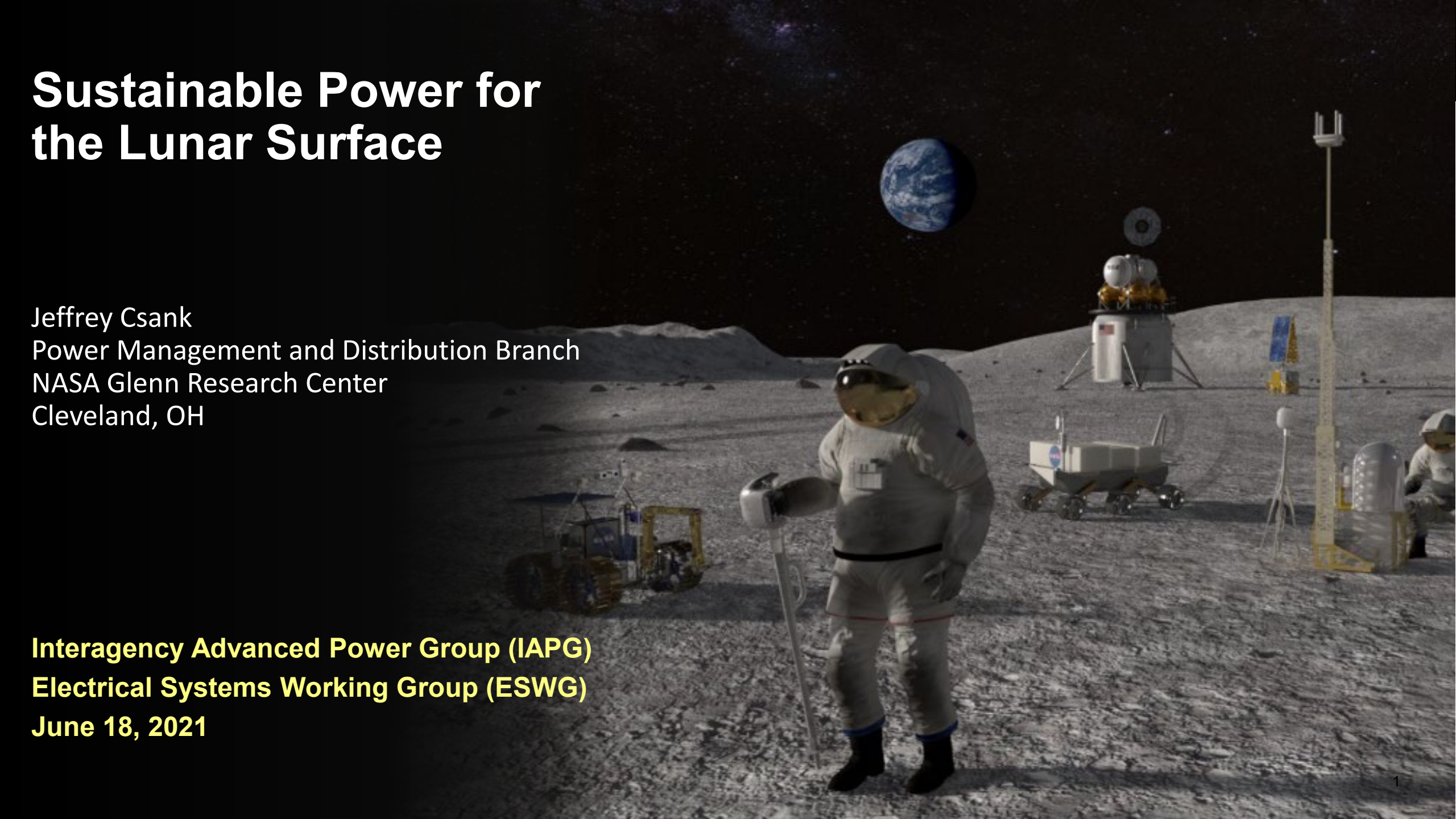
Sustainable Power for the Lunar Surface

Jeffrey Csank
Power Management and Distribution Branch
NASA Glenn Research Center
Cleveland, OH

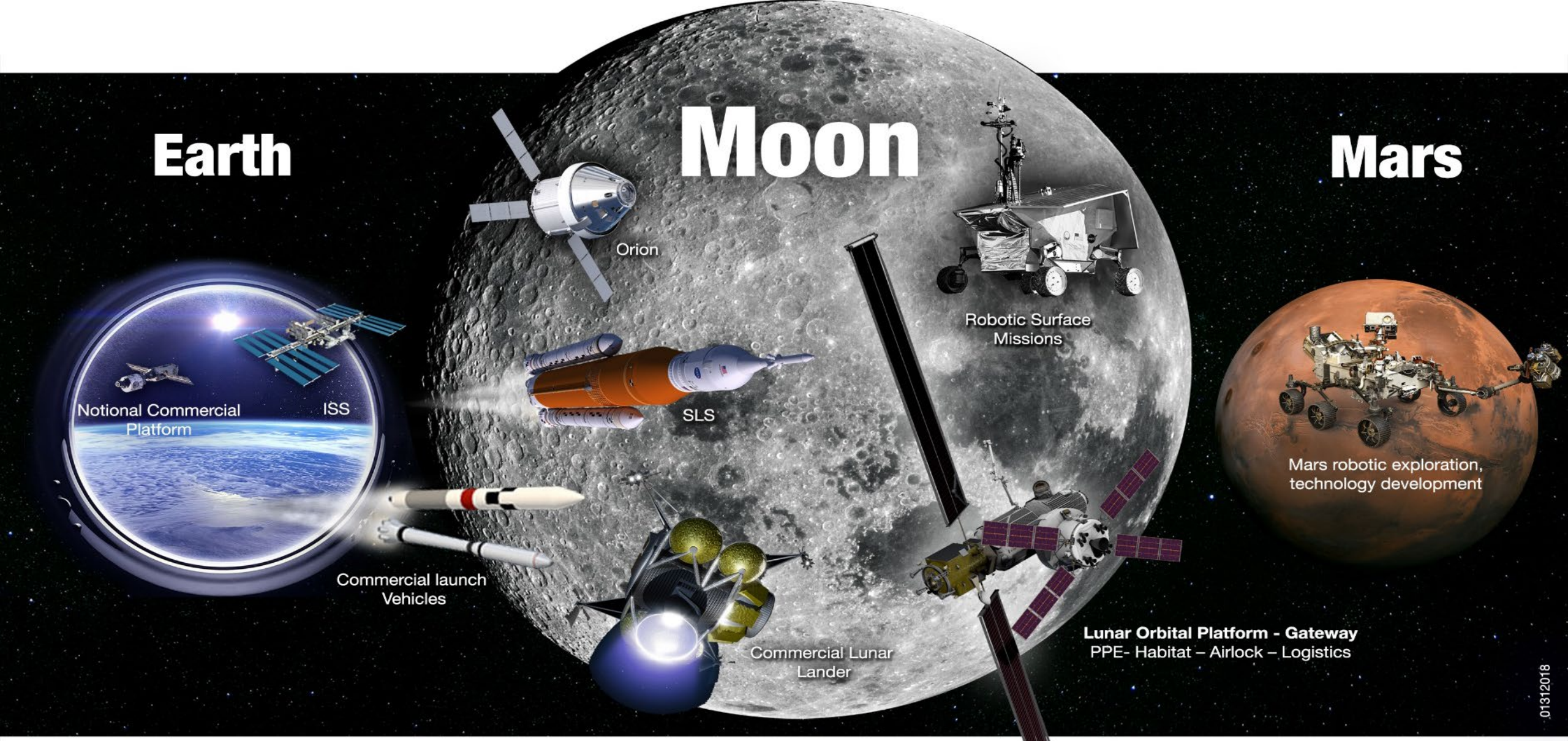


Interagency Advanced Power Group (IAPG)
Electrical Systems Working Group (ESWG)
June 18, 2021

Agenda

- NASA's plans for the Lunar Surface
- Sustainable Lunar Surface Power
- Lunar Surface Microgrid
- Autonomous Hierarchical Microgrid Control

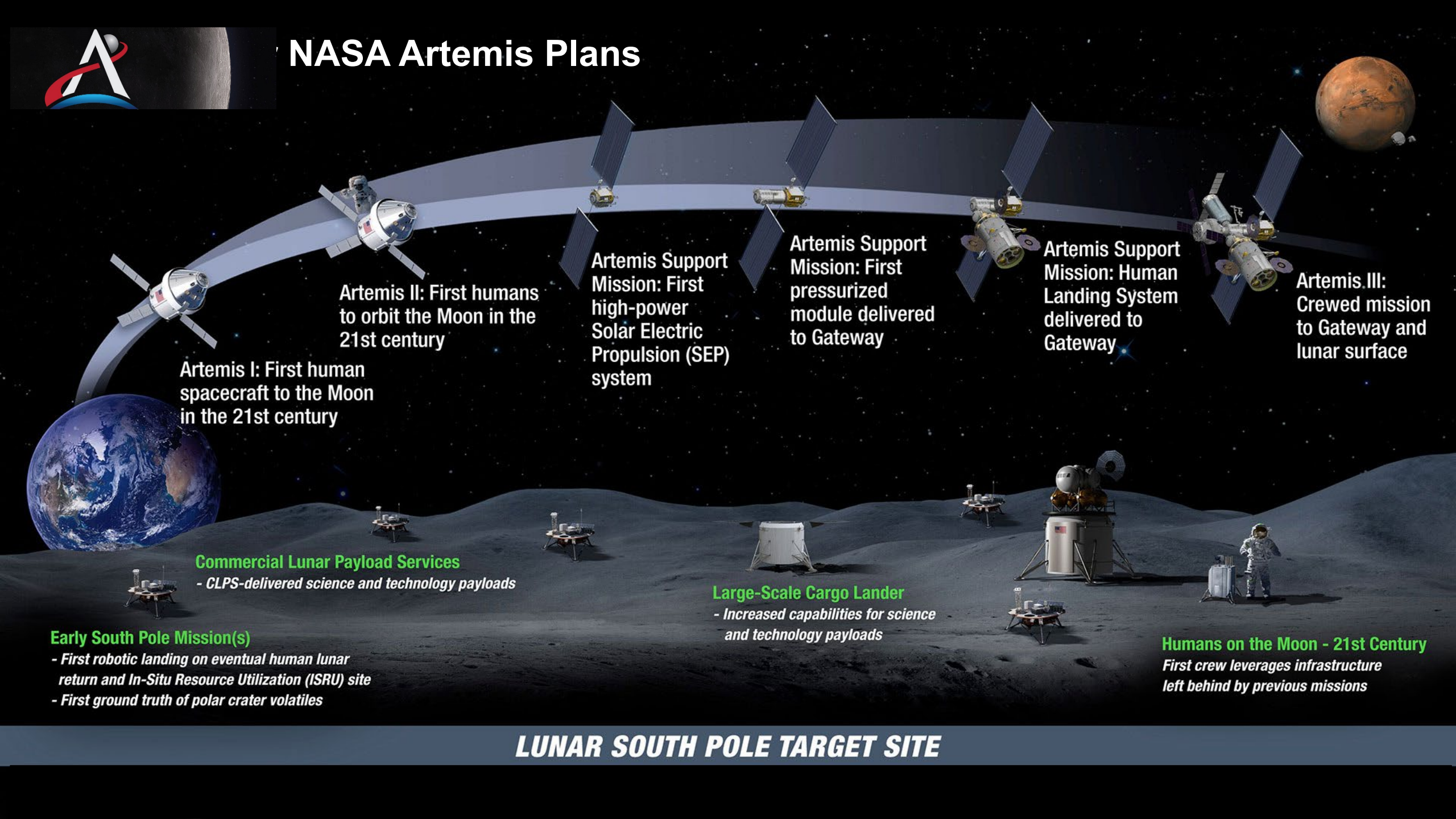




In LEO
Commercial & International partnerships

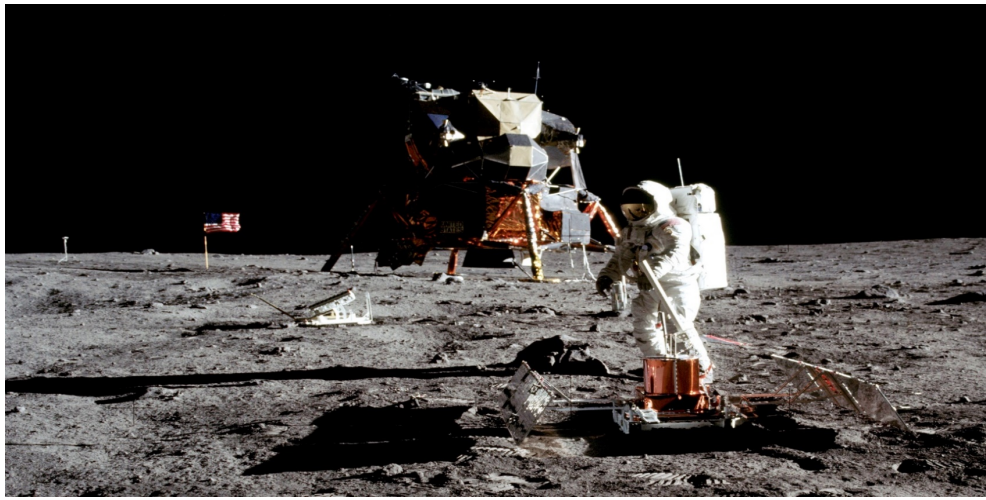
In Cislunar Space
A return to the moon for long-term exploration

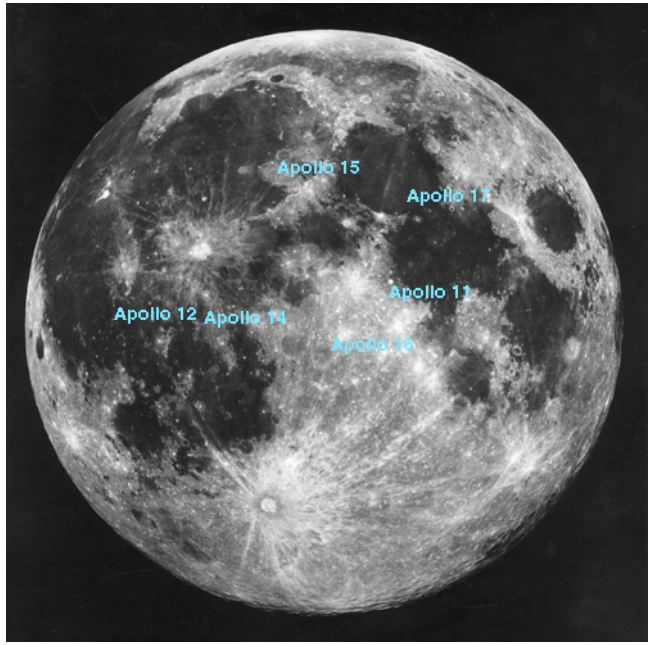
On Mars
Research to inform future crewed missions


NASA Artemis Plans
Artemis I: First human spacecraft to the Moon in the 21st century
Artemis II: First humans to orbit the Moon in the 21st century
Artemis Support Mission: First high-power Solar Electric Propulsion (SEP) system
Artemis Support Mission: First pressurized module delivered to Gateway
Artemis Support Mission: Human Landing System delivered to Gateway
Artemis III: Crewed mission to Gateway and lunar surface
Commercial Lunar Payload Services
- CLPS-delivered science and technology payloads
Large-Scale Cargo Lander
- Increased capabilities for science and technology payloads
Early South Pole Mission(s)
- First robotic landing on eventual human lunar return and In-Situ Resource Utilization (ISRU) site
- First ground truth of polar crater volatiles
Humans on the Moon - 21st Century
First crew leverages infrastructure left behind by previous missions
LUNAR SOUTH POLE TARGET SITE

Lunar Exploration

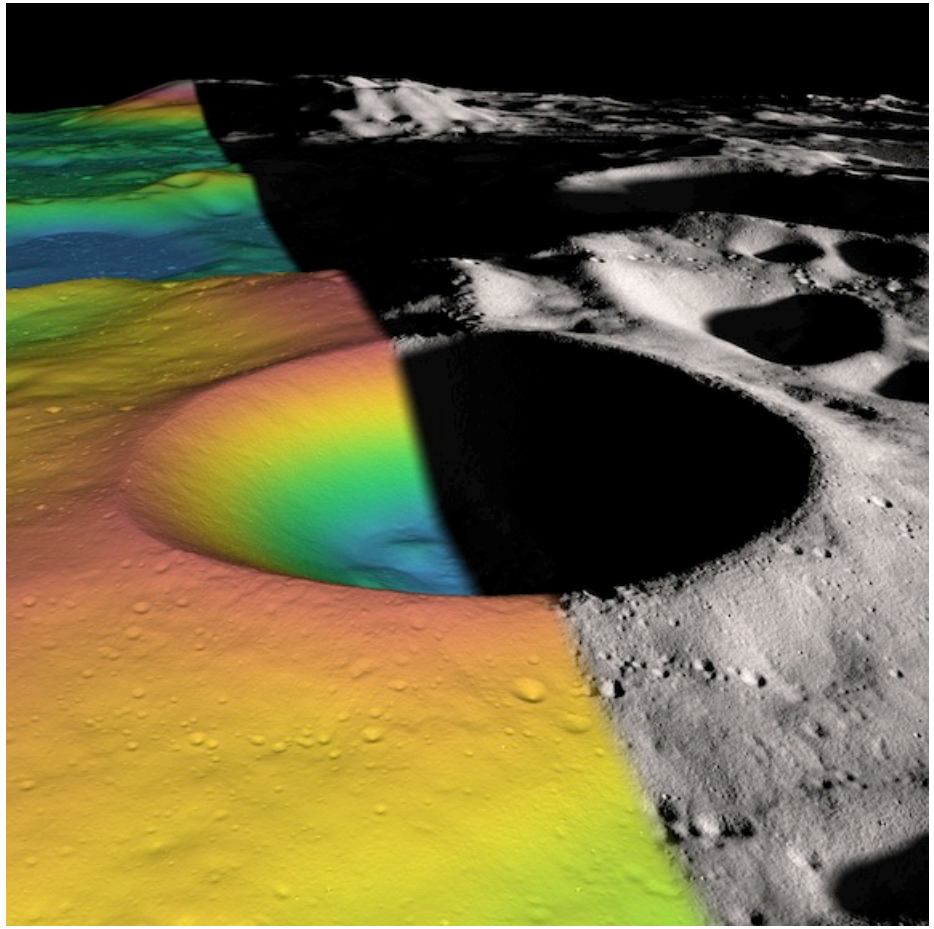
- **Past Exploration**
  - 100+ robotic spacecraft missions
  - Only celestial body beyond Earth visited by Humans
    - Apollo missions (1969 – 1972)
      - Equatorial region
    - 12 Apollo Astronauts walked on the lunar surface
    - ~10 days on lunar surface / 80 hours outside of lander
- **Future Human Missions**
  - Living beyond Earth
    - Testing and demonstrating technologies for sustained presence (Lunar and Mars)
      - 30+ day missions on the surface
  - Lunar South Pole
    - Polar Regions have limited temperature swings and more continuous sunlight
      - Minimizes energy storage
      - Contains volatiles





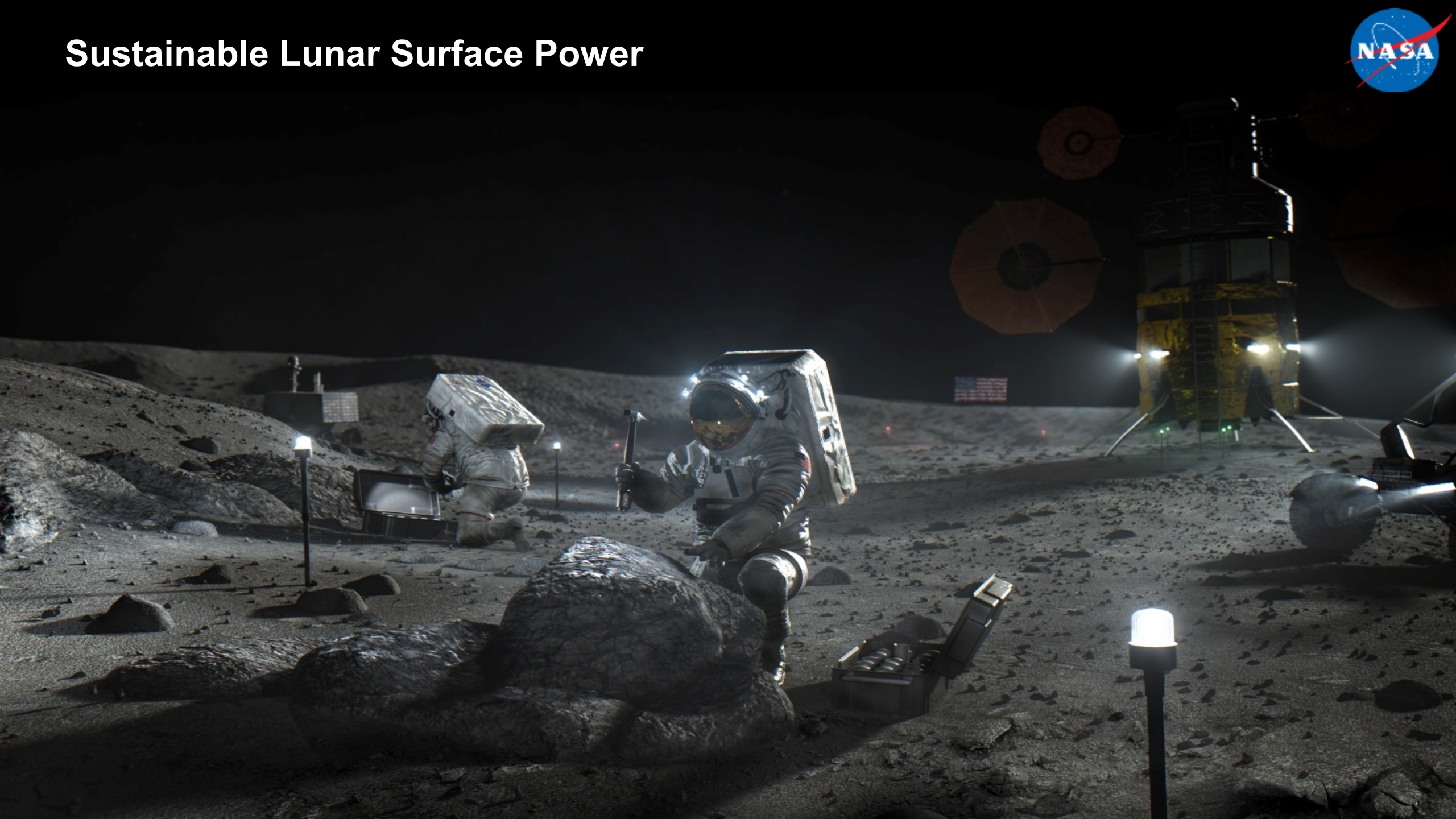
Shackleton Crater

- **Impact crater at the South Pole**
- **Named after Antarctic Explorer Ernest Shackleton**
- **Size:**
  - 21 km (13 mi) in diameter and 4.2 km (2.6 mi) deep
- **Rims are in almost continuous sunlight**
- **Interior is perpetually in shadow (eternal darkness)**
  - Average temperature -183 C (90 K)
  - Temperature never exceeds -173 ºC (100K / -280 ºF)
  - Any water vapor that arrived at the lunar surface from comets or meteorites would have been trapped



*Haruyama, Junichi; et al. "Lack of Exposed Ice Inside Lunar South Pole Shackleton Crater". *Science*. **322** (5903): 938–939. November 7, 2008

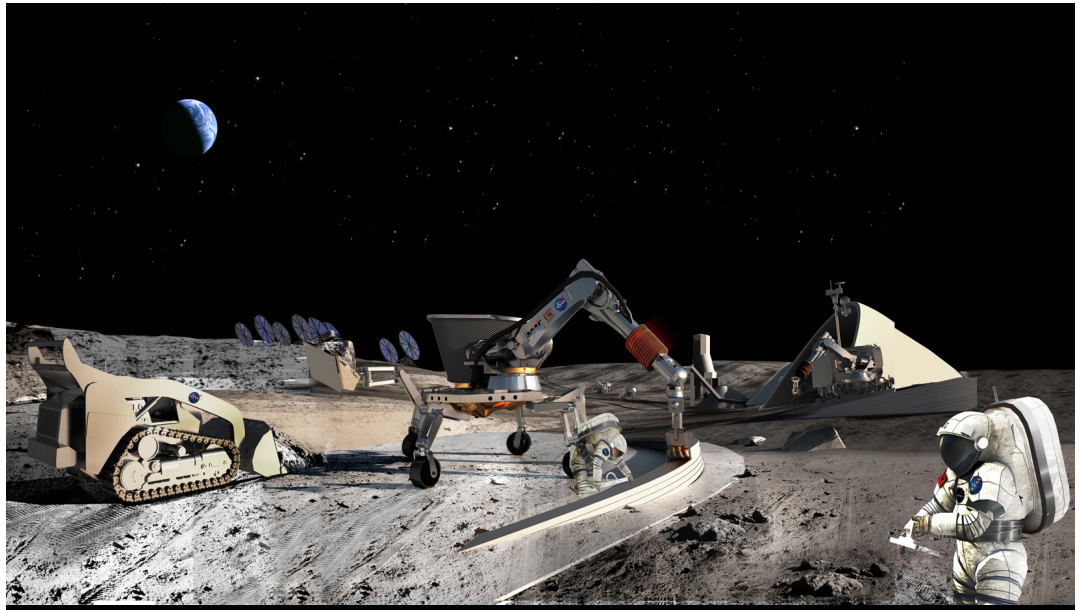
Sustainable Lunar Surface Power

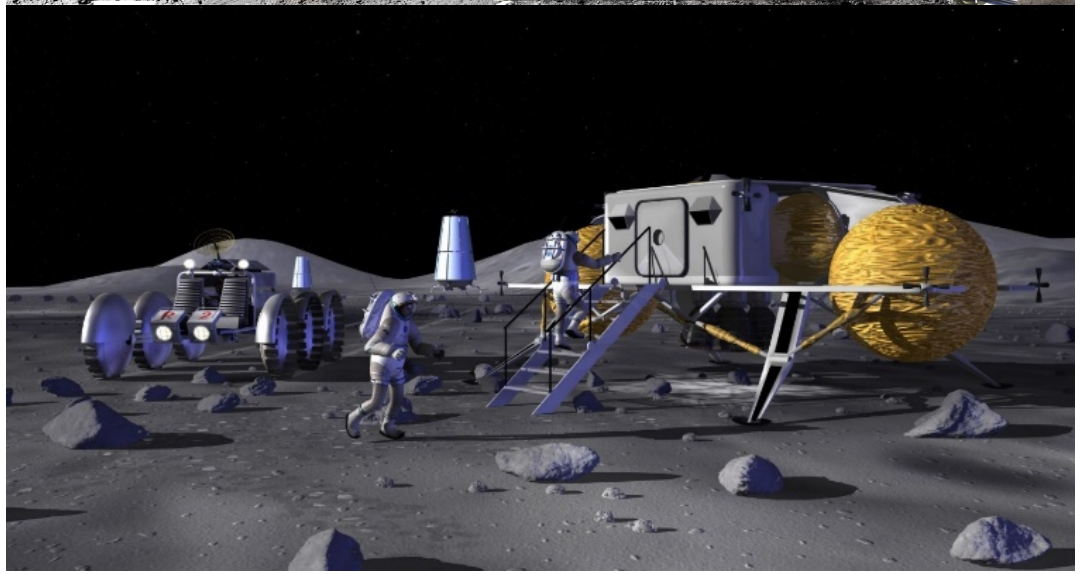


Sustainable Presence Lunar Surface Activities

- **Manufacture propellant**
  - Fuel landers for round trips between the Lunar surface and Gateway
    - Mining/excavation regolith
    - In-Situ Resource Utilization (ISRU)
- **Support a crew / crew operations**
  - Crew of four for at least 30 days stay four times per year
- **Lunar science and technology demonstrations**

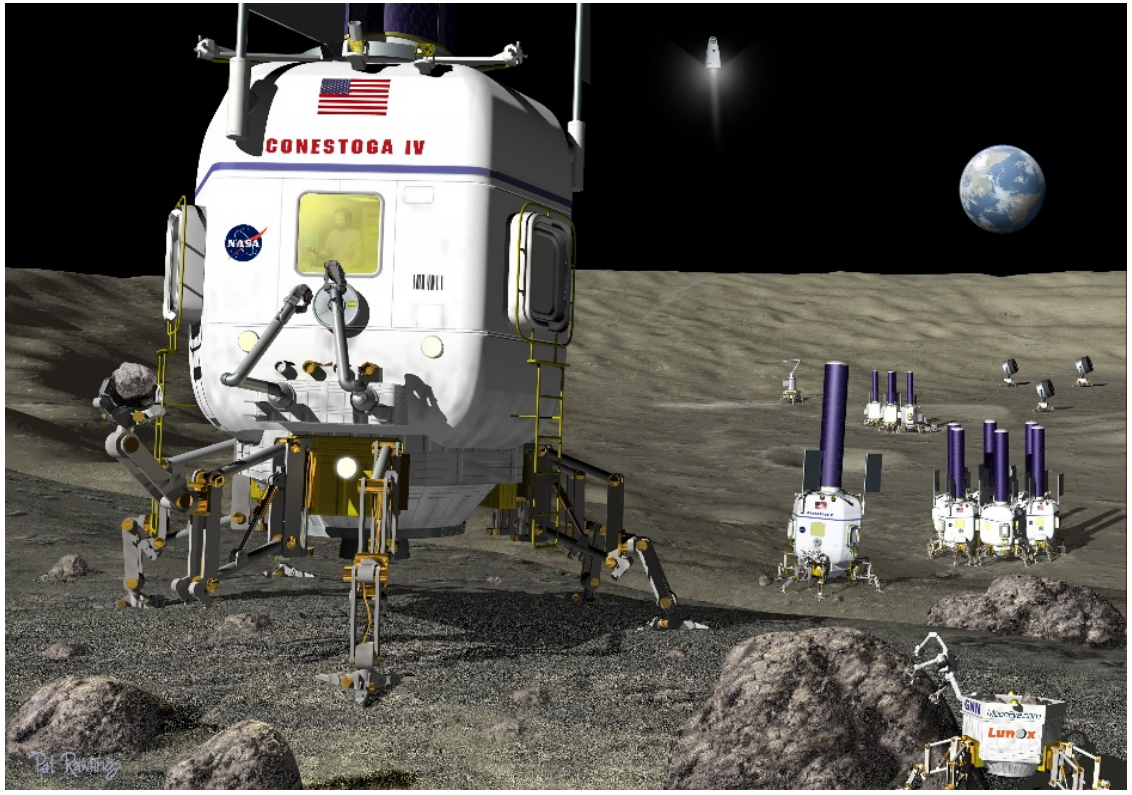
A sustainable Lunar presence will require electrical power that is highly reliable and available (electrical power on Earth)





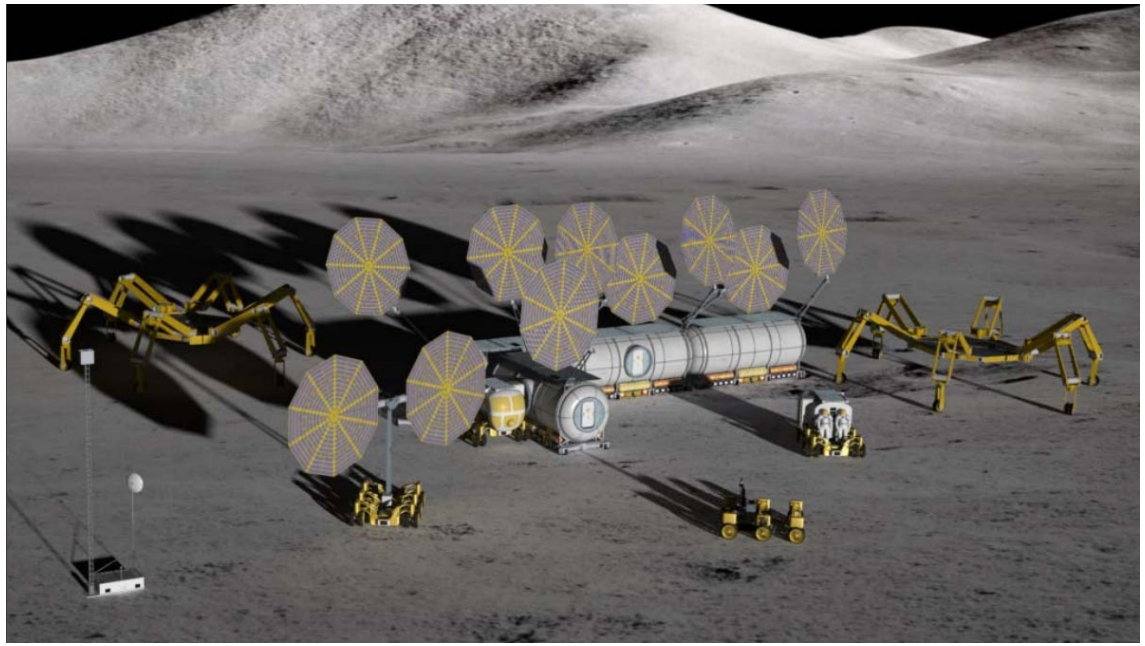
Lunar Surface Sustainable Power Challenges

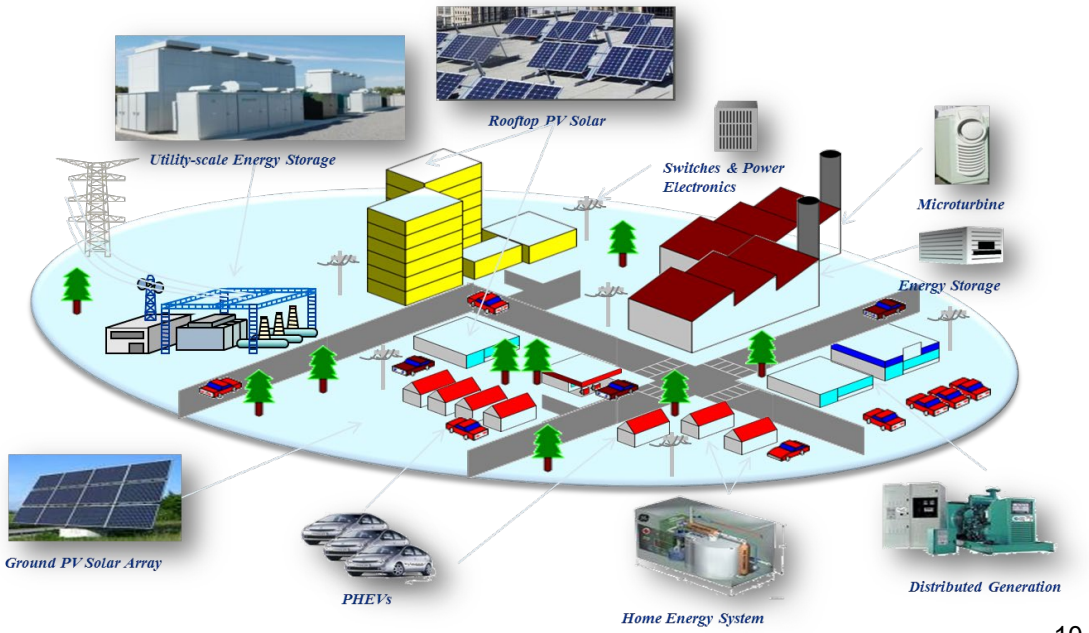
- **Power Availability**
  - Lunar surface power needs/uses will grow and evolve over time.
    - Power strategy will need to evolve over time.
  - Accommodate distributed power system resources (mix of generation, storage, and loads)
  - Availability – Large amounts of power is needed regardless of time of lunar day.
- **Power System Operations**
  - Robotically deployable PMAD / power systems
  - Autonomous operation for extended periods
- **Power Components**
  - Mass minimization
  - High efficiency generation and transmission
  - Ability to survive the lunar environment
    - Cold temperatures / lunar dust / radiation hardening from cosmic rays



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**

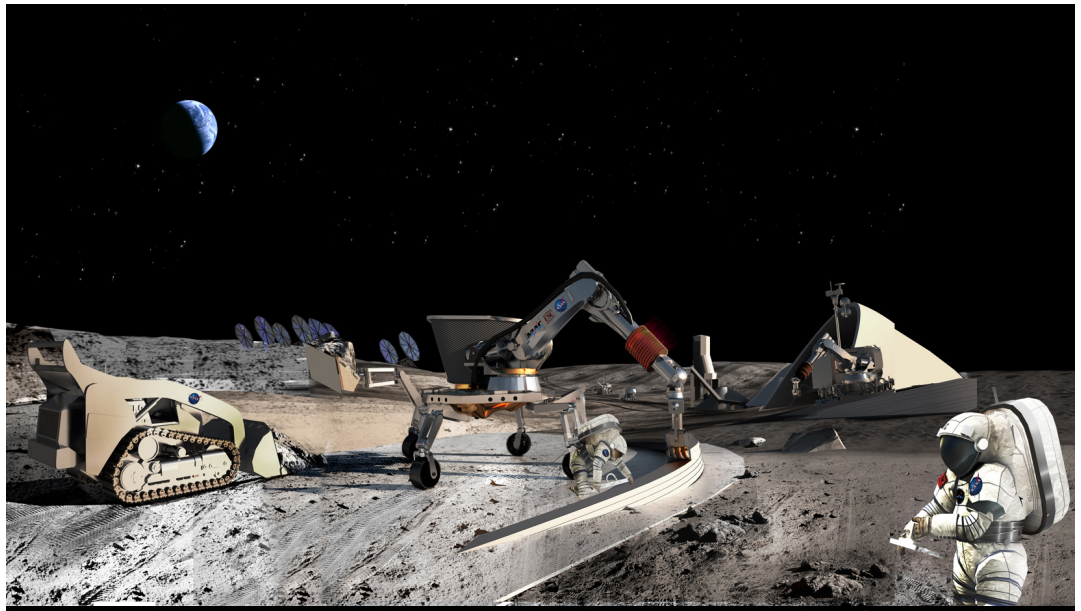


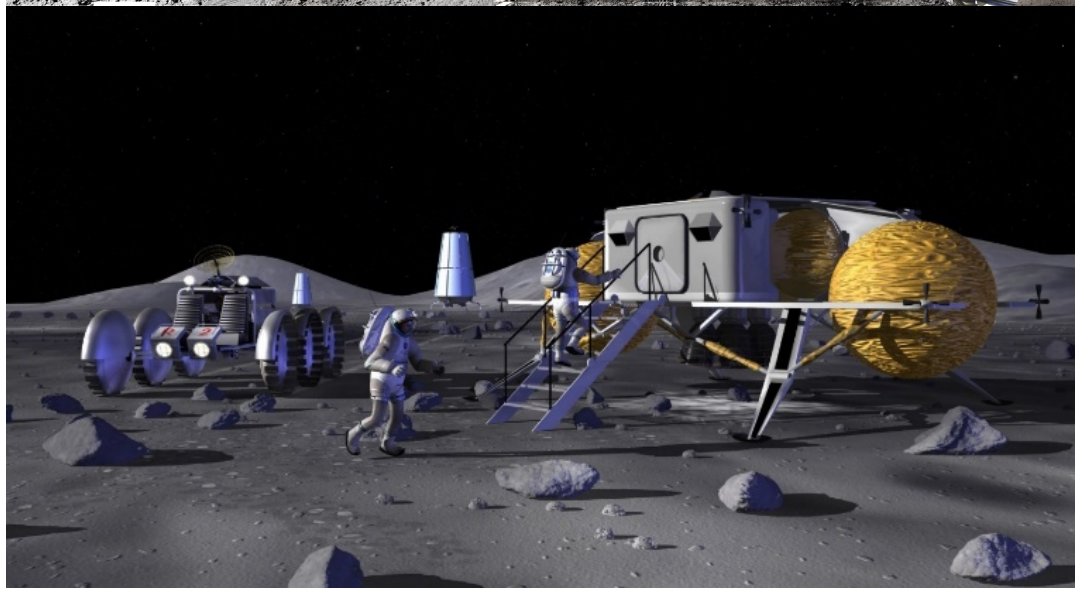


Lunar Surface Microgrid



Power Users

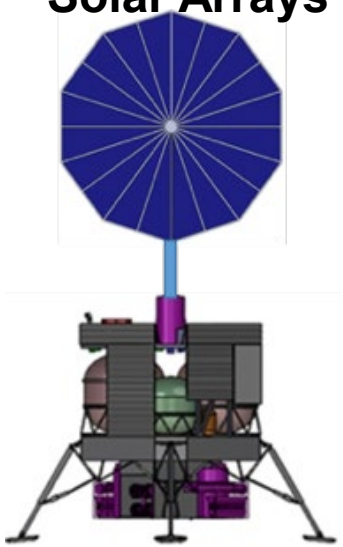




- **In-Situ Resource Utilization (ISRU)**
  - Largest power user 60+ kW
  - Power is needed over long distances
  - Restricted to operate during periods of heavy insolation
- **Habitat**
  - Second larger power user during habitation
    - 20 – 50 kW
  - Crew of 4 for 30+ days – 4 times per year
  - Habitation restricted to periods of heavy insolation
- **Lunar science / Exploration**
  - Various rovers @ 500 W each
  - Hopper @ TBD power
  - Power beaming @ TBD power
- **Technology Demonstrations**
  - ISRU
  - Etc.

Power Generation & Energy Storage

Solar Arrays

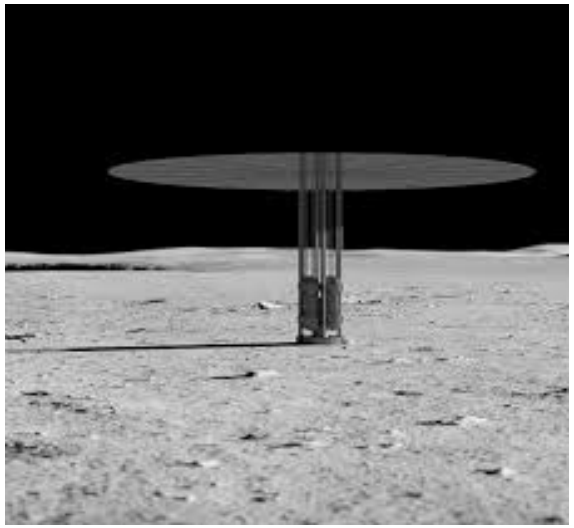




Primary Fuel Cells

Radioisotopes (RTG, RPS, etc)

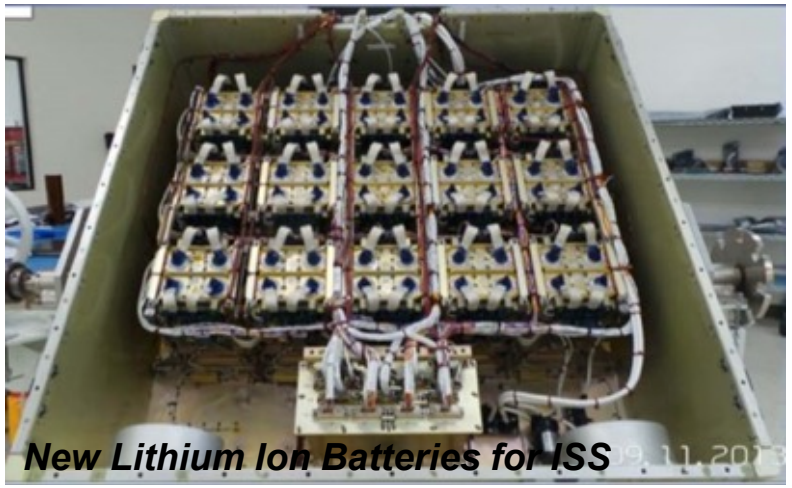




Fission Surface Power

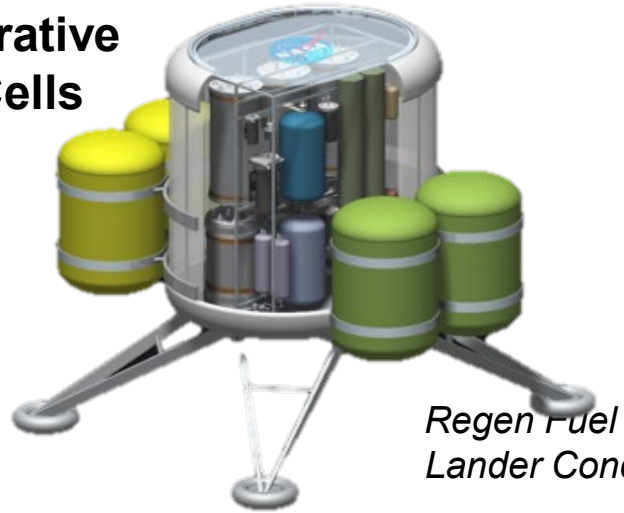
Tech Demo

Batteries



New Lithium Ion Batteries for ISS

Regenerative Fuel Cells

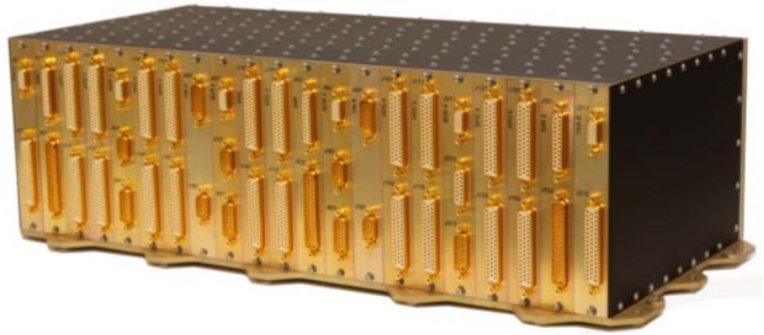


Regen Fuel Cell Lander Concept

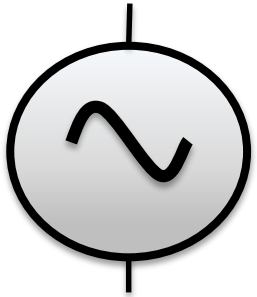
Primary Power Distribution (Transmission)



Traditional Space Power Distribution (120 VDC / 28 VDC)
• High TRL & experience in Space Applications
• Mass & loss concerns for long distances (cabling) • Robotic deployment (cable thickness)



High DC Voltage
• Lower cable weight compare to traditional space power distribution
• Fault control may be challenging • Low TRL for space applications



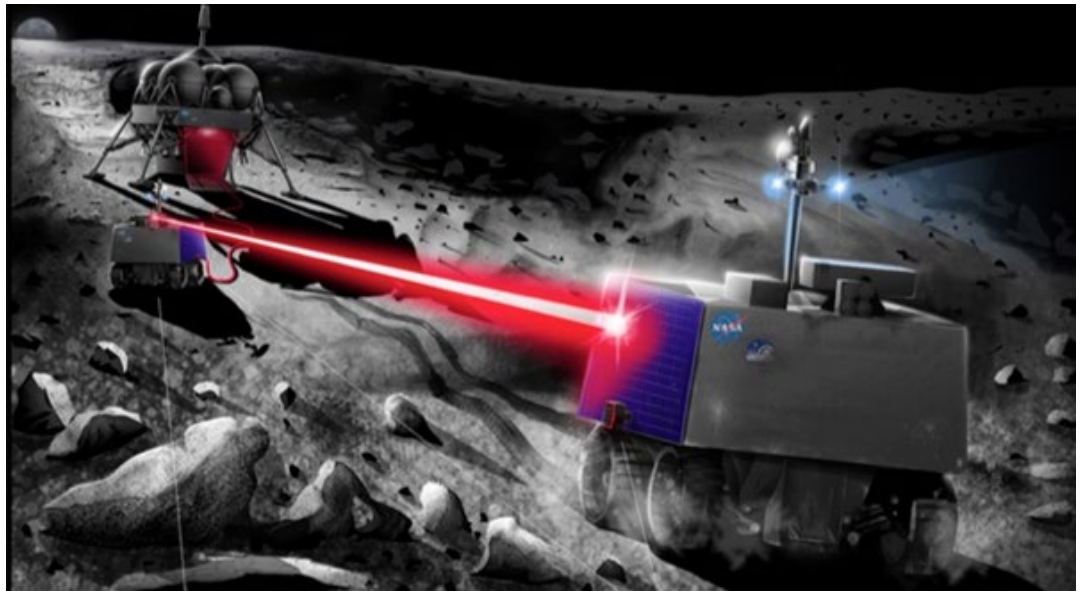
AC Power
• Ease of voltage conversion and fault control • Resembles terrestrial grid
• AC frequency may cause issues related to power factor correction, deployment of 3-phase systems, relative size / mass of voltage conversion at low frequency. • Low TRL for space applications • Large change (DC to AC) for space operations

Primary Power Distribution (Transmission)

Wireless Power Transmission

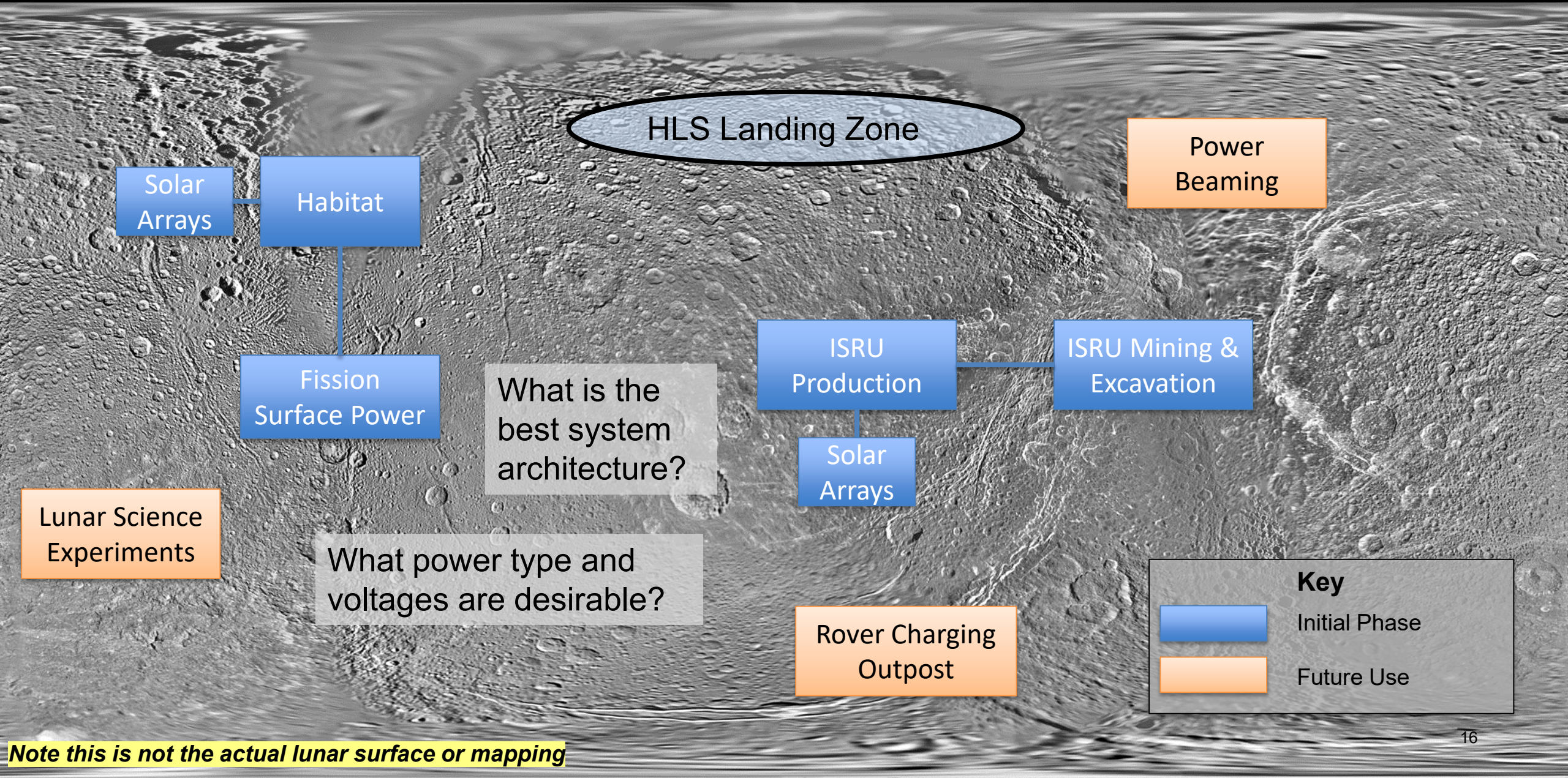
- Convert source electricity to laser or microwave energy & transmit wirelessly (beam)
- No need for robotic deployment of cables and connectors
- Effective distance is line-of-sight with no degradation in power
    - Allows for exploration/operations in difficult terrain

- Requires active tracking for acceptable performance
- Low end-to-end efficiency (~25%) results in increase power source
- Components and systems are low maturity





Baseline Lunar Microgrid



Note this is not the actual lunar surface or mapping

NASA Lunar Microgrid Funding

- **Microgrid Definition and Interface Converter for Planetary Surface (MIPS)**
  - Science Technology Mission Directorate (STMD) FY21 New Start
    - Game Changing Development Program
  - FY21 & FY22 Lunar Surface Power Architecture
    - Design of a Lunar Surface power architecture that can integrate dissimilar power sources and is evolvable, reconfigurable, and reliable (Lunar microgrid)
    - Define grid parameters such as power type (DC/AC) and voltage level
    - Define grid architecture (String, Ring, etc)
  - FY23 & FY24 Universal Modular Interface Converter (UMIC)
    - Design and demonstration of a Universal Modular Interface Converter
    - Create common interface for connecting loads (at 2 standard space power voltages) to the grid

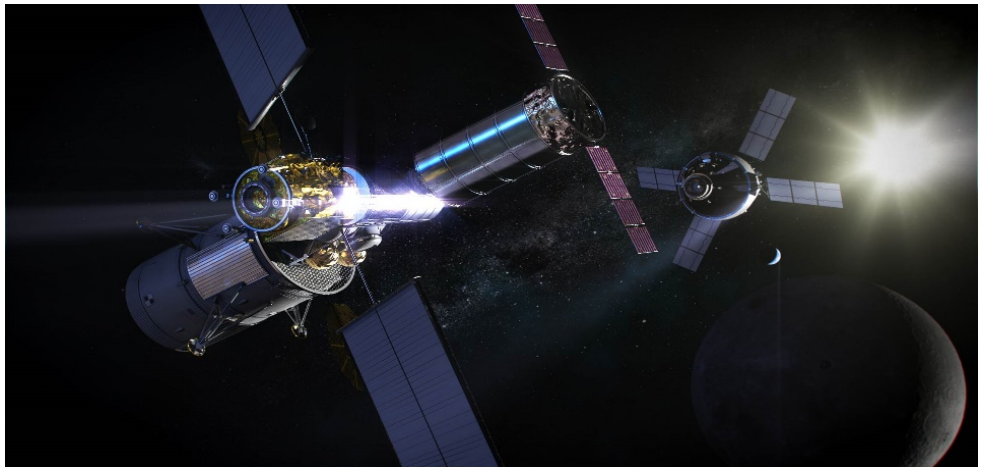


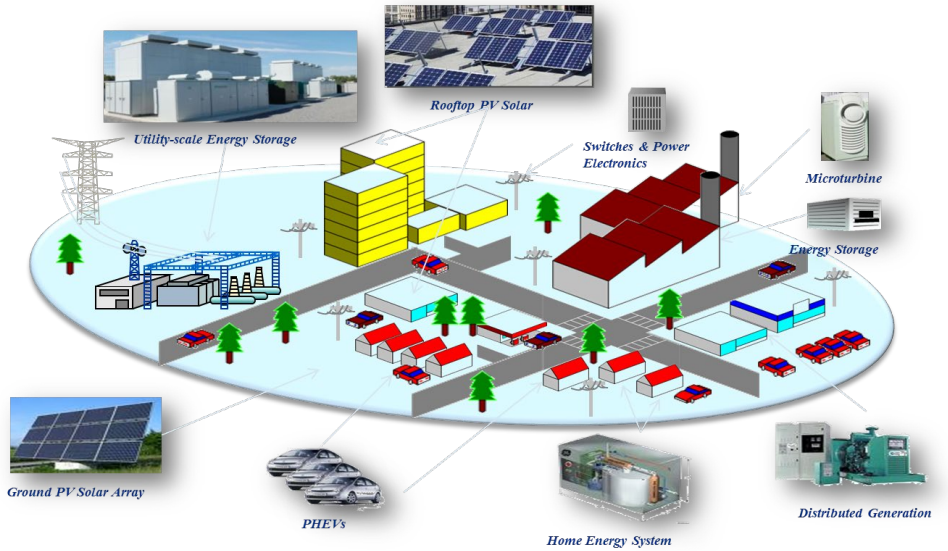
Autonomous Hierarchical Microgrid



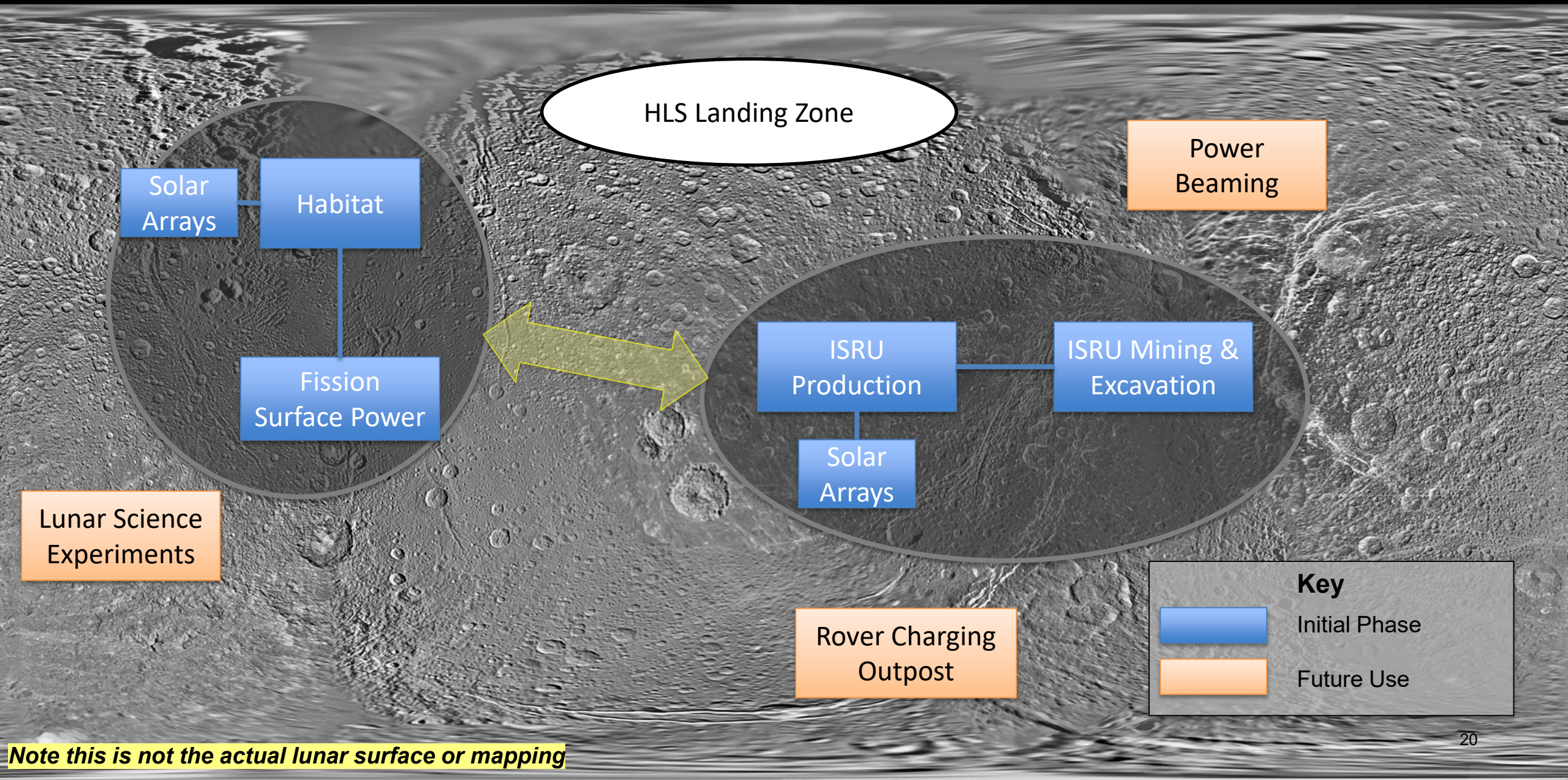
Space Power Control

- **Power System Objectives**
  - Provide power to as many high priority loads as possible
  - Operate safely - within power system constraints
    - Power generation / energy storage constraints
    - Power distribution limits
- **Power Control Objectives**
  - Manage the power system
    - Energy Management
    - Fault Management
    - Contingency Management
- **NASA Autonomous Power Controller Objectives**
  - Manage the power system without human intervention
  - Permit humans (Astronauts) to consent to an operations /actions during habitation



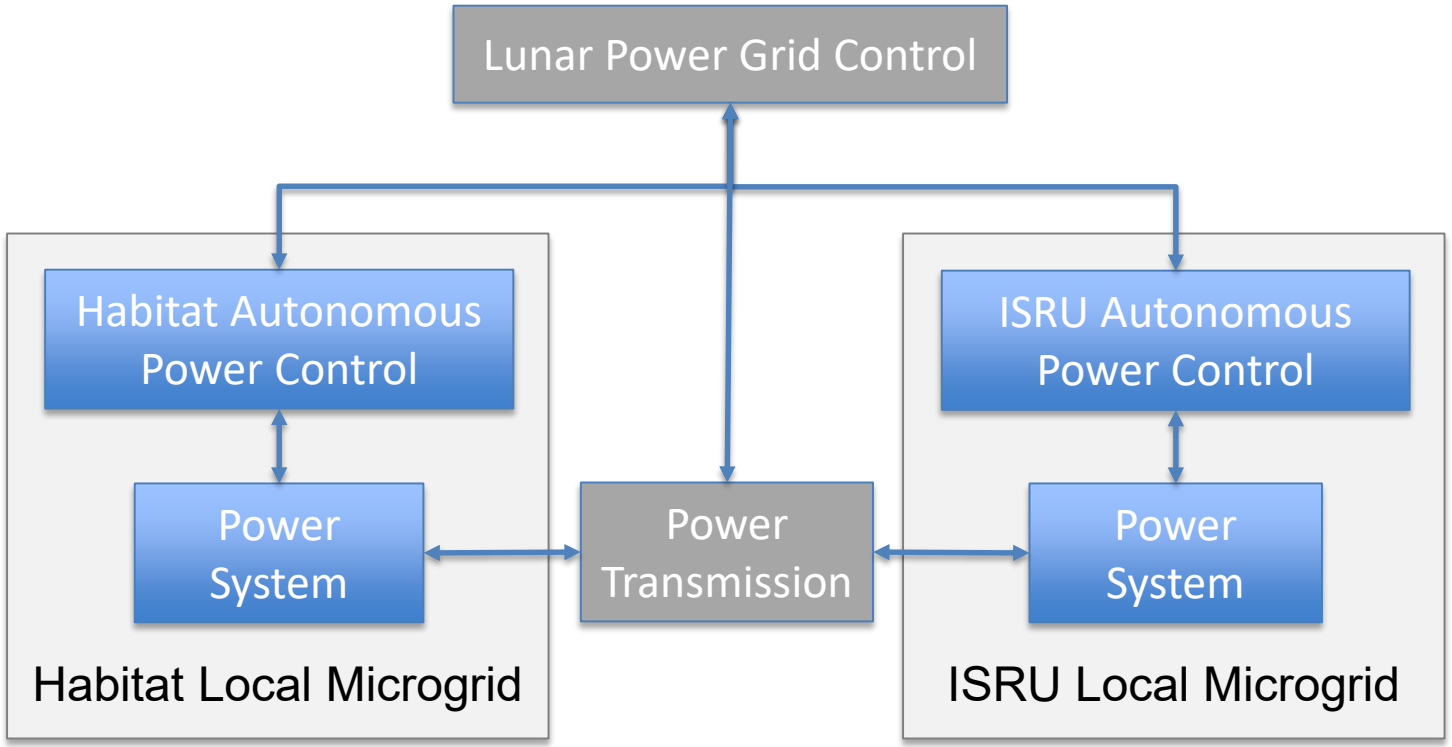


Proposed Distributed Lunar Microgrid



Note this is not the actual lunar surface or mapping

Hierarchical Microgrid Control



- **Controllers to manage power system constraints within each region**
  - Energy storage constraints, power distribution limitations, etc.
- **Overall Grid controller to ensure system objectives are met and allow sharing between regions**

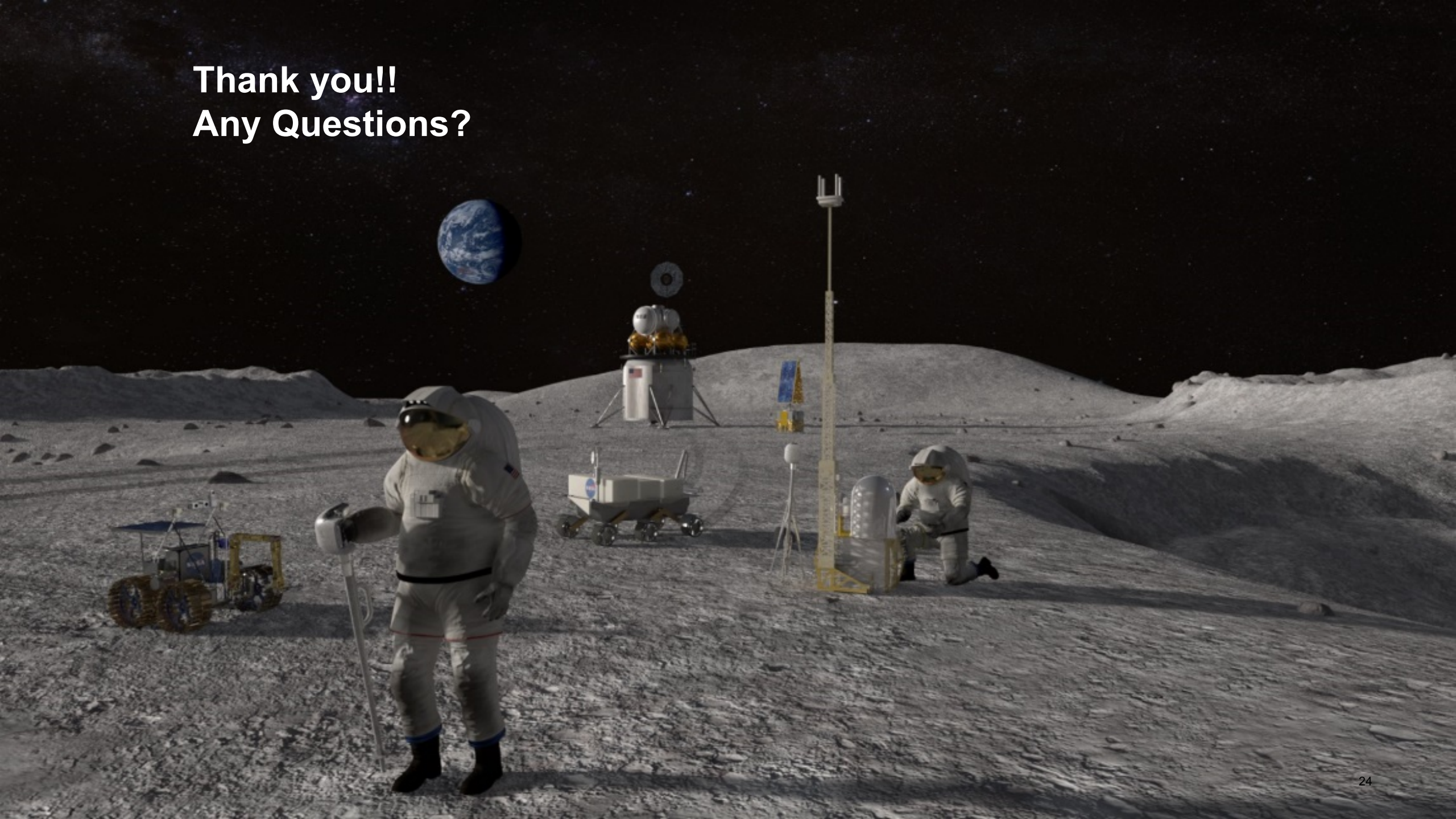
NASA Autonomous Power Control

- **NASA Advanced Exploration Systems – Autonomous Power Control**
  - Large funding cut in FY21
- **Received funding for collaboration on Autonomous Hierarchical Microgrid**
  - Robust, Autonomous, and Fault-Tolerant DC Microgrids
  - Autonomous Hierarchical Microgrid Concept
    - Grid control to manage overall energy management & resolve conflicts
    - Element Autonomous controllers to meet system objectives, perform fault management, energy management, & reconfiguration



Summary

- **Lunar Surface Power**
  - Requires reconfigurable, highly available and reliable power to support a sustainable presence
    - Integration of dissimilar power sources
    - Autonomous operation
- **Rising interest in microgrid technology**
  - Space, Military and Terrestrial applications
    - Need for higher reliability, availability and reconfigurability
    - Desire for alternative (renewables) power sources (generation & storage)
  - Microgrids require complex operational scenario to achieve maximum benefit
    - Successfully integrate dissimilar or alternative power sources (interoperability)
    - Ability to reconfigure the system and switch between power sources quickly
    - Quickly detect faults/failures and reconfigure the system to avoid power disruptions
  - These complex scenarios are driving the need for autonomous power to deliver uninterrupted service regardless of application


Thank you!!
Any Questions?

Lunar Surface Power Connectors

Traditional Space Connectors

- High power & efficiency

- Lunar dust intolerance
- Mating / De-mating limitations

Dust Tolerant Connectors (in-testing)

- Dust tolerance
- Robotically deployable
- High power & efficiency

- Mass limitations

Inductive Connectors

- Dust tolerant
- Robotically deployable

- Low maturity, especially for high power applications
- Lower efficiency
- Mass limitations

