployable 40 kWe Lunar Fission Surface Power Concept"* Nuclear and Emerging Technologies for Space (NETS) 2022.
2) Barth, C. and Pike, D. *"Lunar power Transmission for Fission surface power"* Nuclear and Emerging Technologies for Space (NETS) 2022

Dynamic Radioisotope Power Systems (DRPS)

- **New prototype convertors were delivered in 2020/2021 through a ROSES solicitation aimed to increase technology readiness level**
  - Requirements focused on increased robustness based on past lessons learned
  - Four Stirling convertors delivered and tested at GRC's Stirling lab
  - Demonstrated performance, environmental testing is in progress
- **Contractor system concepts were delivered in 2020**
  - Multiple convertor designs enable single fault tolerance and high reliability
  - Generator concepts include six ~60 W_e Stirling units in synchronized pairs
  - Nominal thermal power input: 1,000 W_{th}
  - System Efficiency: 24%
  - 17-year life requirement
- **NASA and DOE are collaborating on development of a Dynamic Radioisotope Power System for a lunar demonstration by late 2020s with extensibility to Mars and outer planets**
  - DOE has designated Idaho National Laboratory to manage the development contract
  - Aerojet Rocketdyne was selected for a Phase 1 design contract, in progress
  - Required power level is 300-400 We



238 W_{dc} SRSC-based Generator Concept



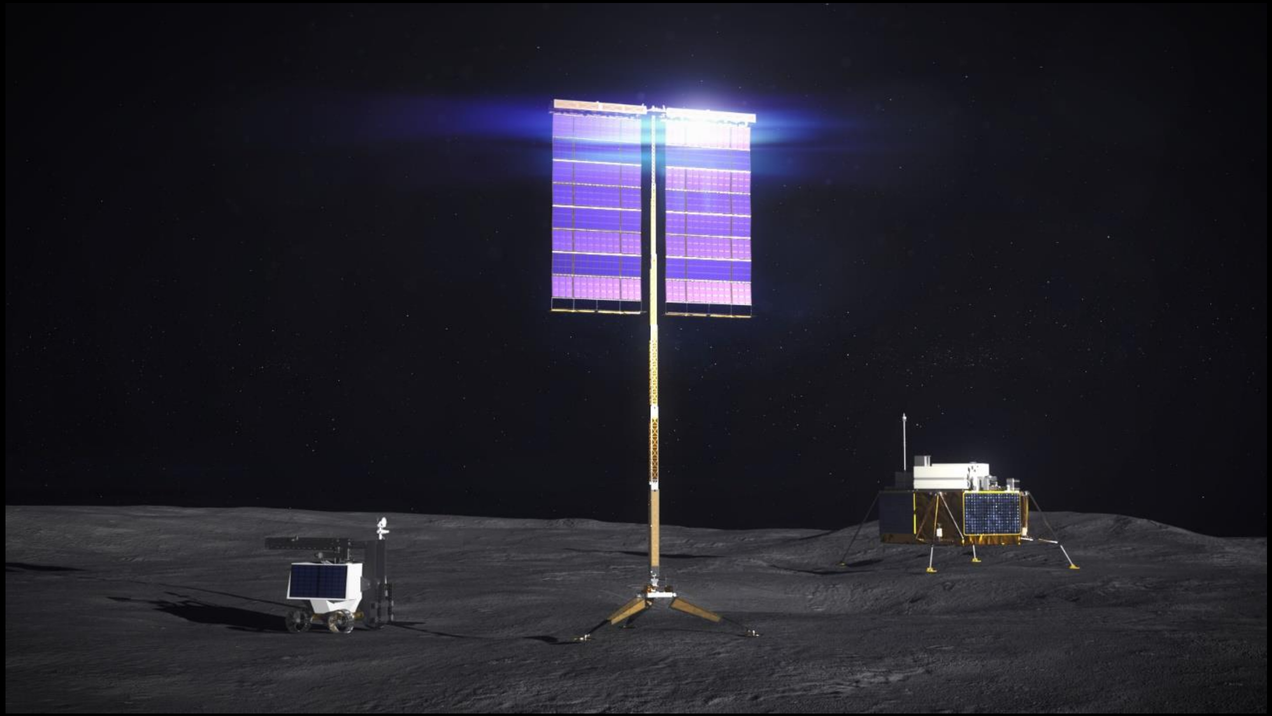
237 W_{dc} FISC-based Generator Concept

Solar Array Development – Lunar Surface

- Vertical Solar Array Technology (VSAT) project led by STMD's Game Changing Development program and NASA Langley in collaboration with NASA Glenn
- Autonomous deployment systems of 30 ft masts, stable on steep terrain, resistant to abrasive lunar dust and minimized both mass and packaged volume for ease in delivery to the lunar surface

Base period contracts, valued at up to $700,000 each, awarded as 12-month fixed price contracts to:

- Astrobotic Technology, Pittsburgh, PA
- ATK Space Systems (Northrop Grumman), Goleta, CA
- Honeybee Robotics, Brooklyn, NY
- Lockheed Martin, Littleton, CO
- Space Systems Loral (Maxar Technologies), Palo Alto, CA



The companies will provide system designs, analysis, and data.

The agency plans to down select up to two companies and provide additional funding, up to $7.5 million each, to build prototypes and perform environmental testing, with the ultimate goal of deploying one of the systems on the Moon's South Pole near the end of this decade.

Photo credit: NASA

Electrochemical Power Generation and Energy Storage

Power Generation

- *Fuel cells provide primary power to support DC electrical power bus*
  - *Use pure to propellant-grade O_2 / H_2 or O_2 / CH_4 reactants*
  - *Uncrewed experiment platforms*
  - *Crewed/uncrewed rovers*
  - *Electric aircraft / Urban Air Mobility (UAM)*
- *Applications*
  - *Mars/Lunar Landers (~ 2 kW to ≤ 10 kW)*
  - *Lunar/Mars surface systems (~ 2 kW to ≤ 10 kW modules)*
  - *Urban Air Mobility (120 kW to > 20 MW)*

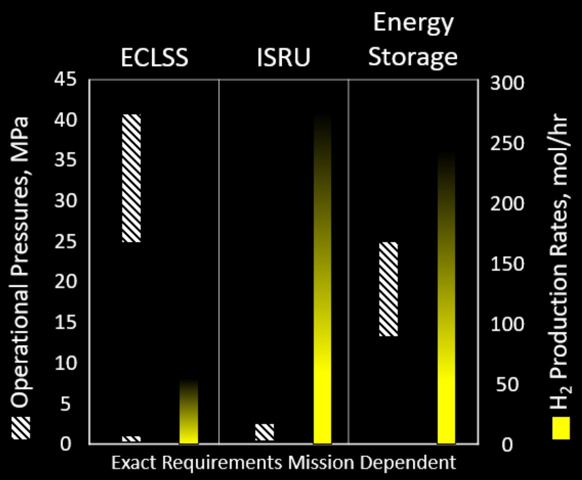
NASA's all-electric X-57 Maxwell prepares for ground vibration testing at NASA's Armstrong Flight Research Center in California. Credits: NASA Photo / Lauren Hughes

Center for High-Efficiency Electrical Technologies for Aircraft (CHEETA) Design Study for Hydrogen Fuel Cell Powered Electric Aircraft using Cryogenic Hydrogen Storage.

Energy Storage

- *High specific energy (W·hr/kg) Regenerative Fuel Cells (RFC) to store and release both electrical & thermal energy*
  - *RFC specific energy 320 to 650 W·hr/kg depending on mission energy requirements (Packaged Li-ion batteries ~ 160 W·hr/kg)*
  - *Lunar night: ~100 hrs (south pole) to 367 hrs (equator)*
  - *Waste heat helps systems survive the lunar thermal environment (-173°C to +105°C)*
  - *Includes high pressure (O_2 = H_2 @ ≤ 2500 psia) and contaminated water electrolysis*
- *Applications*
  - *Crewed Lunar surface systems (36 kW·hr to ≥ 1 MW·hr)*
  - *Lunar sensor network (≤ 5 kW·hr)*

Notional Electrolysis Requirements



All applications Power and Mass Constrained

Microgrid Definition and Interface Converter for Planetary Surfaces (MIPS)

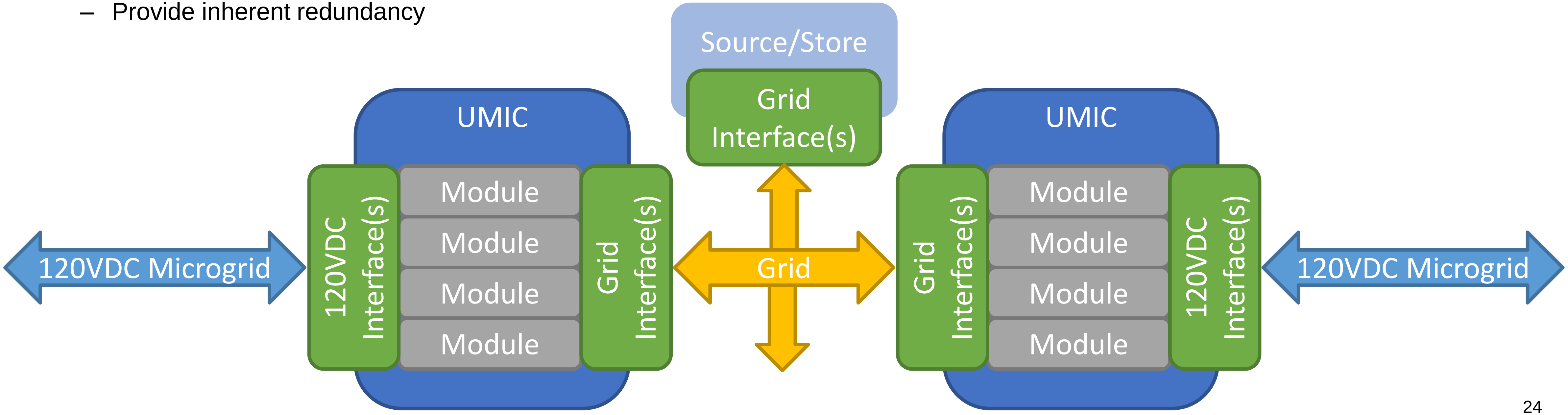
The MIPS Universal Modular Interface Converter (UMIC) is a power converter that provides bidirectional power flow between the power transmission voltage and the primary distribution voltage (120VDC), connecting islanded microgrids to form a grid.

The UMIC is truly modular, as modules can be easily:

- Replaced if damaged
- Relocated to more critical areas (reusable)
- Spared (extras/backups) at low mass and volume
- Paralleled to:
  - Increase total power capability (scalable)
  - Provide inherent redundancy

Prototype development will focus on:

- Developing standard interfaces and specifications:
  - Vendor agnostic; grid-tie regulations
- Determining control strategies (local and grid)
- Characterizing performance (limits, efficiency, etc.)



Flexible DC-Energy Router based on Energy Storage & Integrated Circuit Breaker

PI: Jin Wang, The Ohio State University, wang.1248@osu.edu

Lunar Surface Technology Research

PROJECT OBJECTIVES

The main objective of the project is to combine the

- T-Breaker, which is a modular and scalable dc circuit breaker, and the
- Smart Resistor concept, which is a control method enabled by wide bandgap gap (WBG) devices and energy storage systems,

to realize a flexible DC-Energy Router (DC-ER) between and within a wide range of lunar microgrids.

TECHNICAL APPROACH

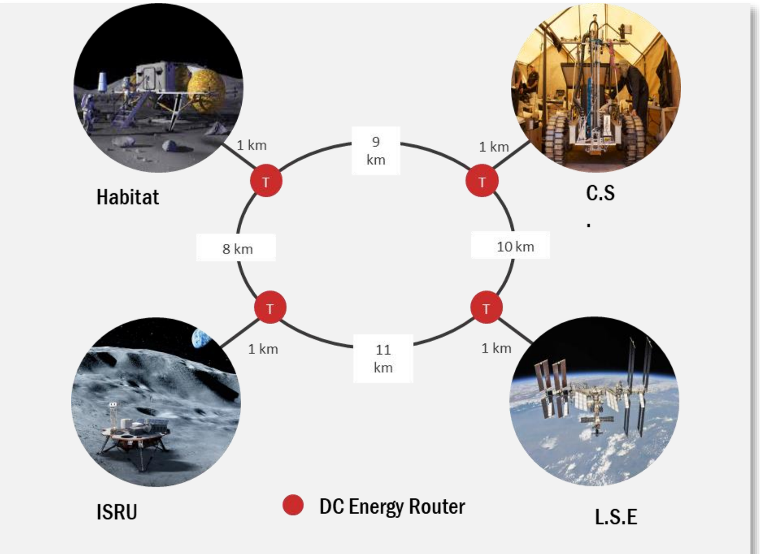
- Architecture study of lunar microgrids
- Three layers of planning and control of microgrids
  - I. Routing, fault diagnostics, reconfiguration strategies
  - II. Energy management system
  - III. Modular T-Breaker based energy router with smart resistor function
- Gallium Nitride based Dc Energy Router prototype
- Scaled down power hardware-in-the-loop based test bed

PROJECT TEAM

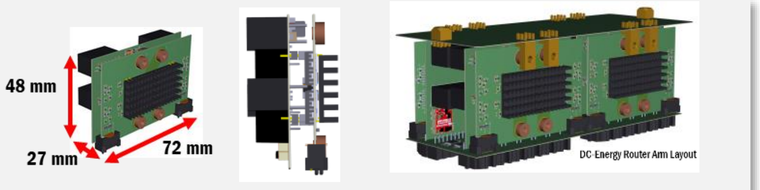
Ohio State University

- Center for High Performance Power Electronics (CHPPE)
- Center for Automotive Research (CAR)

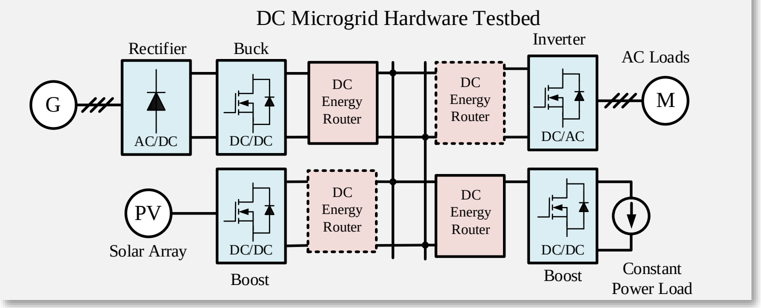
Raytheon Technologies Research Center (RTRC)



Inter-connected lunar microgrids with DC Energy Routers



Design of the GaN based Modules for the DC-ER



SIGNIFICANT ACCOMPLISHMENTS IN THE FIRST TWO QUARTERS

- Established the baseline lunar dc microgrid architecture
- Planning & System Resiliency (Layer 1 Control)
  - Proposed a three-stage methodology for planning
  - Implemented hybrid-edge rewiring strategy to improve the resilience of interconnected microgrids
- Energy Management System (Layer 2 Control)
  - Finished the study of load strategies
- Smart Resistor Control (Layer 3 Control):
  - Finished the analysis, modeling and simulation of DC-ER based smart resistor control to improve system stability against voltage and load transients.
- Hardware Design & Microgrid testbed
  - The electrical and thermal designs of the DC-Energy router are close to complete. Some key components have been ordered
  - The design of the dc microgrid hardware test bed started

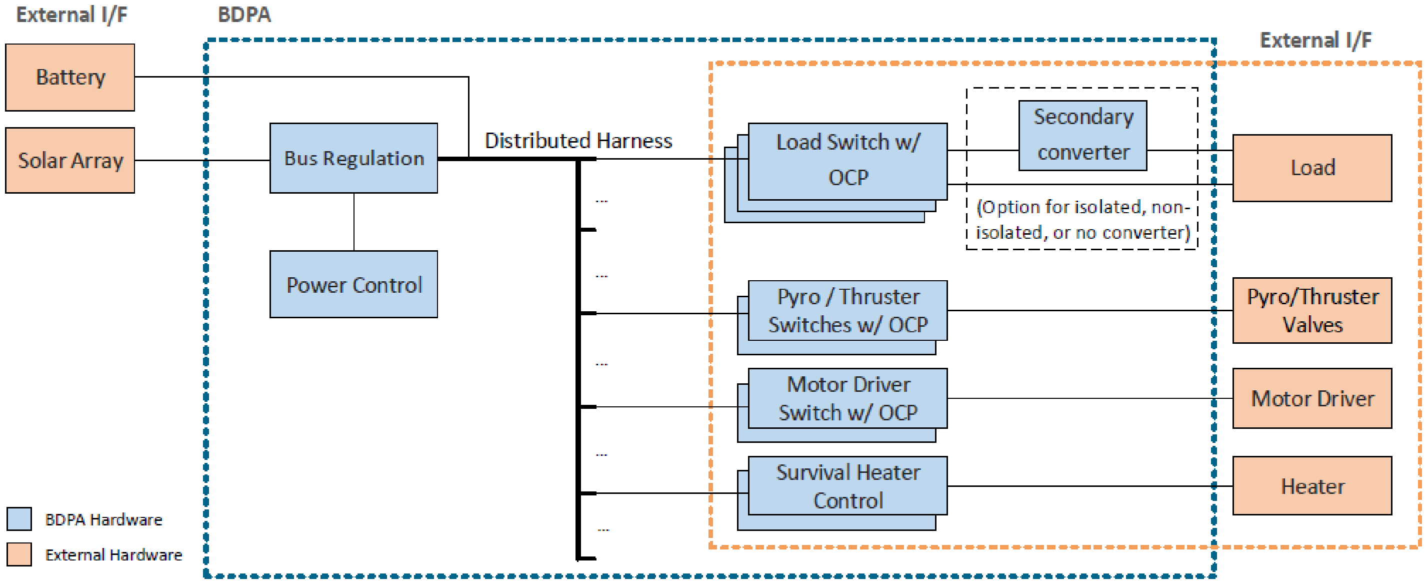
PROJECT IMPACT

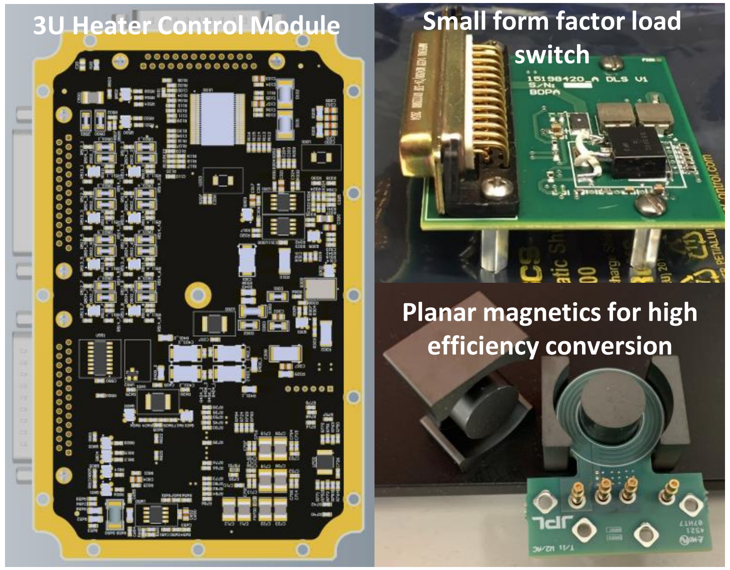
- Modular and flexible solution for control and protection
- Improved stability and resiliency
- Weight and size optimizations of photovoltaic systems and batteries
- High power density design of GaN based circuit building blocks with natural convection
- The first comprehensive model of interconnected lunar dc microgrids at a university
- Routing, reconfiguration and energy management strategies that would be applicable to all types of microgrids
- Graduate student training (10 graduate students have been involved)

Breakthrough Distributed Power Architecture (BDPA)

Description and Objectives

- **Develop a highly-efficient (>95%), low-mass (1kW/kg), high-density (2W/cm^3), distributed power subsystem for *in situ* platforms on the Moon and beyond. The developed system will provide:**
  - Common power and communications busses for all units, enabled through distributed digital control
  - Distributed bus converters for >95% efficiency to loads with localized digital control/telemetry
  - Distributed load switches & linear heater controls to maximize thermal system efficiency
  - Common modules that can be used throughout rover, orbiter, or base power distribution systems

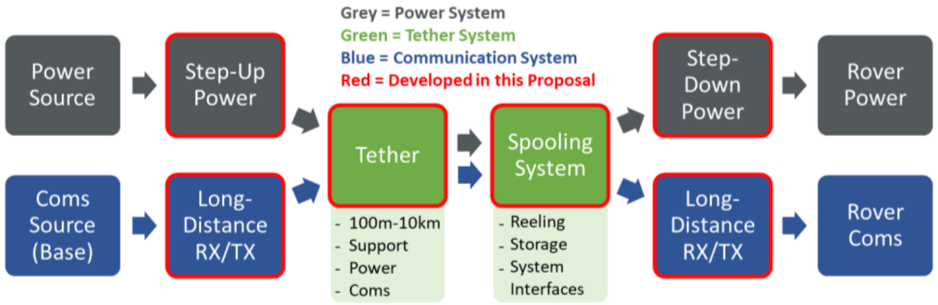




Tethered Power Systems for Lunar Mobility and Power Transmission

Our objective is to develop a tether-based power transmission system to provide power over several kilometers to serve remote loads. The end-to-end tether power system will deliver 100 W – 10 kW of power at above 90 % efficiency and provide communications to:

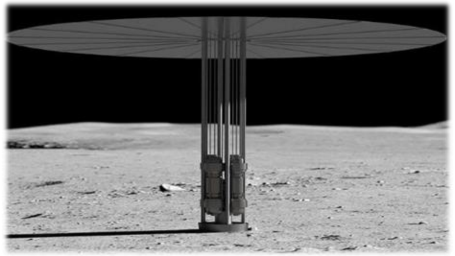
- Enable high-power transmission capabilities for nuclear or solar power systems
- Enable rover access to extreme terrain, like lunar craters, pits, caves, and lava tubes

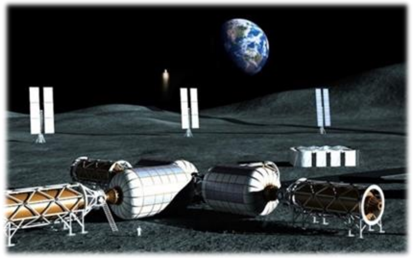


Key Performance Parameter	State-of-the –Art (SOA)	Threshold Value	Goal Value
Step-Up Converter Efficiency	90 %	92.5 %	97 %
Step-Down Converter Efficiency	N/A	92.5 %	97 %
Converter Power Density	0.3 W/cm^3	1 W/cm^3	2 W/cm^3
Converter Specific Power	250 W/kg	500 W/kg	1 kW/kg
End-to-End Efficiency	N/A	80 %	90 %
Tether Communications	N/A	4 mbits @ 10 km	8 mbits @ 10 km

Applications for the TYMPO system include a number of end-users for the lunar surface and other planetary bodies throughout the solar system, such as Mars and Enceladus. Some specific end users include:

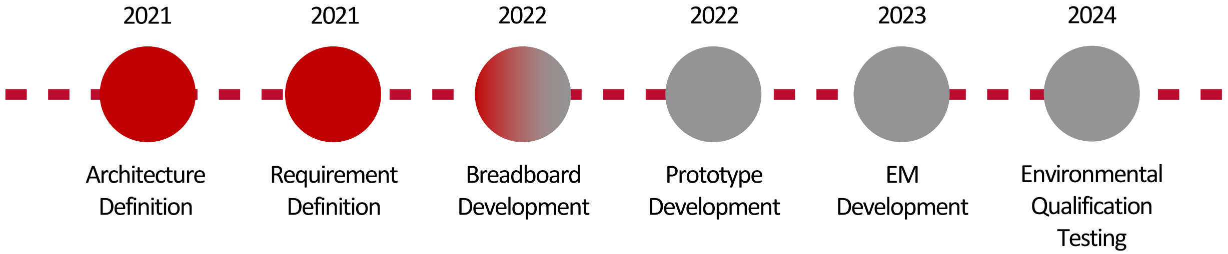
- Fission Surface Power and Surface Solar Power • 1 km • 10 kW • Fiber comms
- Moon Diver (Tethered Lunar Pit Descender) • 300 m • 100 W • Copper comms
- EELS (Enceladus Vent Crawler) • 3 km • 200 W • Fiber Comms
- PRIME (Europa Melt Probe) • 50 m • 200 W • Fiber coms
- FARSIDE (tethered telescope array for the Moon) • 12 km, 70 W, Fiber coms





Develop a stand-alone tether power subsystem that can be integrated into landers, rovers, and power transmission systems for numerous lunar applications. The system elements below will be developed and raised to TRL 6 over 3 years:

- GaN-Based Modular multilevel converter (MMC) DC-DC converter modules for step up and step down conversion at 1 kW+, 95% efficient from 100 V to 1.5 kV
- A high voltage (500 V - 1.5 kV) tether capable of 100 m – 10 km
- Dual communications system supporting both fiber optic and data over power lines uplink (8 kbps) and downlink (8 mbps) communications for various mission types



Autonomous Power Control (APC)

Project Overview

Why is this project important?

- *Future NASA missions require advancements in electrical power system technology that will provide unprecedented levels of resilience, reliability, and autonomy.*
- *Solves the very real and practical problems of power management during mission critical environments beyond low-earth orbit (LEO), such as the lunar surface*

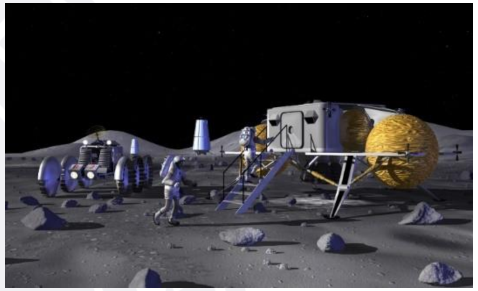
Objectives

- Increase the resilience, reliability, and autonomy of an electric power system using a hierarchical, multi-layer control structure
  - Services include voltage regulation, power sharing, fault tolerance, reconfiguration, interoperability, etc.

Current Activities

- **Collaboration with Sandia National Laboratories for *robust, autonomous, and fault-tolerant DC microgrids* to enable sustainable lunar surface power.**
- **Implementation and evaluation of the US Army developed Tactical Microgrid Standard for space power systems.**

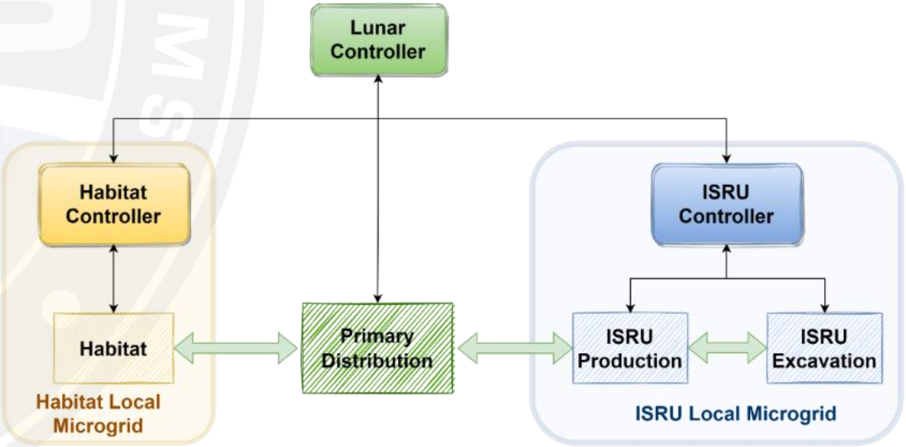
Lunar Surface Habitat



Demonstrate technology required for Mars Missions

Mars Surface Habitat

Communication latency time drives autonomous power needs



Hierarchical control architecture

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

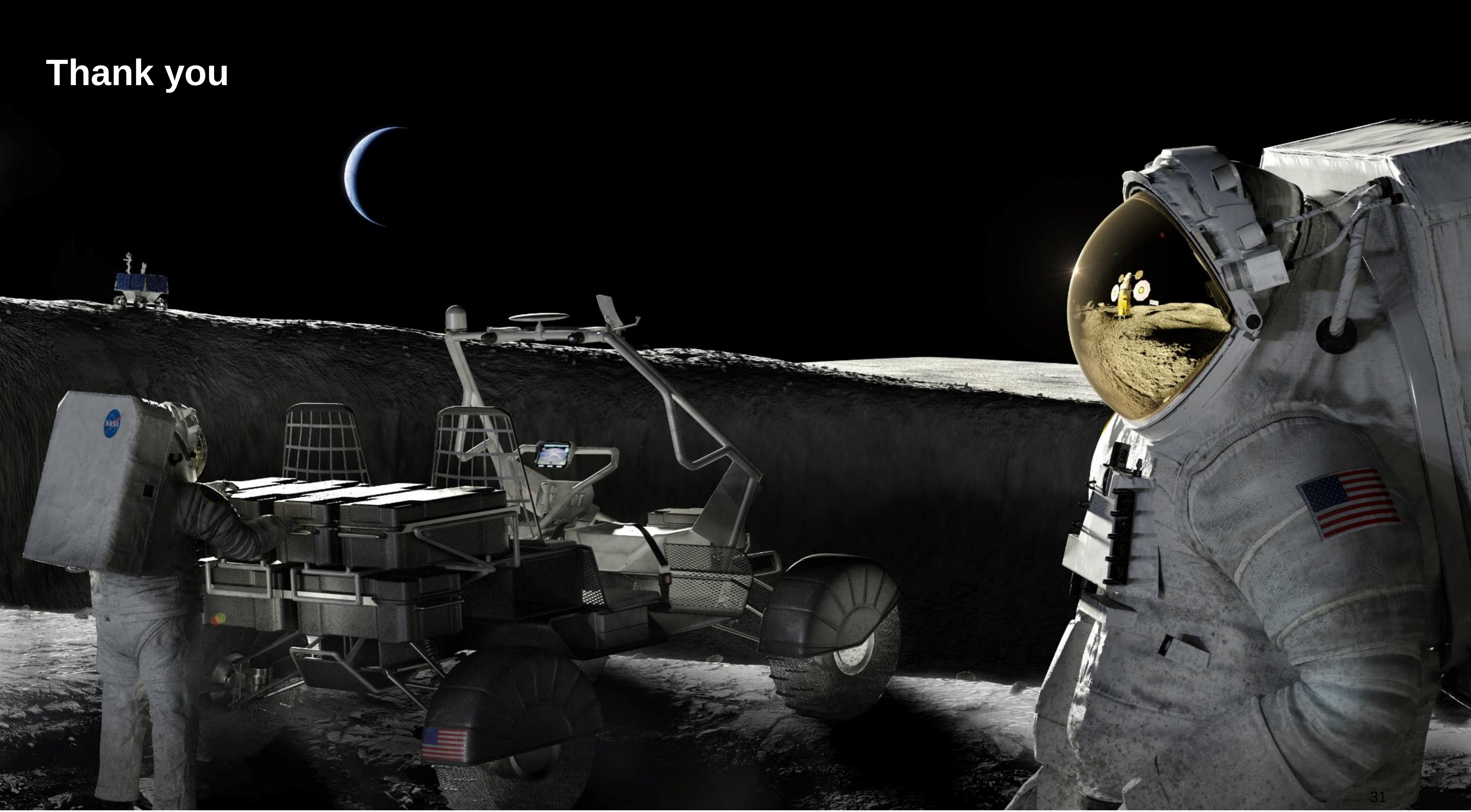
Final Thoughts

- **National long-term interest in growing beyond lunar science missions**
  - Demonstrate technologies required to sustain human presence on the lunar surface (Moon2Mars)
  - Further globalization of the Moon (commercialization)

- **Sustained lunar presence requires technology development (especially for power)**
  - Rad-hard power electronics
  - Power generation and energy storage devices to meet lunar needs
  - High voltage – space qualified PMAD

- **For more information regarding NASA technologies / partnerships / collaborations**
  - Jeffrey Csank – Electrical Engineer
    - jeffrey.t.csank@nasa.gov
  - John Scott – Principal Technologist, Power and Energy Storage
    - john.h.scott@nasa.gov

Thank you

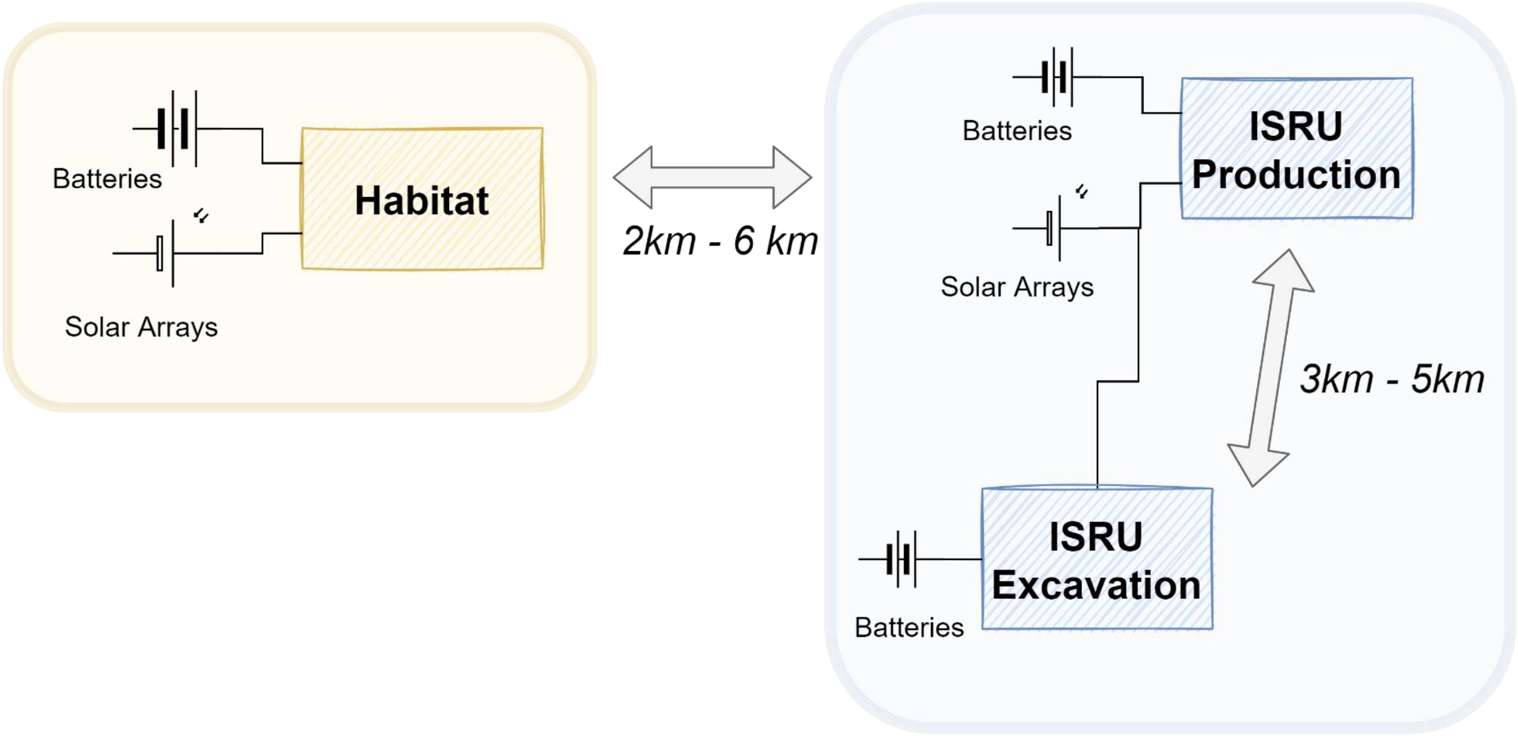


Evolution of Lunar Power Systems

- **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, fission surface power, regenerative fuel cells and batteries
- **Full Lunar Economy (~100s MW – 1 GW)**
  - In-space manufacturing, commercial operations, etc.
  - Sources: solar arrays, primary fuel cells, fission surface power, regenerative fuel cells and batteries

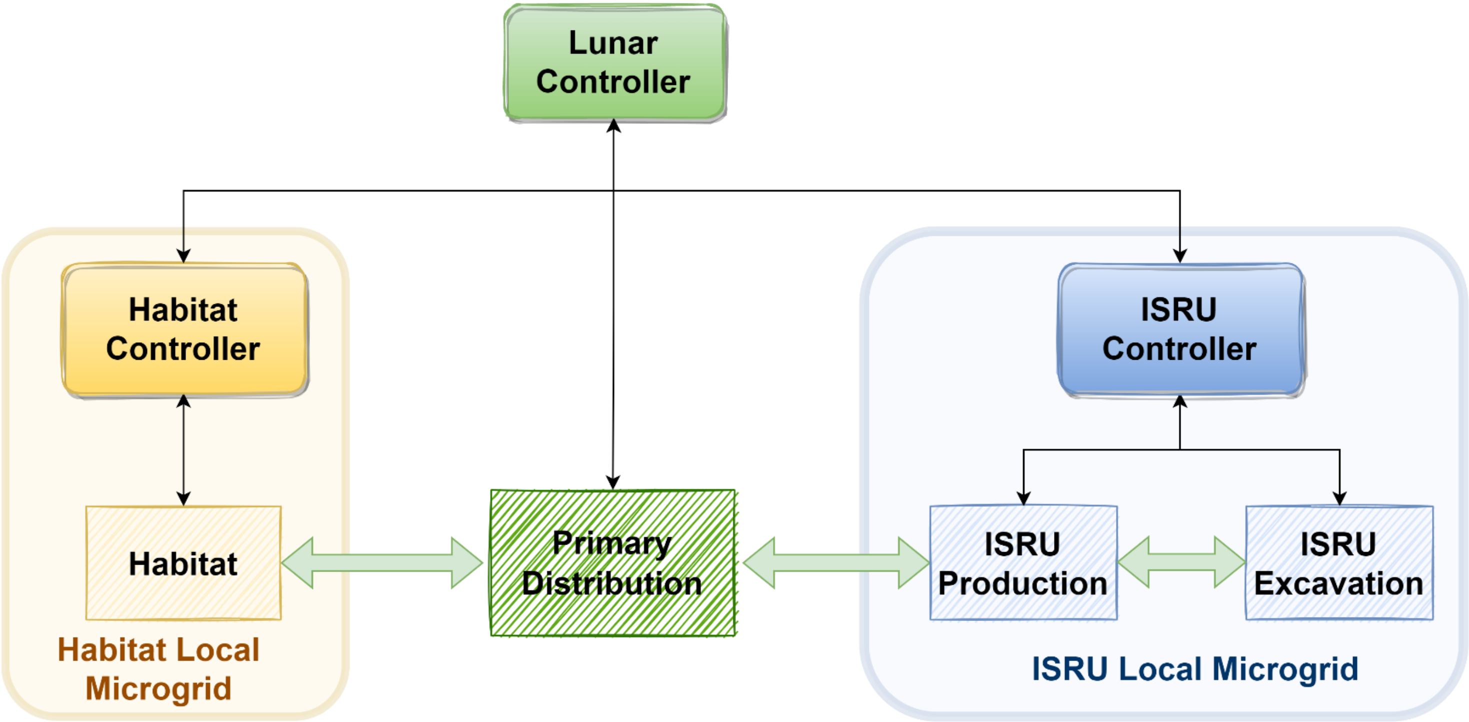
- As lunar surface operations expand, there are benefits to
  - Being able to reutilize existing infrastructure
  - Share excess power between assets during normal operations
  - Providing power to highest priority loads during failures

Baseline Artemis



- **Two independent microgrids (Habitat and ISRU)**
  - Contain their own power sources (generation, storage)
  - Can independently manage their own power

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