Sustainable Power for the Lunar Surface

Jeffrey Csank and James Soeder
NASA Glenn Research Center
Cleveland, OH

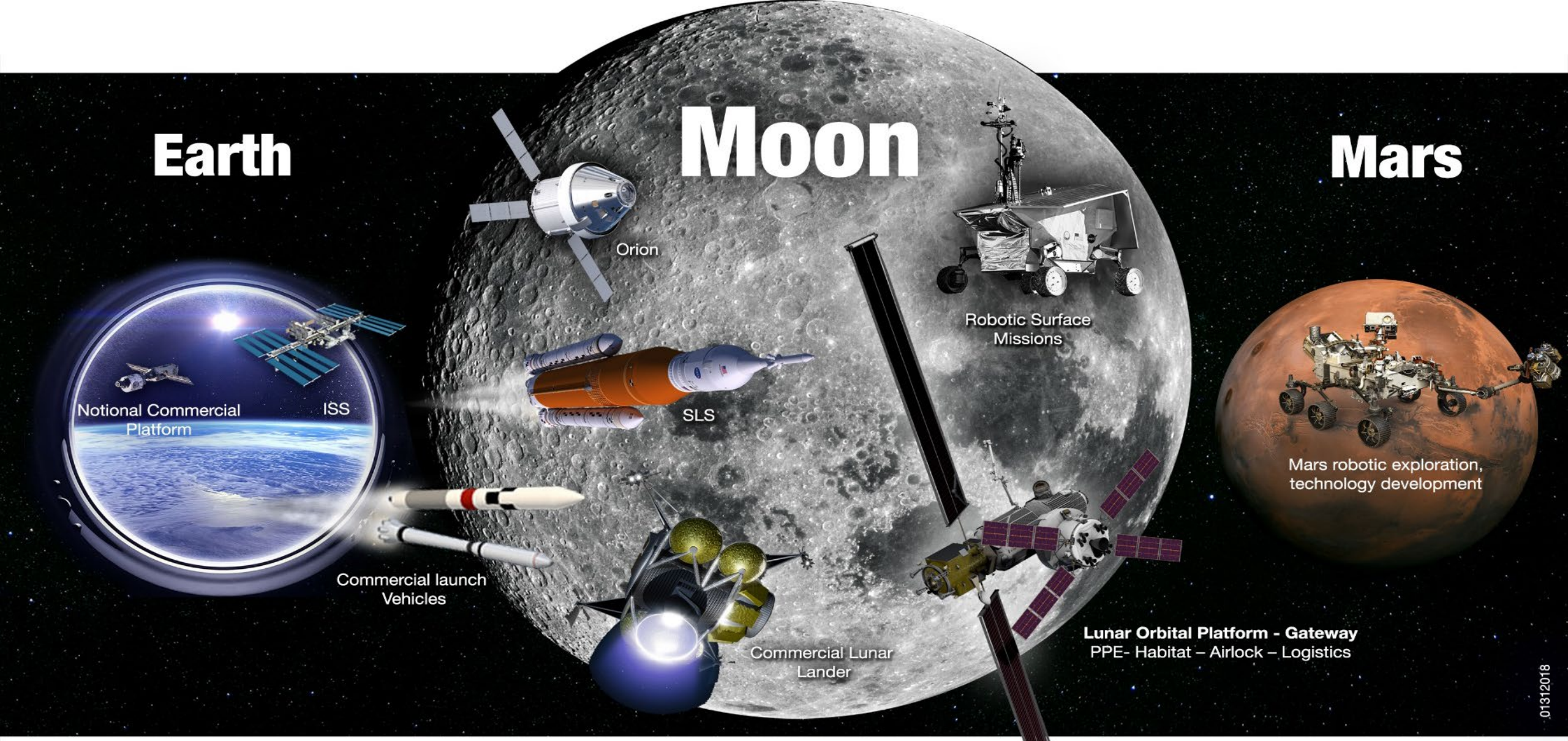


Power and Propulsion Systems Alliance (PPSA)
Controls and Health Management
March 26, 2021

Agenda

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

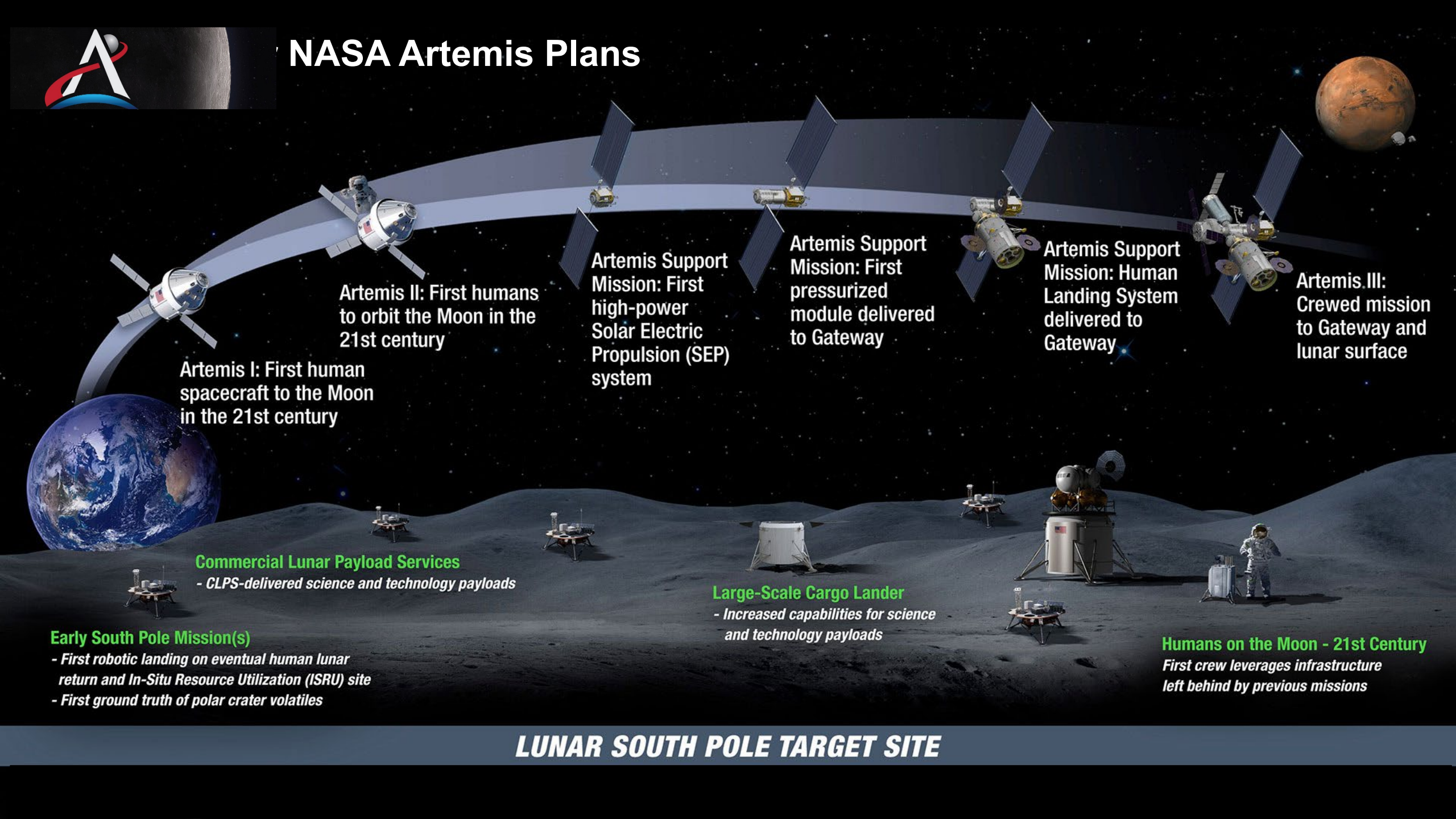




In LEO
Commercial & International partnerships

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

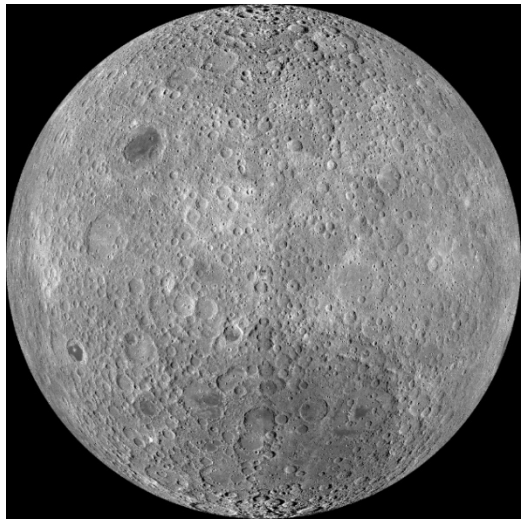
On Mars
Research to inform future crewed missions


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

The Moon

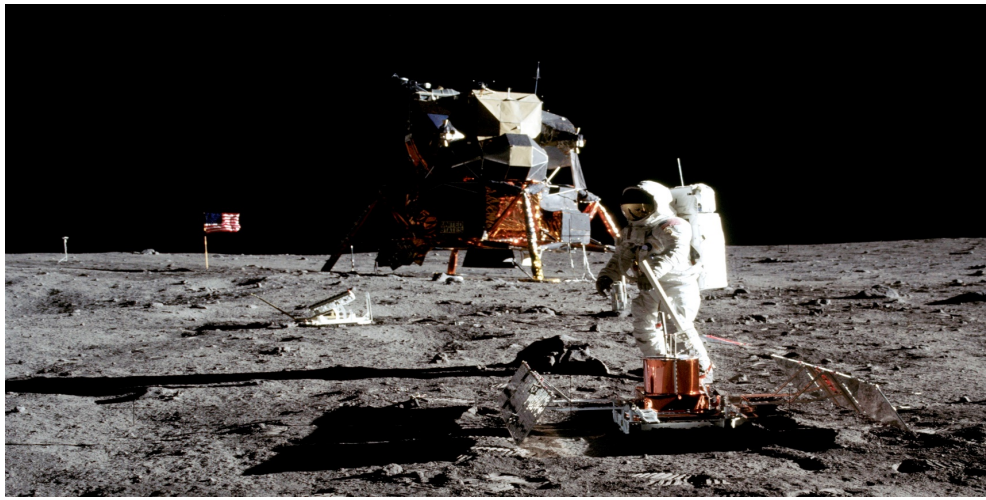
- **Size:**
  - Equatorial radius of 1,738.1 km ~ 0.2725 of Earth
    - 5th largest moon in our solar system
    - Largest moon in solar system relative to size of the planet
- **Orbit period / length of day**
  - 27 days
  - Earth and moon are tidally-locked
    - Earth will only see one side of the moon
    - Inclination to the Ecliptic is 5.1 degrees
    - Despite what Pink Floyd says – the Far Side of moon gets as much sunlight as the Near Side – There is no “dark side of the moon”

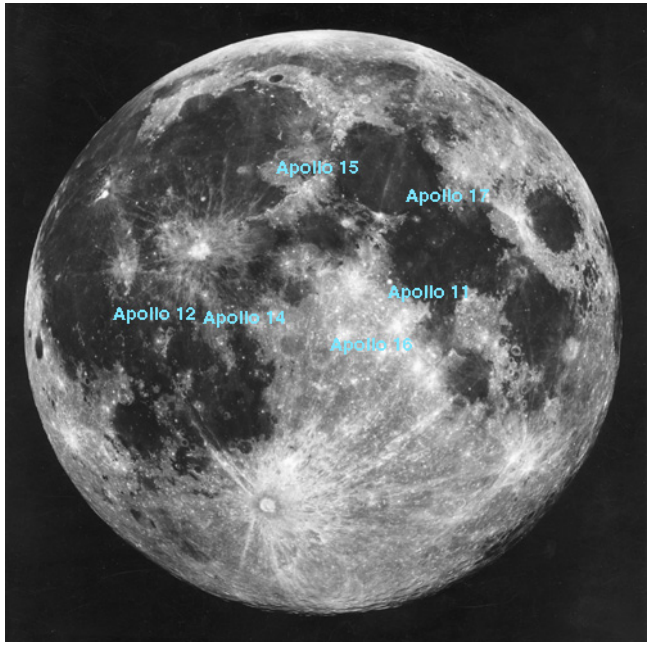




Lunar Exploration

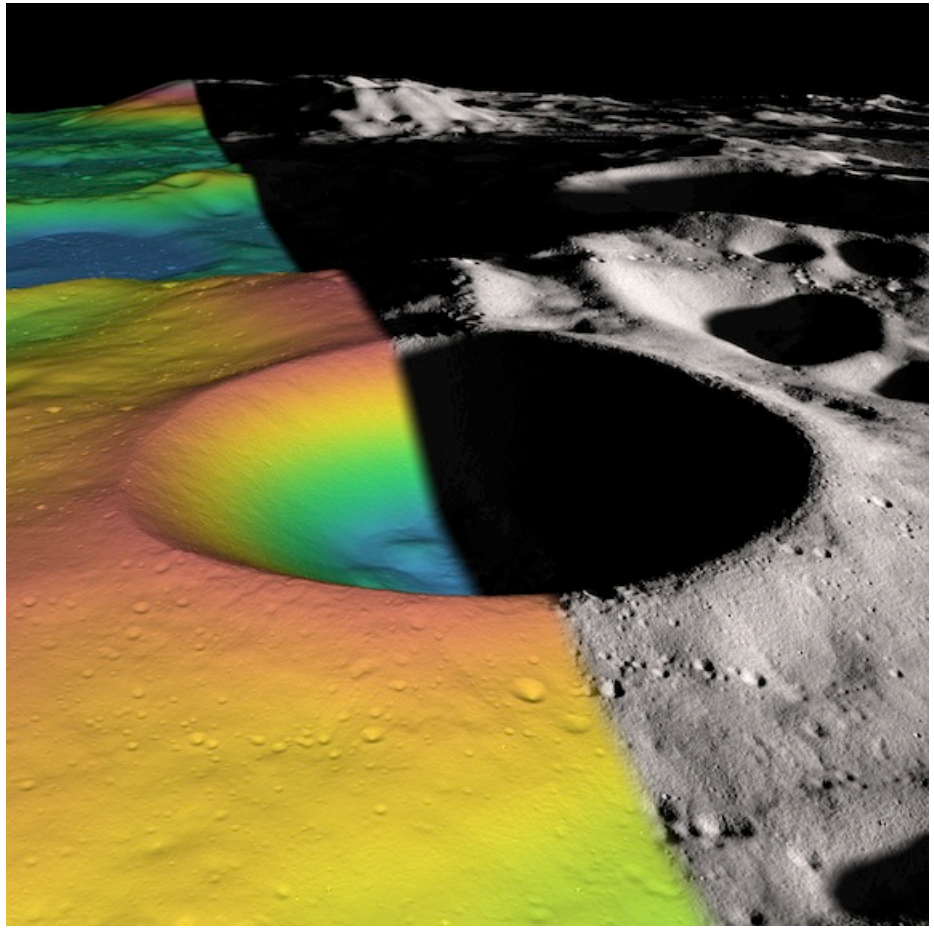
- **Past Exploration**
  - 105+ robotic spacecraft missions
  - Only celestial body beyond Earth visited by Humans
    - Apollo missions (1969 – 1972)
      - Equatorial region
    - 12 Apollo Astronauts walked on the lunar surface
    - ~10 days on lunar surface / 80 hours outside of lander
- **Future 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

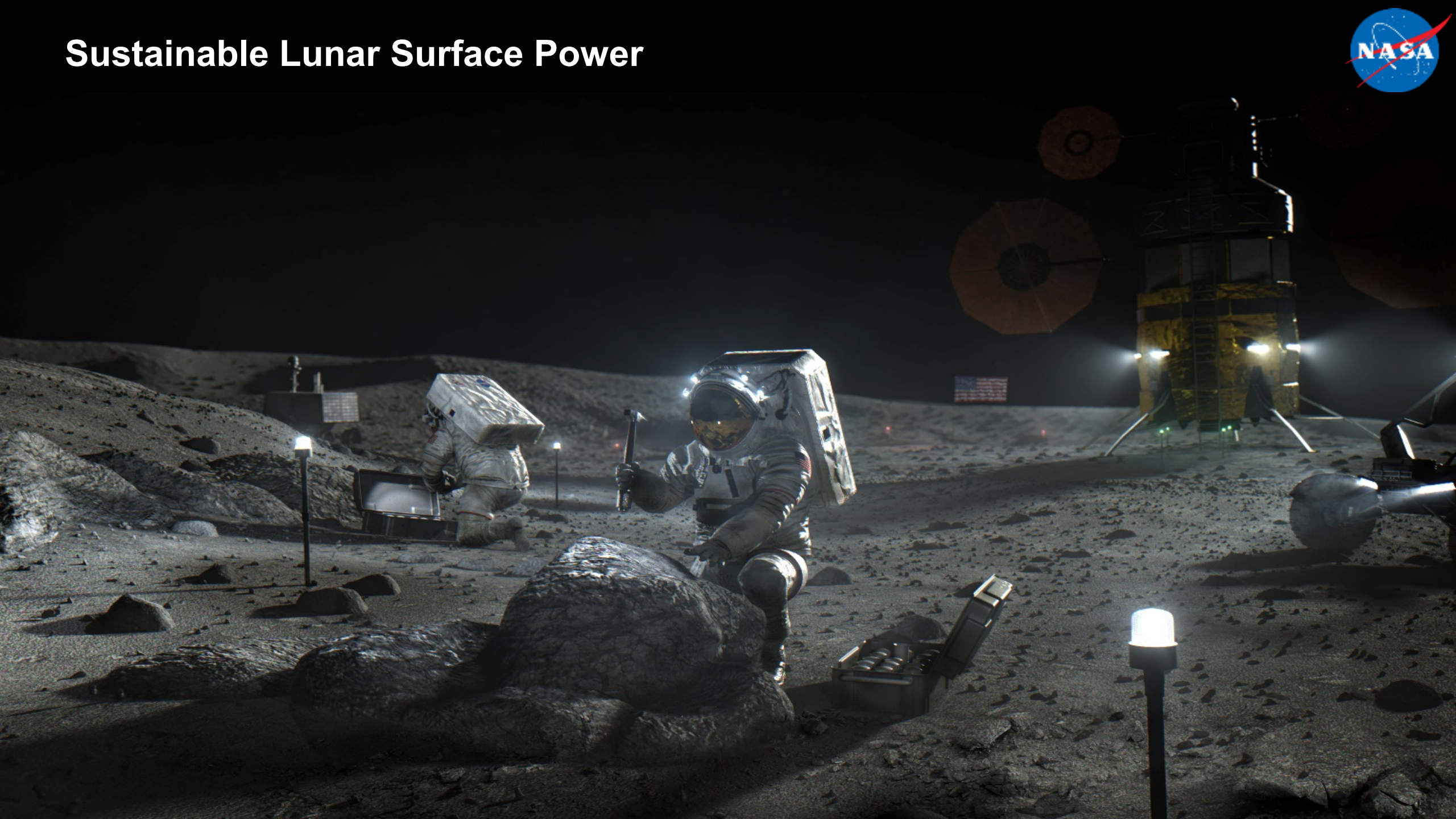
- **Impact crater at the South Pole**
- **Named after Antarctic Explorer Ernest Shackleton**
- **Size:**
  - 21 km (13 mi) in diameter and 4.2 km (2.6 mi) deep
- **Rims are in almost continuous sunlight**
- **Interior is perpetually in shadow (eternal darkness)**
  - Average temperature -183 C (90 K)
  - 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



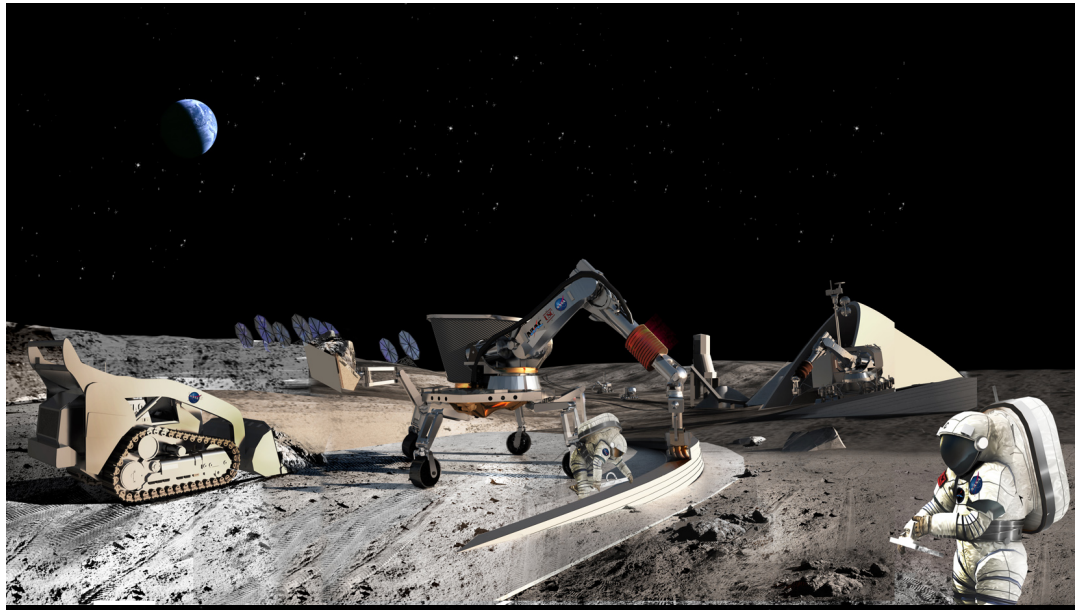
Sustainable Lunar Surface Power

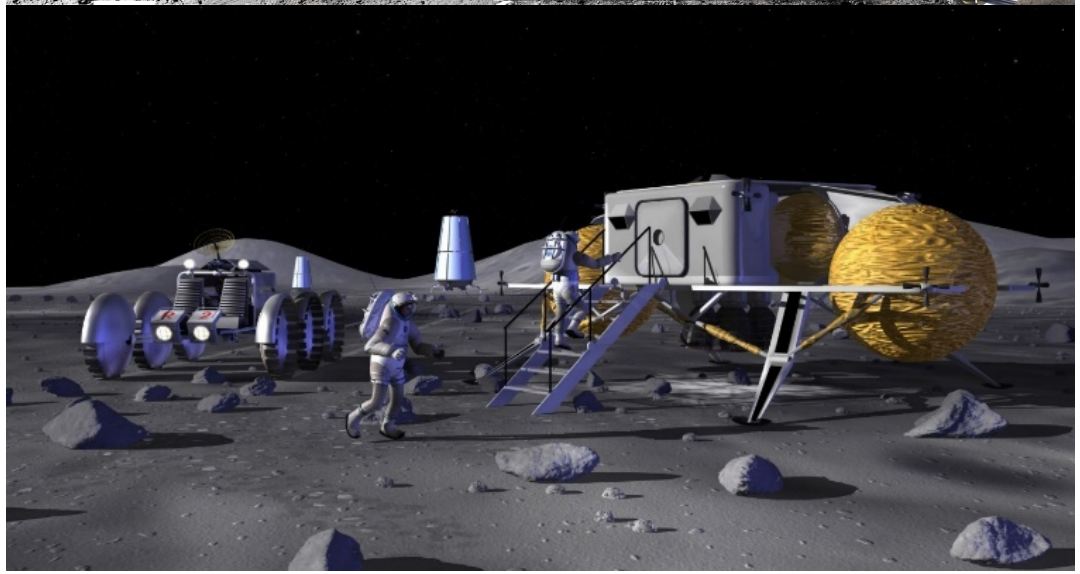


Sustainable Presence Lunar Surface Activities

- **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**

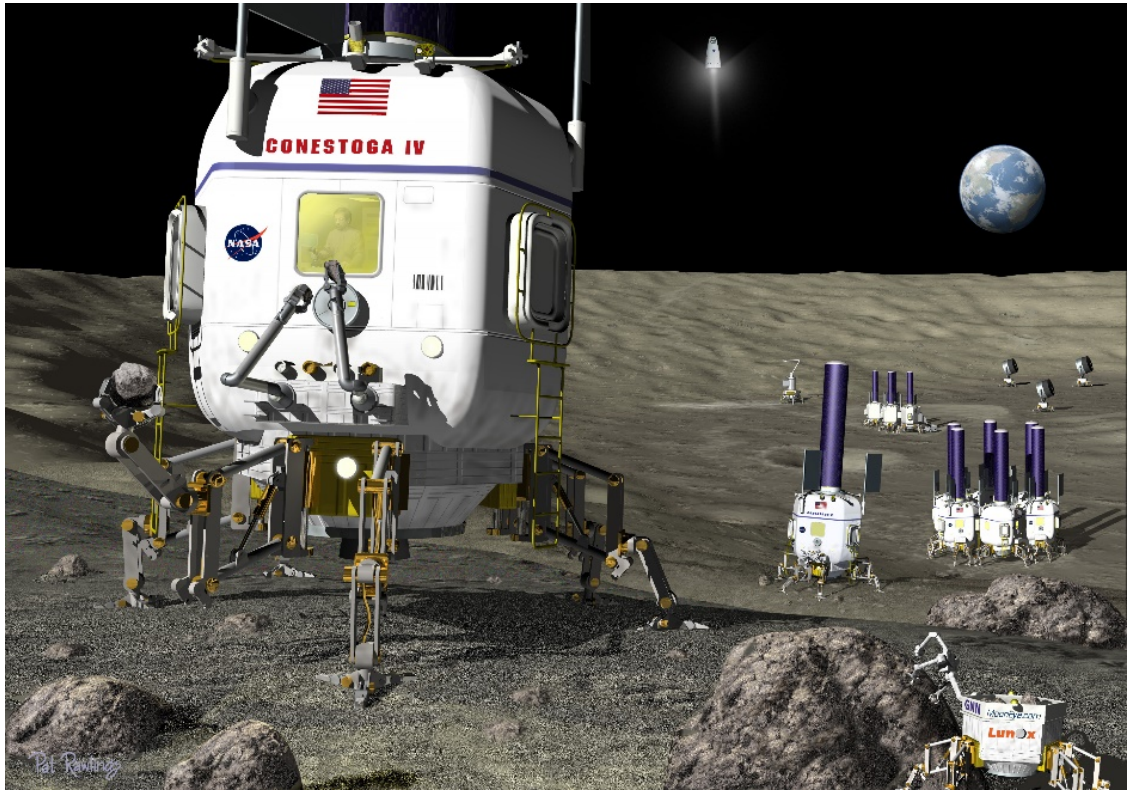
A sustainable Lunar presence will require electrical power that is highly reliable and available (electrical power on Earth)





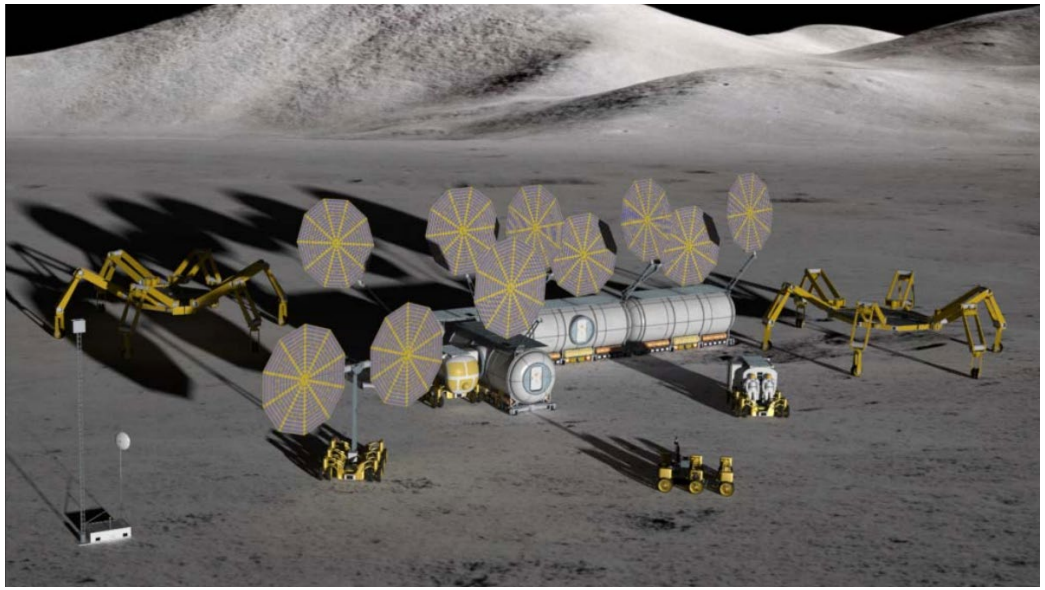
Lunar Surface Sustainable Power Challenges

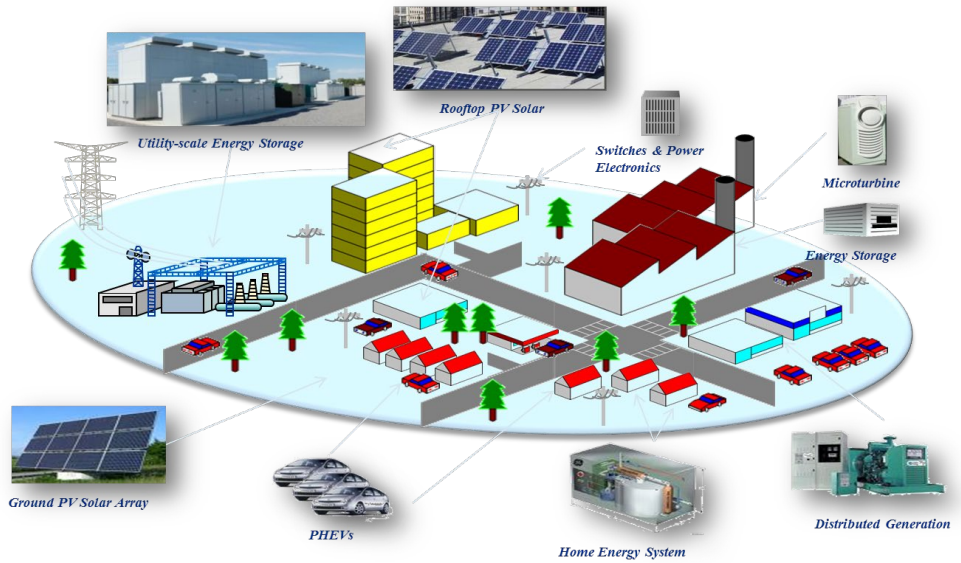
- **Power Use & Availability**
  - Lunar surface power needs/uses will grow and evolve over time.
    - Power strategy (generation / energy storage) will need to evolve over time.
  - Availability – Large amounts of power is needed regardless of time of lunar day.
  - Accommodate distributed power system resources (mix of generation, storage, and loads)
- **Power System Operations**
  - Autonomous operation for extended periods
  - Robotically deployable PMAD / power systems
- **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

- **Designing a Lunar microgrid to provide electrical power**
  - Permits the optimal dispatch of power sources / energy storage to service loads
  - Permits the systematic integration of new sources and loads as the lunar base evolves
  - Permits the addition of dissimilar source and storage methodologies to enhance reliability and availability
  - Permits the enforcement of a common grid interface for source and loads facilitate growth and interchangeability.
  - Allows for the deployment of future science loads that do not need to carry their own power generation

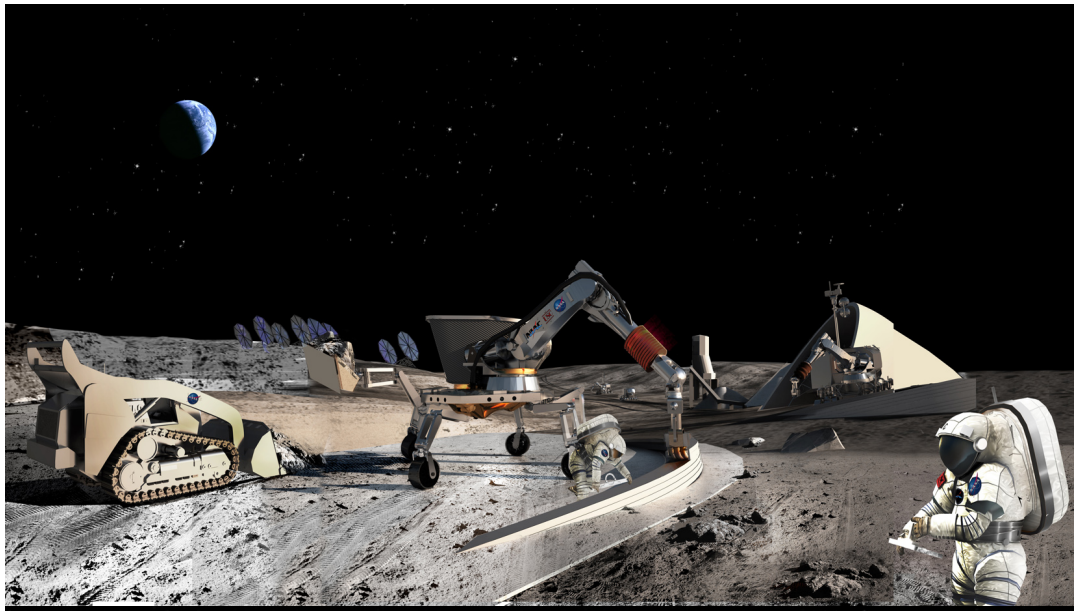


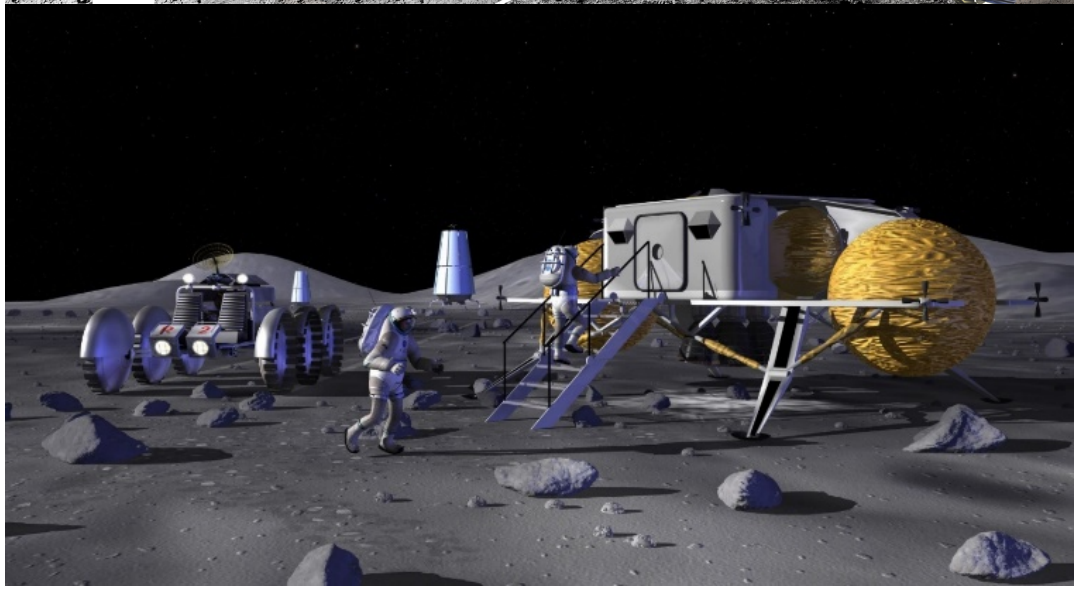


Lunar Surface Microgrid



Power Users

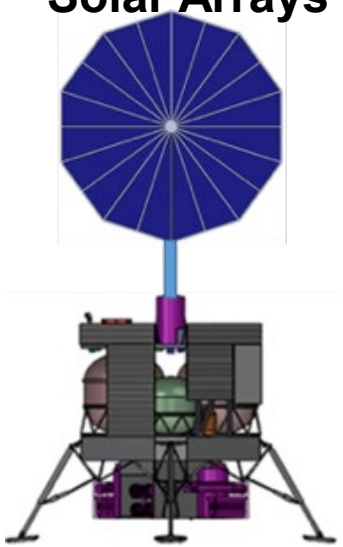




- **In-Situ Resource Utilization (ISRU)**
  - Largest power user 60 – 70 kW
  - Mine regolith and convert into fuel and other resources
  - Operate during periods of heavy insolation
- **Habitat**
  - Second larger power user during habitation (insolation only) (20 kW)
  - Crew of 4 for 30+ days – 4 times per year
- **Lunar science / Exploration**
  - Hopper @ TBD power
  - Various rovers @ 500 W each
  - Power beaming @ TBD power
- **Technology Demonstrations**
  - ISRU
  - Kilopower
  - Etc.

Power Generation & Energy Storage

Solar Arrays

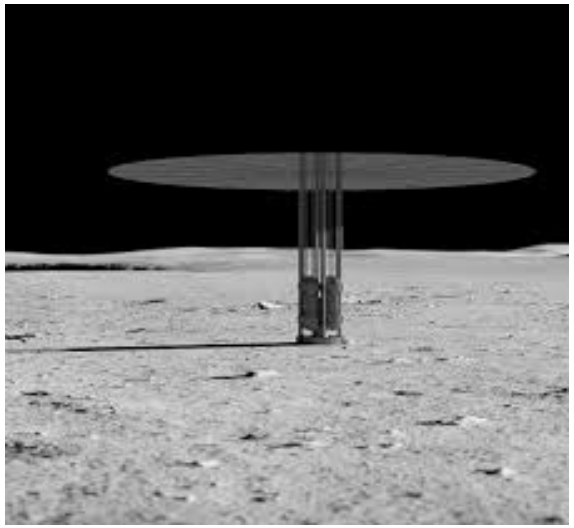




Primary Fuel Cells

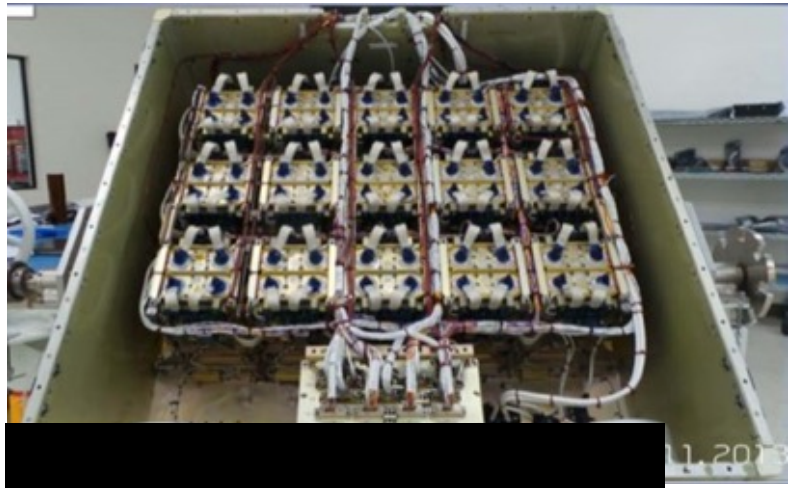
Radioisotopes (RTG, RPS, etc)



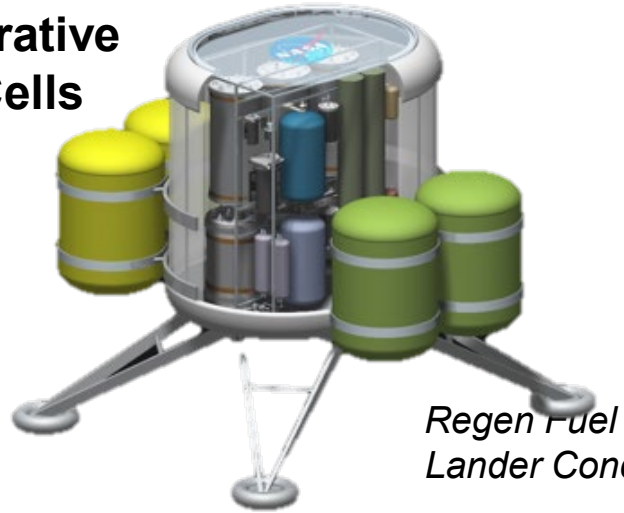


Fission Surface Power

Batteries



Regenerative Fuel Cells

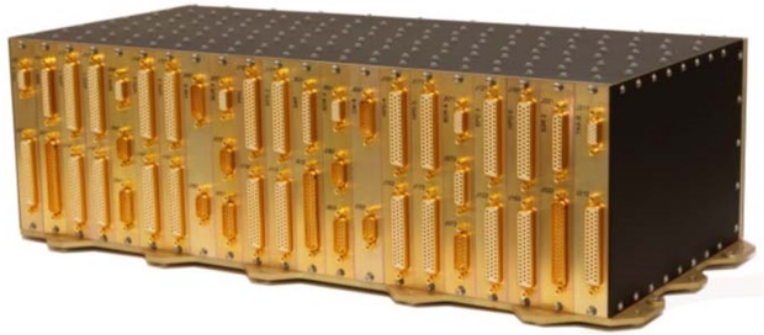


Regen Fuel Cell Lander Concept

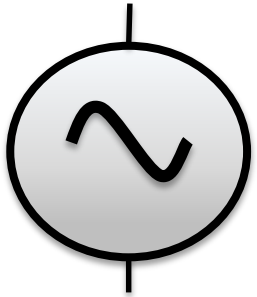
Primary Power Distribution (Transmission)



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



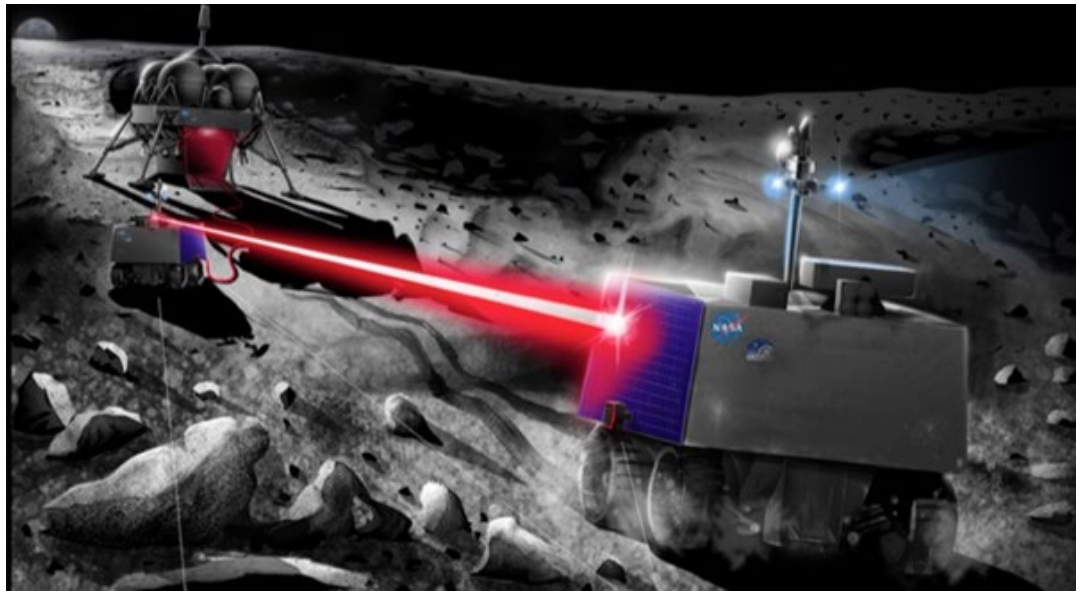
AC Power
• Ease of voltage conversion and fault control • Resembles terrestrial grid
• AC frequency may cause issues related to power factor correction, deployment of 3-phase systems, relative size / mass of voltage conversion at low frequency. • Low TRL for space applications • Large change (DC to AC)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

Primary Power Distribution (Transmission)

Wireless Power Transmission

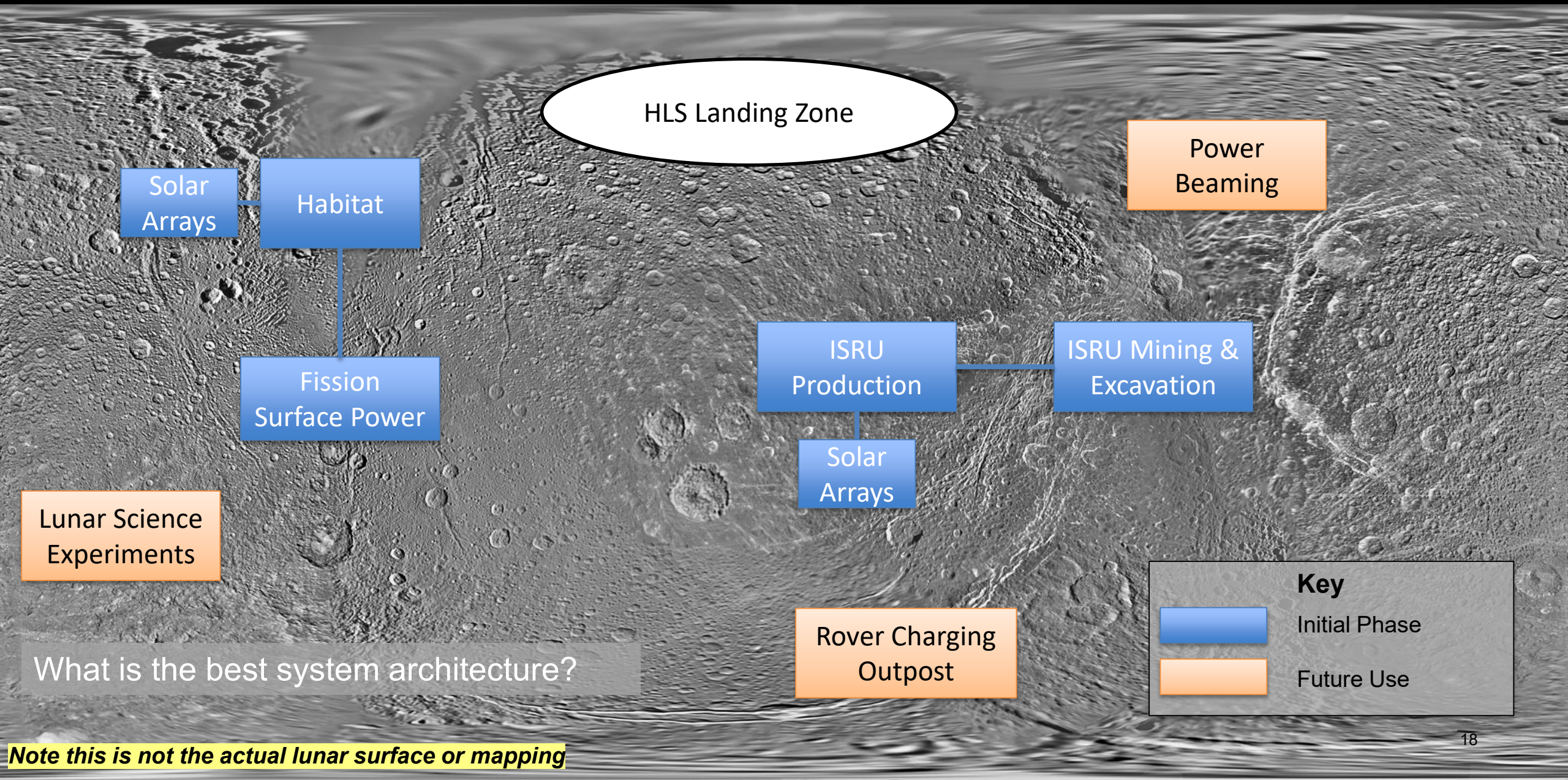
- Convert source electricity to laser or microwave energy & transmit wirelessly (beam)
- No need for robotic deployment of cables and connectors
- Effective distance is line-of-sight with no degradation in power
    - Allows for exploration/operations in difficult terrain

- 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



What is the best system architecture?

Note this is not the actual lunar surface or mapping

NASA Lunar Microgrid Funding

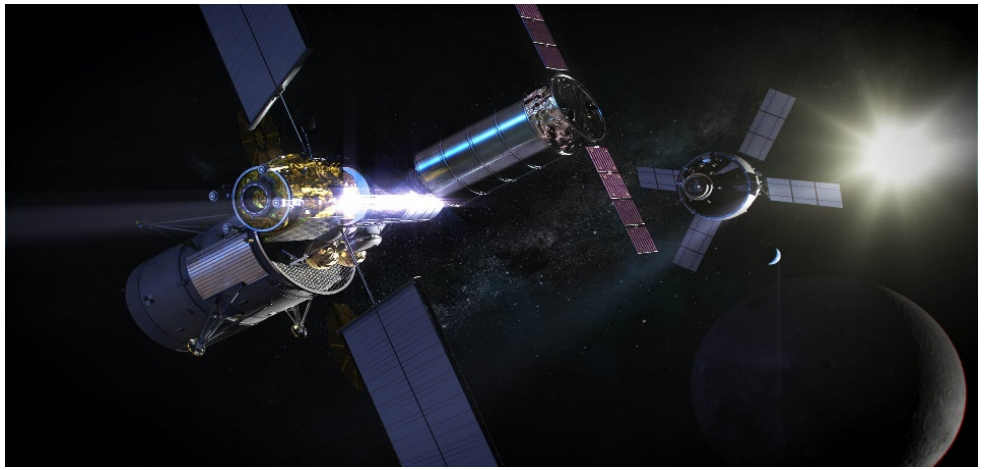
- **Microgrid Definition and Interface Converter for Planetary Surface (MIPS)**
  - Science Technology Mission Directorate (STMD) FY21 New Start
    - Game Changing Development Program
  - FY21 & FY22 Lunar Surface Power Architecture
    - Design of a Lunar Surface power architecture that can integrate 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

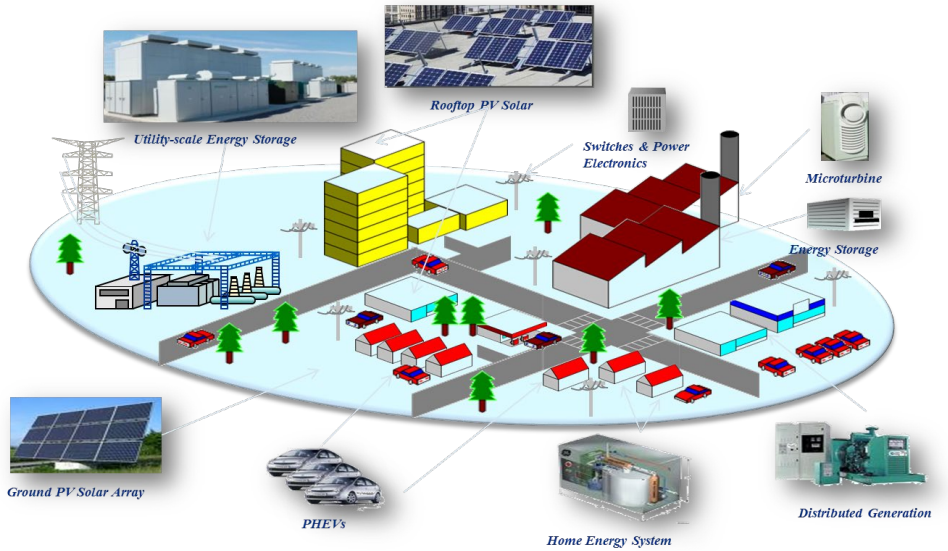
Autonomous Hierarchical Microgrid



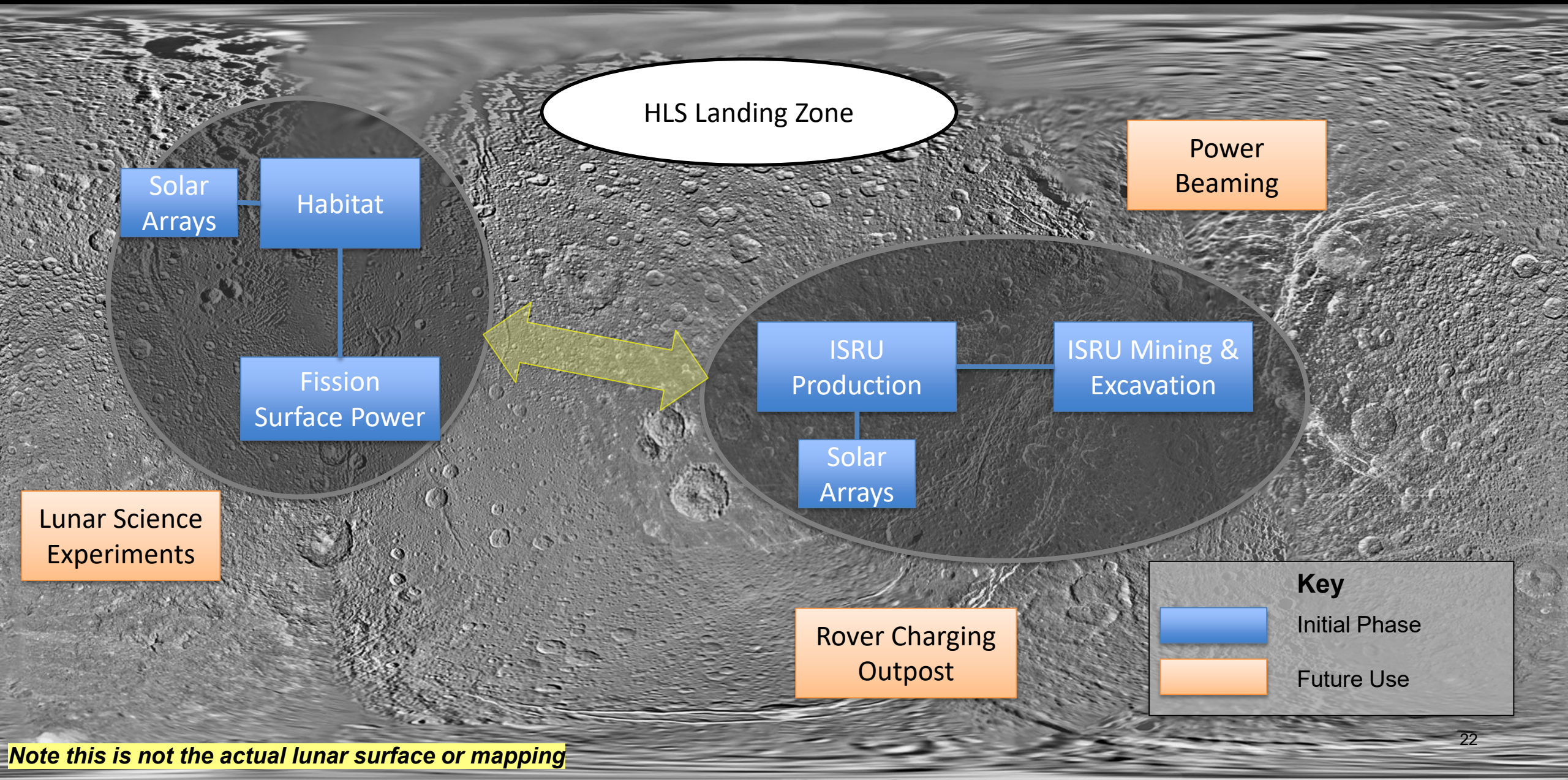
Power Control

- **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
    - Fault Management
    - Energy 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



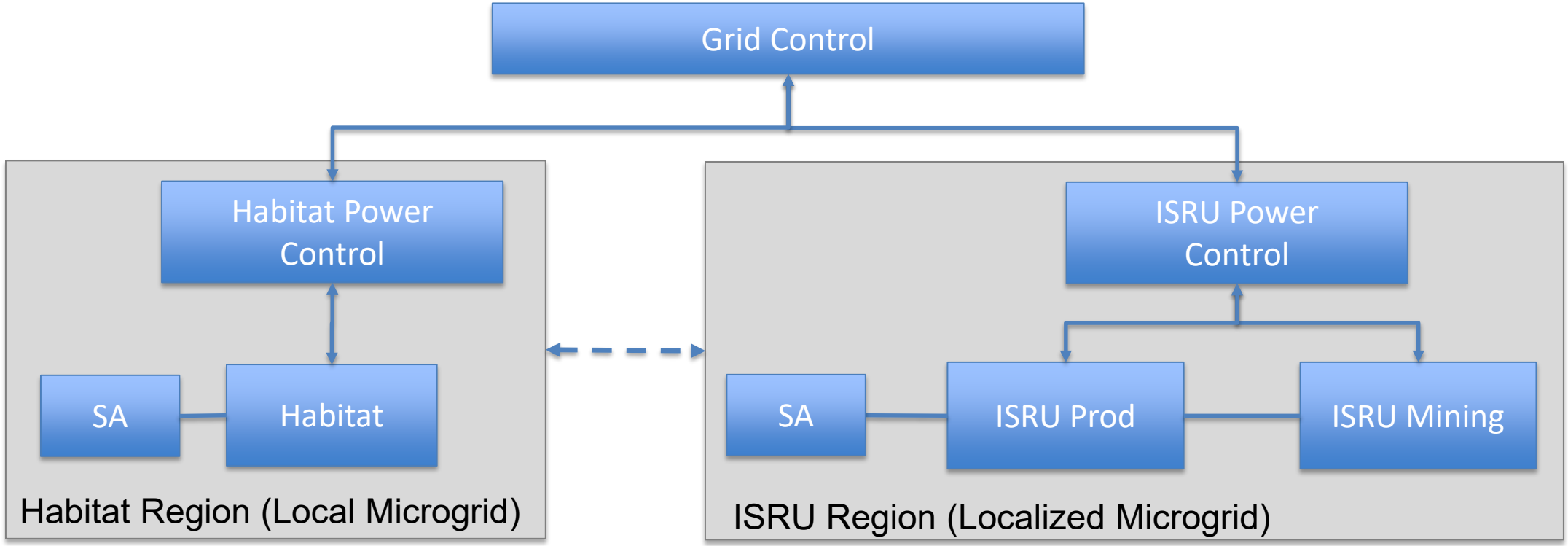


Proposed Distributed Lunar Microgrid



Note this is not the actual lunar surface or mapping

Hierarchical Microgrid Control

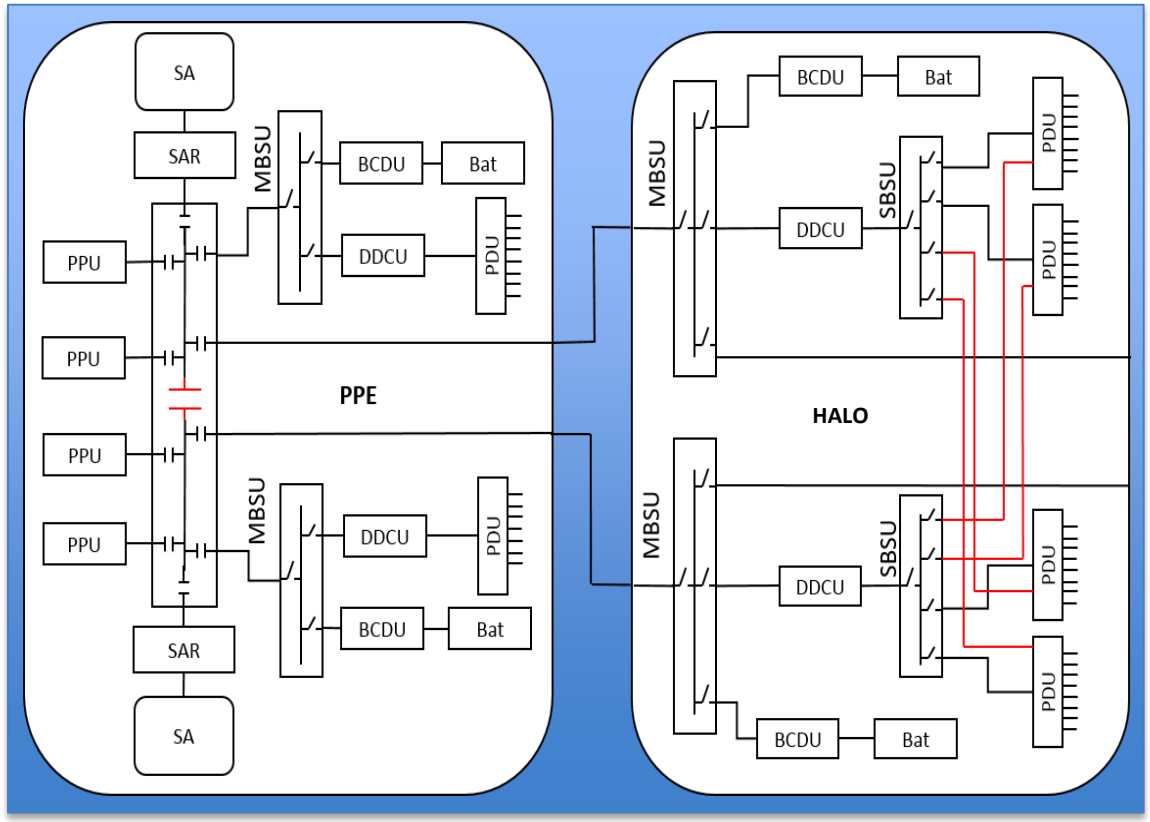


- **Controllers to manage power system constraints within each region**
  - Energy storage constraints, power distribution limitations, etc.
- **Overall Grid controller to ensure system objectives are met and allow sharing between regions**

Collaboration with Sandia National Laboratory

Gateway Power System

- **Leverage technology that was developed under the Advanced Modular Power Systems (AMPS) Program**
  - EPS for the Gateway System
  - More complex power distribution system with more reconfiguration options
  - Distributed Energy Storage
  - More complex energy management system



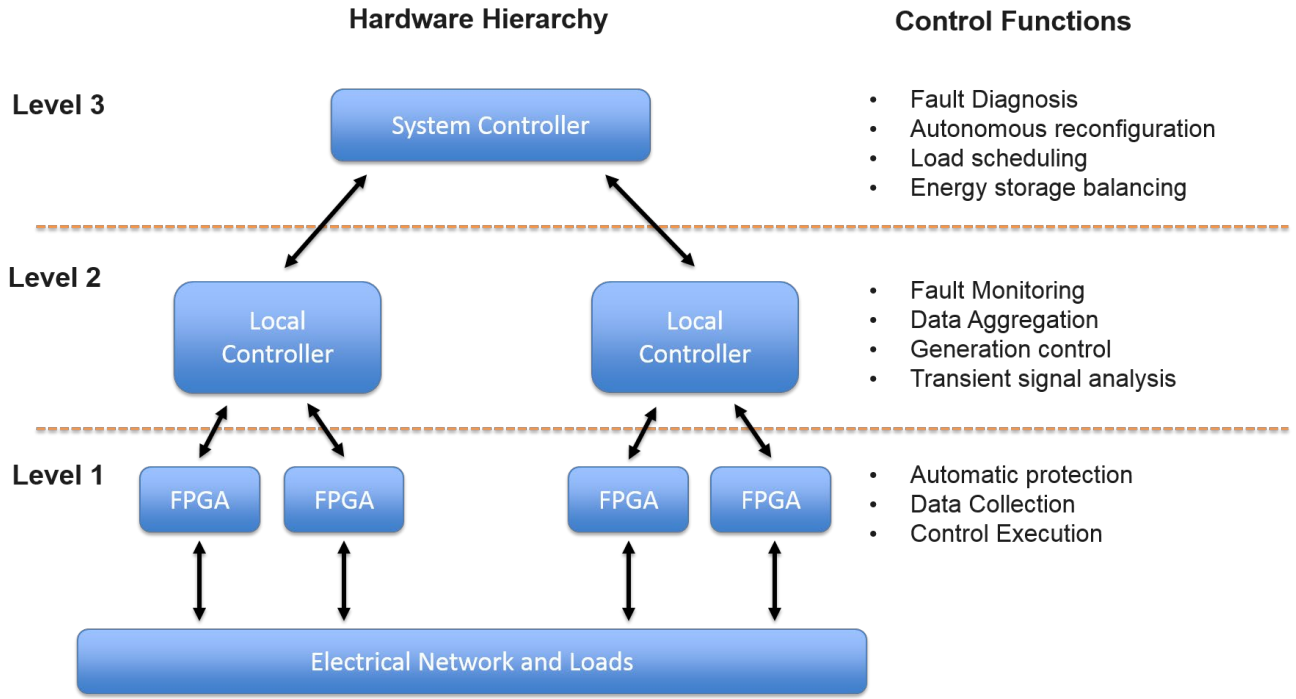
Gateway Electrical Power System Model

Fault Management

- **Detect, isolate, and recover from faults without a human operator in the loop.**

- **Fault Techniques Employed**
  - Classical hard protection (trip curve)
  - Heart beat for communication
  - Analytical redundancy
  - State estimation
  - Model based methods

- **Multiple Fault**
  - Rely on blend of model based and rules based techniques
  - On average, can detect up to ~10 faults before fault manager stops detecting
    - System unobservable
    - Power system no longer functioning

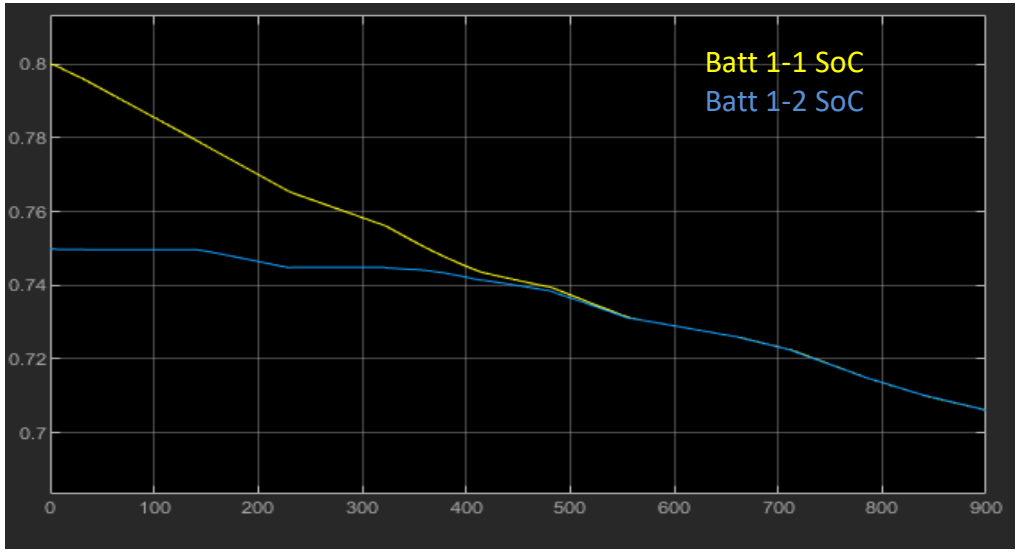


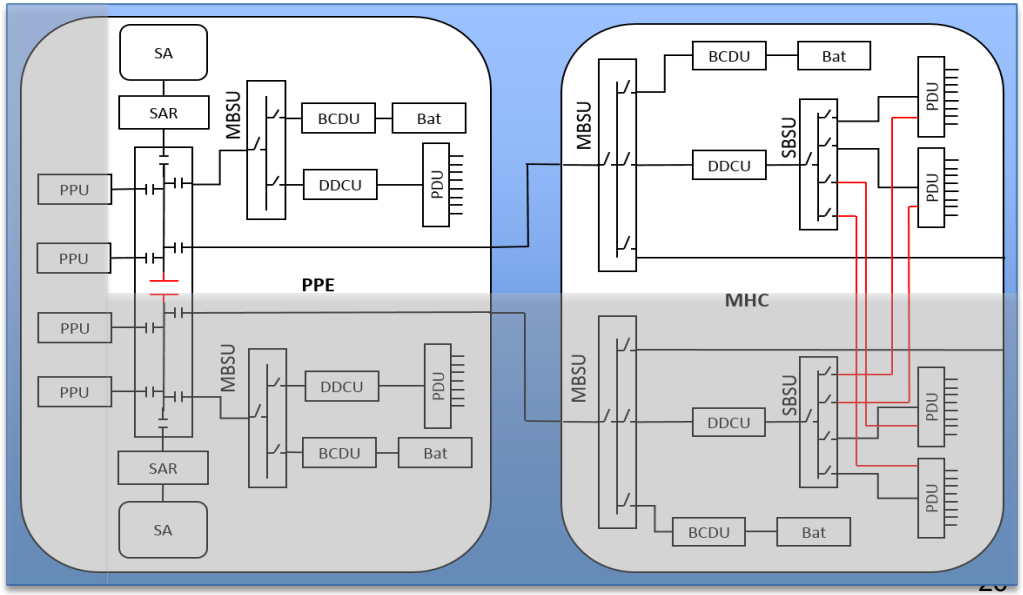
Current Fault Results

- Investigated and tested 380 individual faults
  - 76 hard faults
  - 132 switch faults
  - 24 communication faults
  - 148 sensor faults

Energy Management – Load Sharing

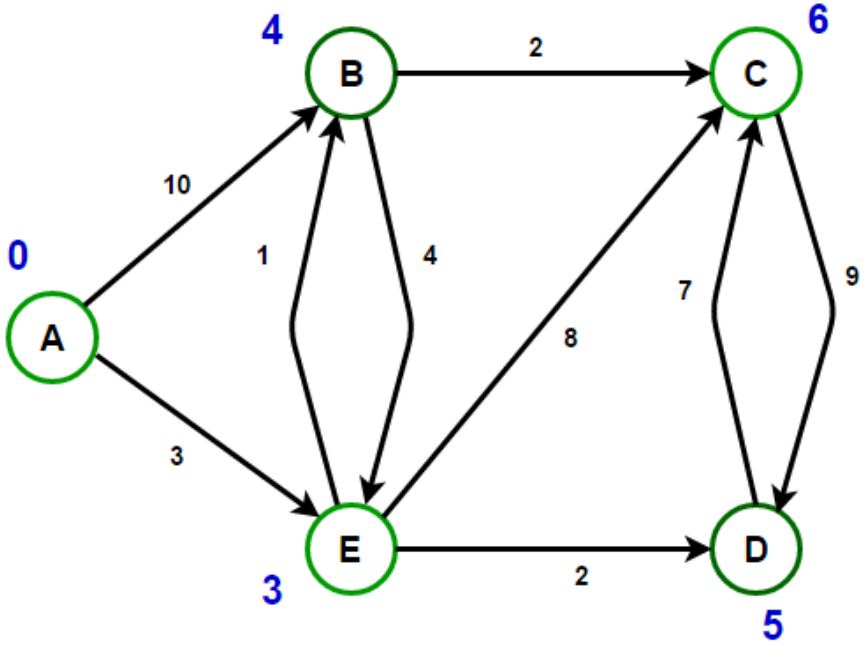
- **Manages the electrical power generation and distribution**
  - Forecasts the available electrical power and energy
  - Manages power system constraints
  - Ensures power system constraints are not violated
    - Approving proposed load schedules
    - Load shed to preserve constraints
- **Optimal Battery Management Solution for Distributed Batteries**
  - Uniformly discharge the distributed batteries
    - Maximizes peak power availability during eclipse.
  - Three-level control solution
    - Reactive layer controls (BCDU)
    - Secondary control (central APC)
    - Tertiary control (central APC)
      - Optimal battery management
      - Control load sharing based on battery SoC

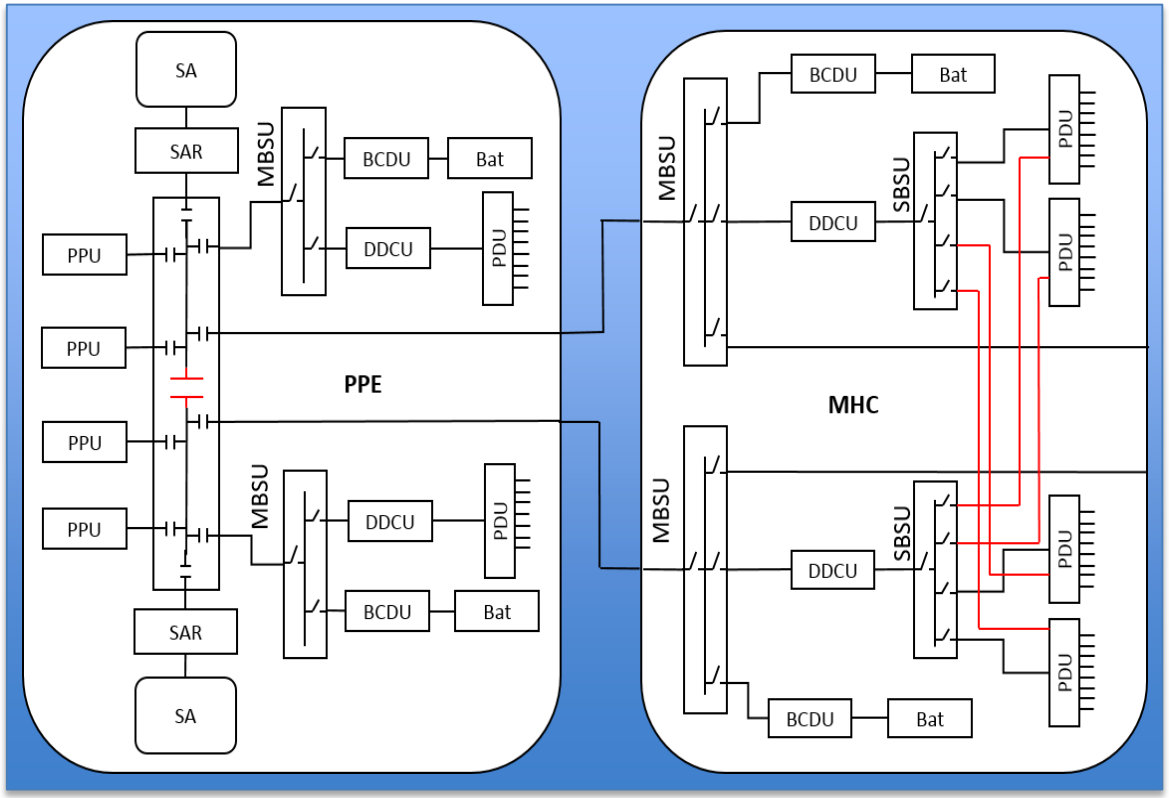




Contingency Management – Smart Reconfiguration

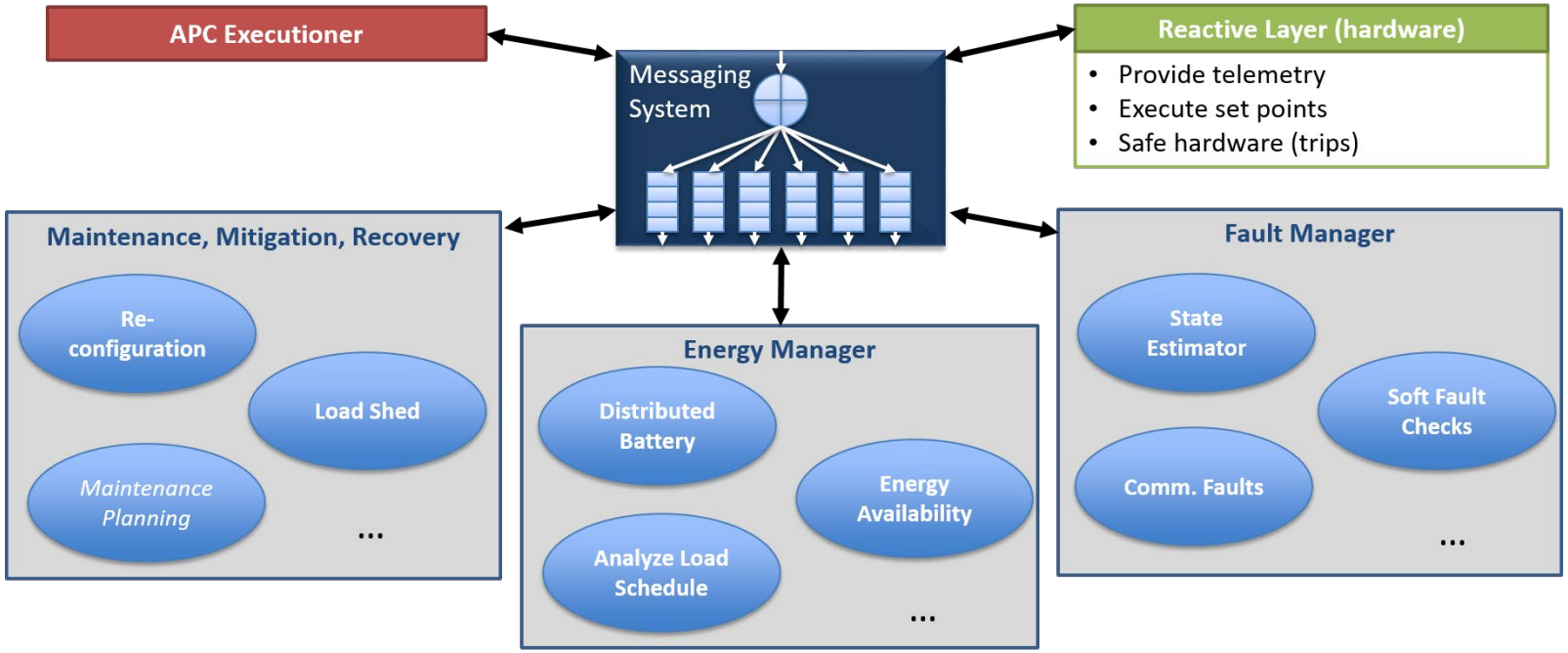
- **Manages system reconfiguration**
  - Fault removes component from service and need to re-route power
  - Need to repair equipment and schedule outage (future capability)
- **Algorithm uses Dijkstra's algorithm**
  - Used in Google's Map
  - Find the optimal path by weighting every line.





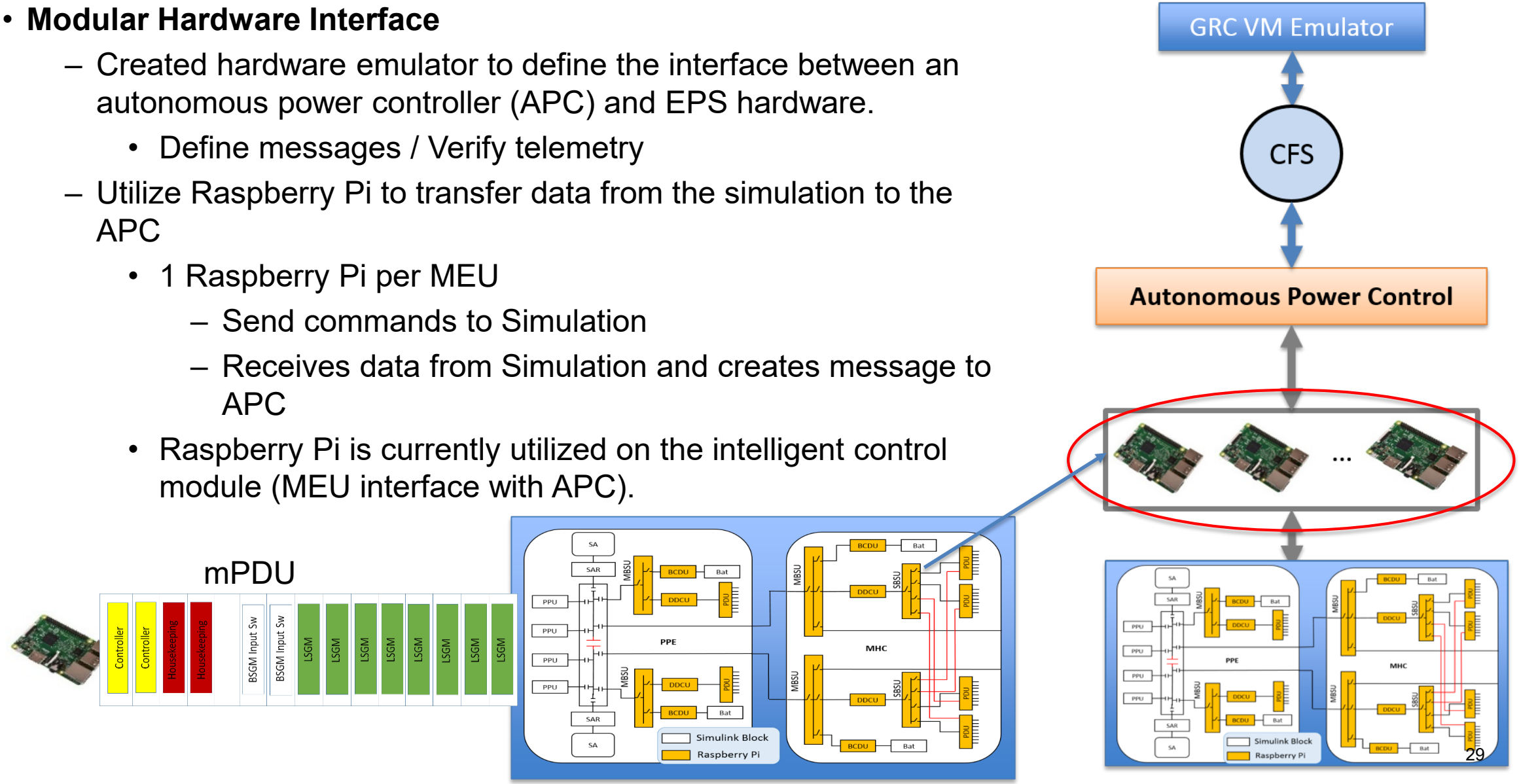
Software Architecture

- **Developed an architecture which breaks all of the control functions into services**
  - 29 services in all to run the APC
    - Energy Management, Fault Management, MMR, Display, system data communication, executioner etc.
- **Implemented a message brokerage system (RabbitMQ) to permit the services to communicate and enable the controller operation**
- **Utilization of this architecture permits multiple implementations of the controller**
  - Operated as one centralized processor that communicates directly with the power system simulation
  - Operated on a distributed set of processors that communicate with the power simulation or power hardware over a network



Hardware Interface

- **Modular Hardware Interface**
  - Created hardware emulator to define the interface between an autonomous power controller (APC) and EPS hardware.
    - Define messages / Verify telemetry
  - Utilize Raspberry Pi to transfer data from the simulation to the APC
    - 1 Raspberry Pi per MEU
      - Send commands to Simulation
      - Receives data from Simulation and creates message to APC
    - Raspberry Pi is currently utilized on the intelligent control module (MEU interface with APC).



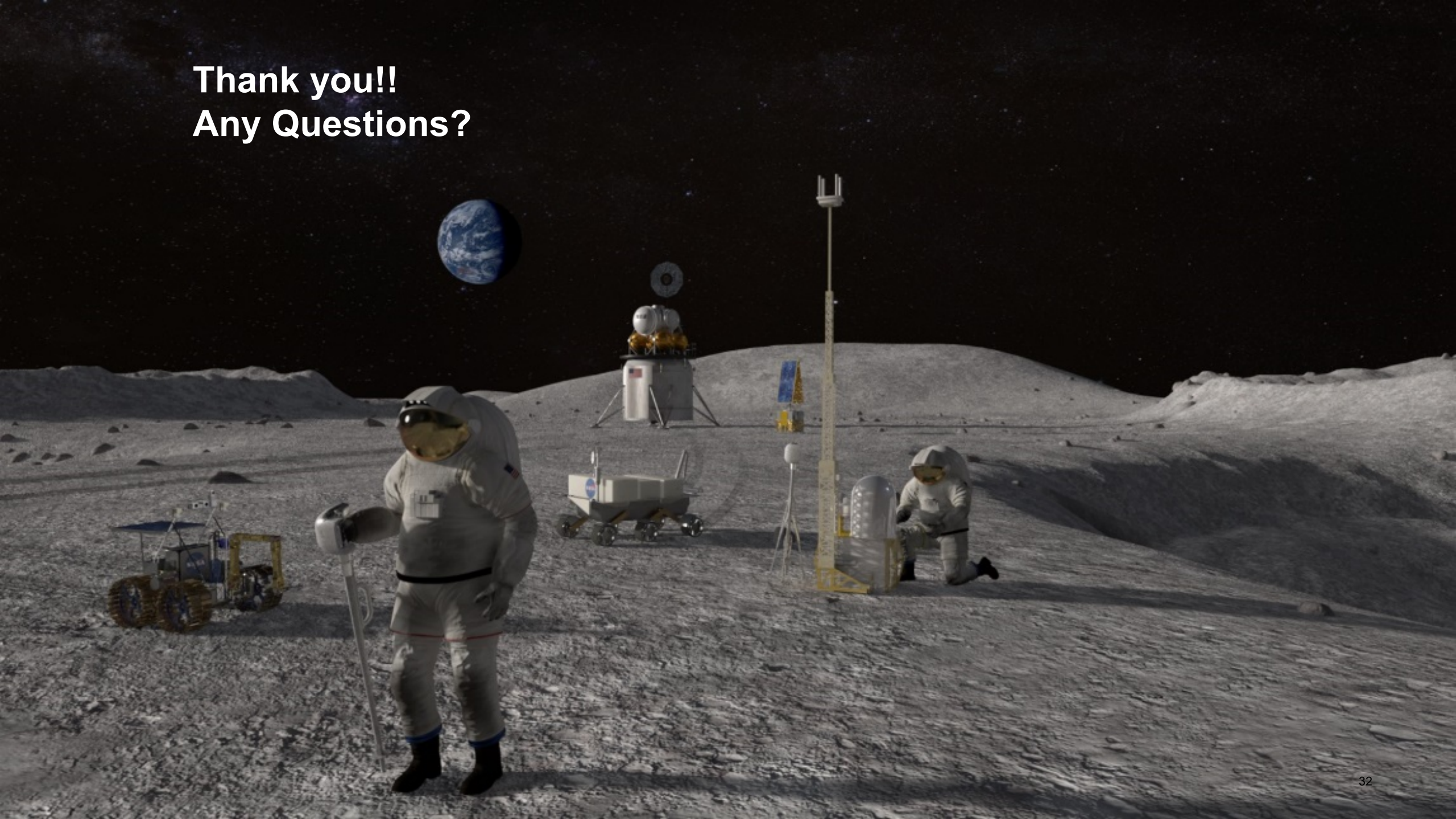
NASA Autonomous Power Control

- **NASA Advanced Exploration Systems – Autonomous Power Control**
  - Large funding cut in FY21
- **Reduced funding for collaboration with Sandia National Laboratory**
  - Working on agreement to collaborate on 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
    - Leverages previous NASA work performed on Gateway

Summary

- **Recent interest in microgrid technology to meet the needs of future electrical power systems**
  - Space, Aeronautics and Terrestrial applications
  - Need for higher reliability and availability
  - Desire for alternative (renewables) power sources (generation & storage)
- **Microgrids require complex operational scenario to achieve maximum benefit**
  - Integration of 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**
  - Lunar Microgrid (space)
  - Tactical / Intelligent Microgrids (military)
  - Residential/Business Microgrids (terrestrial)
- **NASA is interested in further developing microgrid technology**
  - Lunar surface power
  - Autonomous power control

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

