# Micro-grid for Future Planetary Surface Needs

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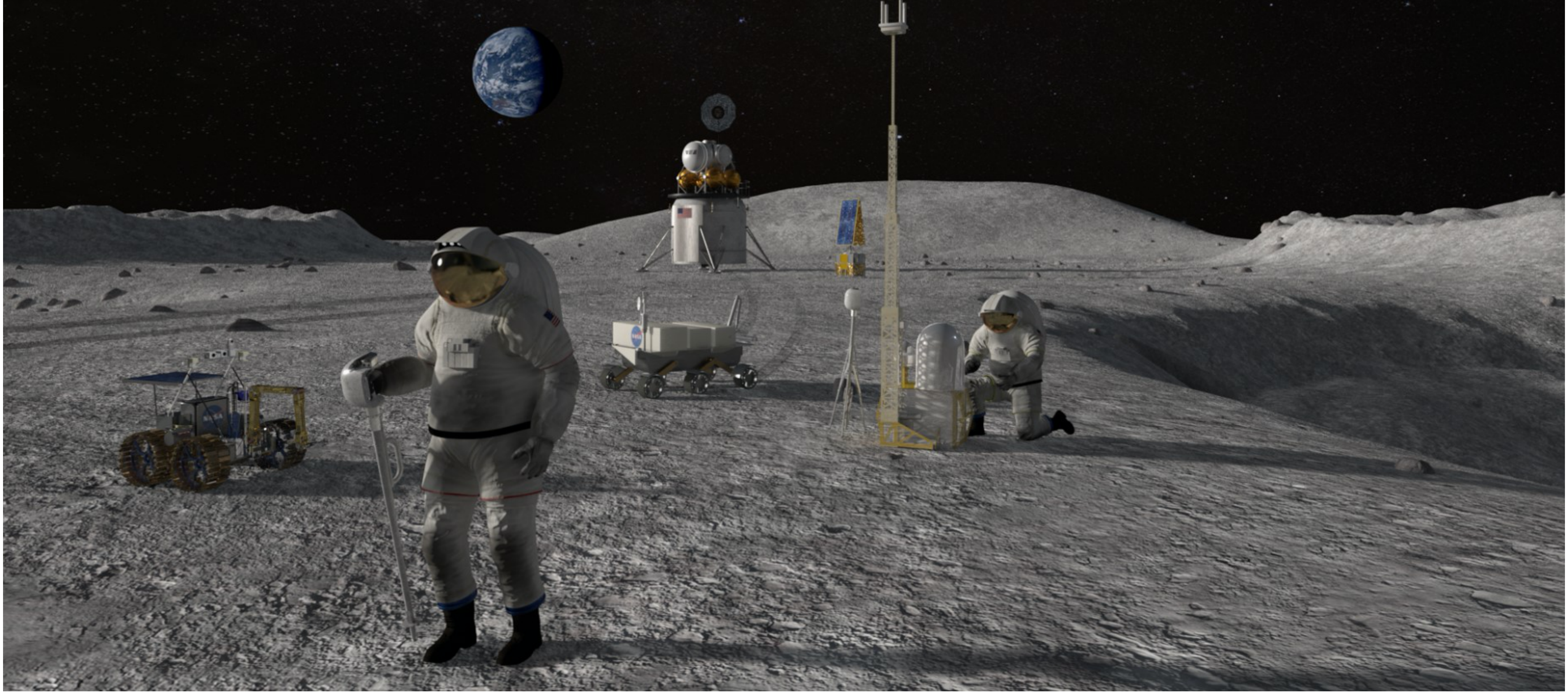
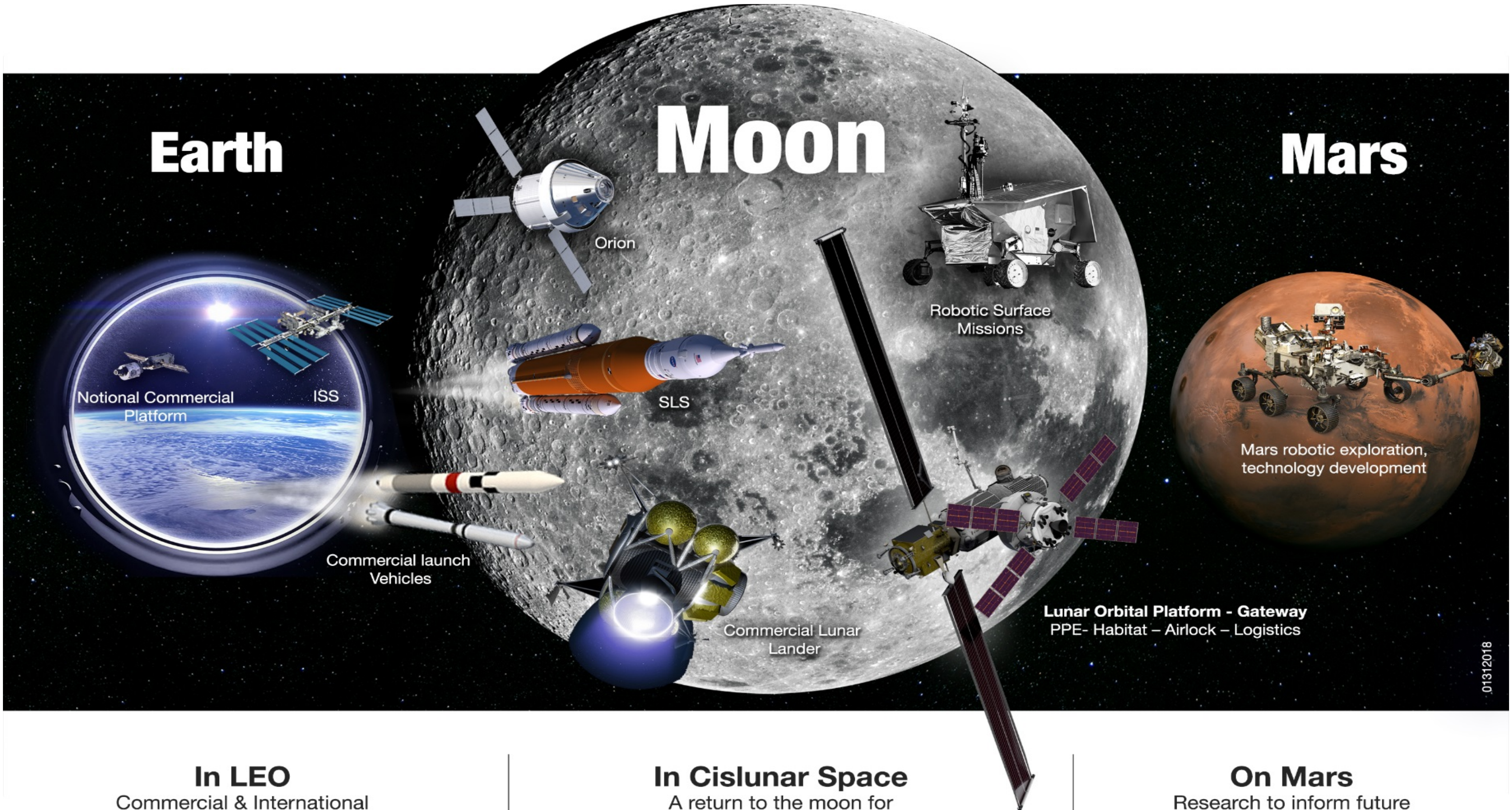





**In LEO**
Commercial & International partnerships

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

**On Mars**
Research to inform future crewed missions

# 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

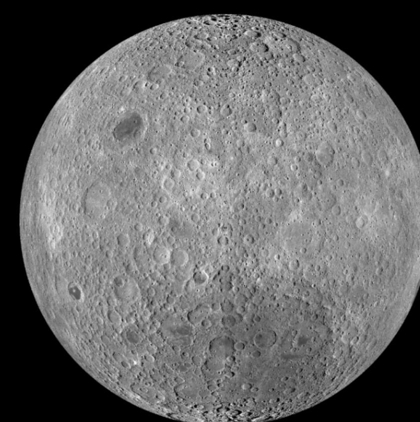
**Orbit period / length of day**

- 27 days
- Earth and moon are tidally-locked
  - Earth will only see one side of the moon

**Exploration**

- More than 105 robotic spacecraft missions
- Only celestial body beyond Earth visited by Humans

Near Side

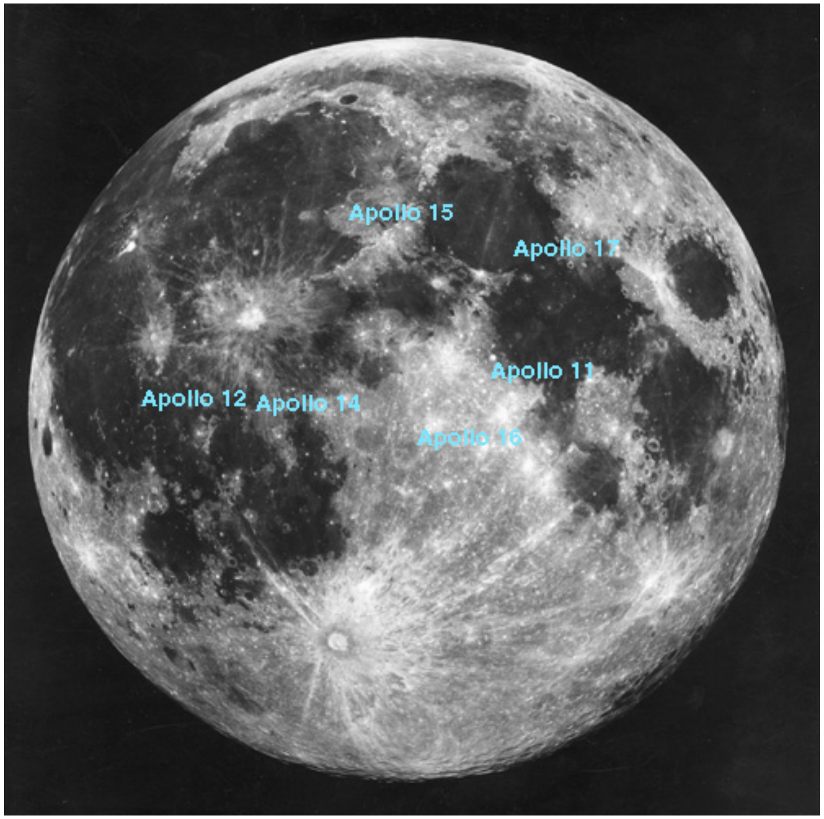


Far Side

# Human Lunar Exploration

**Future Human Lunar Missions**

- Focused on testing and demonstrating technologies for sustained Lunar presence and Mars
- Potential sites & environmental concerns
  - Equatorial Regions
    - Eclipse: 14 day (336 hours)
    - Temperature: -170ºC to 125ºC mean -80ºC
  - Polar Regions
    - Eclipse: 65 to 122 hours
    - Temperature: -230ºC to -80ºC mean -170ºC (NP)
    - “Definitive evidence" of water-ice on the lunar surface*
      - » August 2018 – Moon Mineralogy Mapper, M3
      - » May contain volatiles



# Shackleton Crater

**Impact crater at the South Pole**

**Named after Antarctic Explorer Ernest Shackleton**

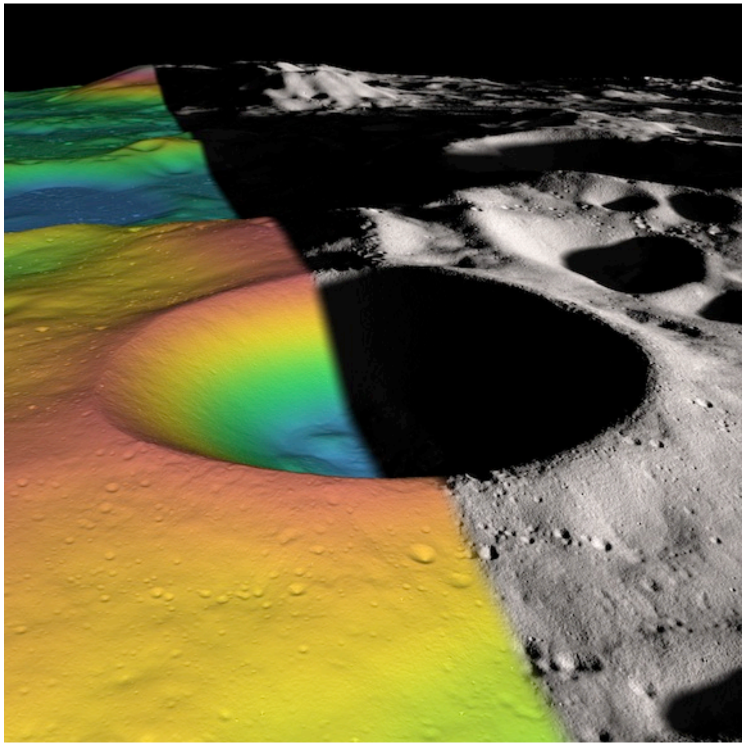
**Size:**

- 21 km (13 mi) in diameter and 4.2 km (2.6 mi) deep

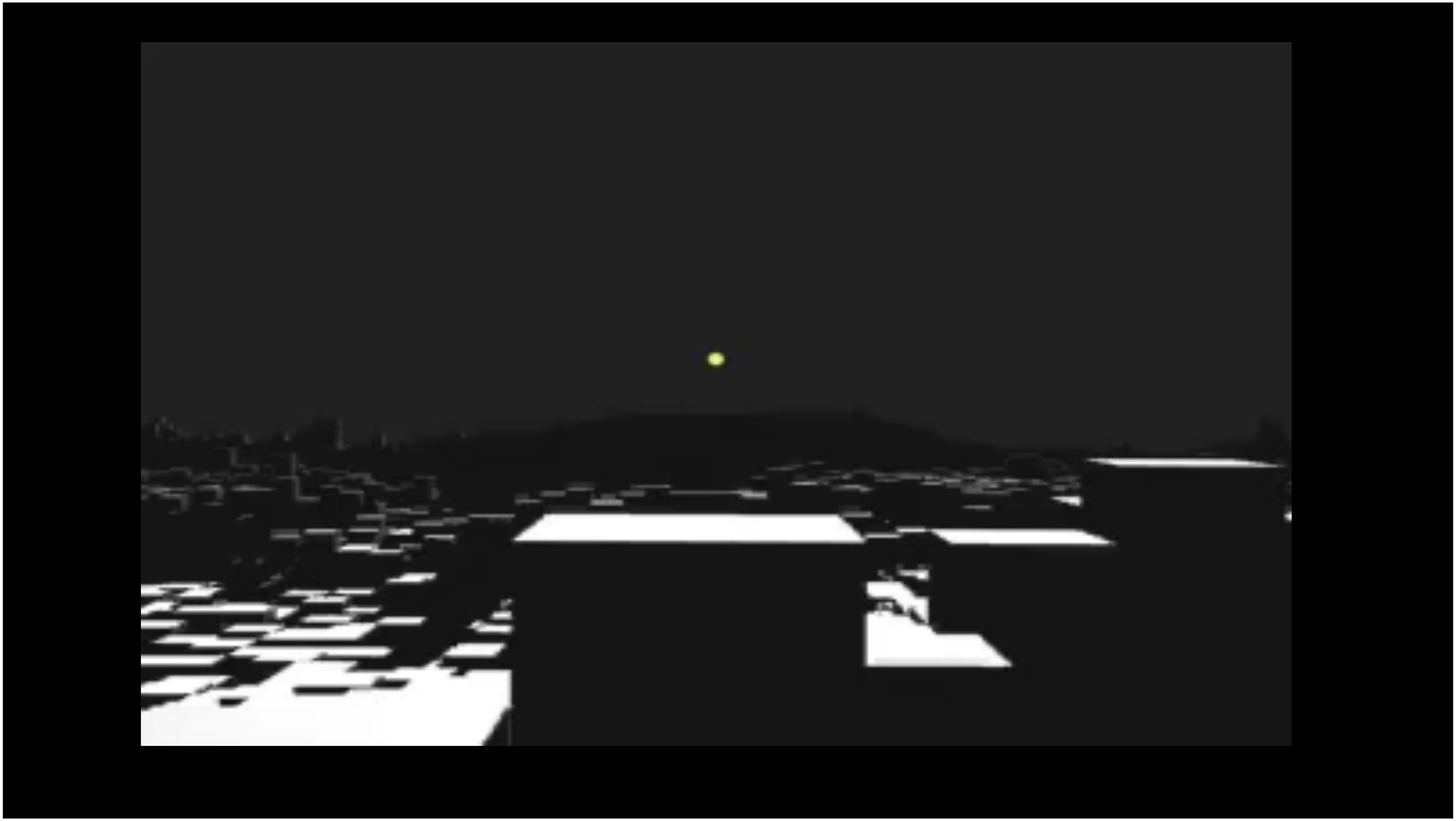
**Rims are in almost continuous sunlight**

**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



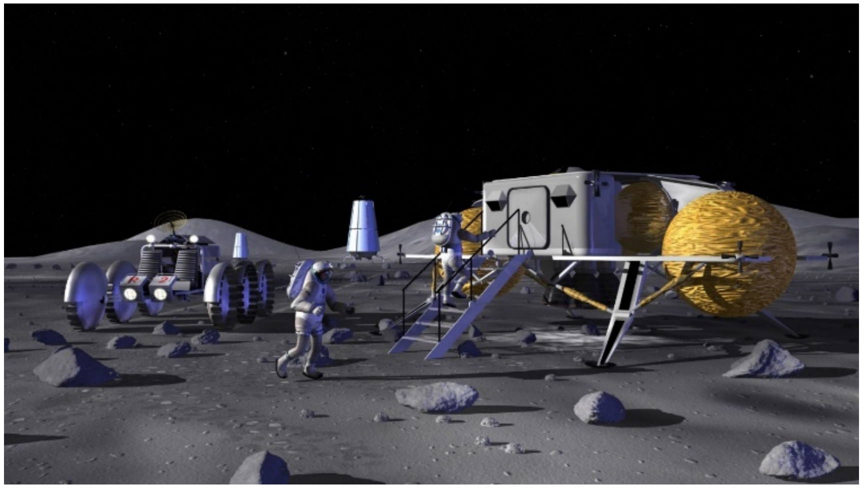
# Electrical Power for the Lunar Surface

- Long Term Vision for Lunar Surface Power
- Evolution of Power on the Lunar Surface
- Grid Challenges and Requirements
- Technologies
  - Power Generation
  - Distribution
  - Micro-grids
  - Interfaces

# Sustainable Presence Lunar Surface Activities

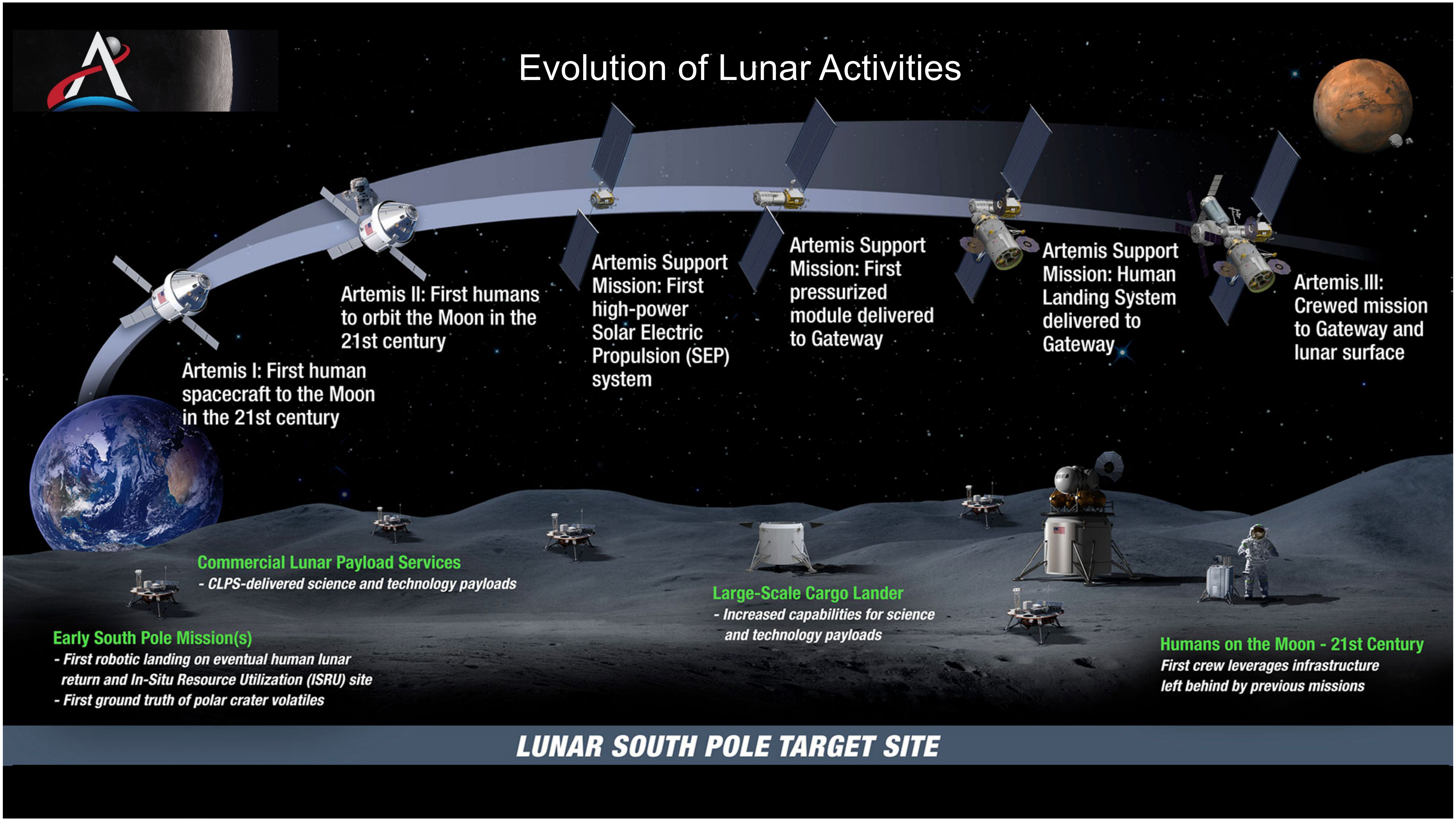
**Lunar Surface Operation Power Needs**

- Manufacture propellant
  - Fuel landers for round trips between the Lunar surface and Gateway at a rate of four flights per year
    - 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
  - Possible human 45-day Moon exploration missions
- Lunar science and technology demonstrations



A sustainable Lunar presence will require electrical power that is highly reliable and available (similar to Earth's Electric Grid)

Austin, Alex, et. al. "Robotic Lunar Surface Operations 2," 70th International Astronautical Congress (IAC), IAF, IAC-19.A3/1/6x/49646, Washington, DC, Oct 21-25, 2019.



Evolution of Lunar Activities
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
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
Large-Scale Cargo Lander
- Increased capabilities for science and technology payloads
Humans on the Moon - 21st Century
First crew leverages infrastructure left behind by previous missions
LUNAR SOUTH POLE TARGET SITE

## Lunar Surface Sustainable Power Challenges

**Lunar surface power needs/uses will grow and evolve over time.**

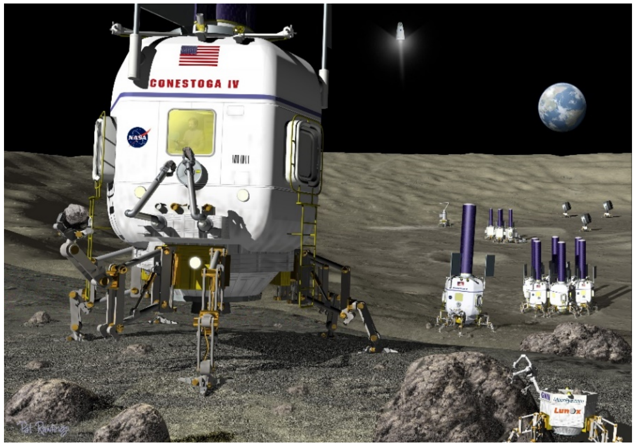
- Power strategy (generation / energy storage) will need to evolve over time.
  - PMAD system must also be able to grow from a point to point distribution system to and integrated micro-grid
- Maintainability/reusability is a key feature, especially for early science missions/payloads.

**Ability to continue lunar surface operations regardless of time of lunar day.**

- Requires a complex power generation and energy storage strategy to provide continuous power.
  - Most likely cannot rely on just batteries/fuel cells to provide all power during lunar night.

**Highly distributed power system.**

- Power sources (generation & storage) and loads will need to be separated by large distances.
  - Physical constraints
    - Engine blast radius to minimize dust contamination
    - Nuclear radiation exclusion.
  - Operational constraints
    - Placement of solar arrays to maximize power generations.
    - Providing power into cold traps for water-ice excavation.



# Lunar Surface Sustainable Power Challenges

**Autonomous operation for extended periods**

- Lunar surface operations will occur without Astronauts being on the surface
  - Routine procedures (excavation, mining, etc.) and construction / build-up

**Robotically deployable PMAD / power systems**

- Need ability for the systems to be assembled / repaired robotically
  - Majority of the time the lunar surface will be unmanned.

**Mass minimization**

- Finite number of landers/flights with mass restrictions.
- Have to include mass of the spares, etc.
  - Modularity / maintainability / reusability can help reduce # of parts and overall mass

**Able to survive the lunar environment**

- Cold temperatures
- Lunar dust (good electrical insulator and low thermal conductivity)
- Radiation hardening from cosmic rays

# Power Users

| | Nominal Power, W | Survival Power, W | Battery Storage, Whr | Notes |
|---|---|---|---|---|
| CLPS | ~100-500 | ~75 | ? | • Likely Solar design; Notional Estimates only |
| Lunar Terrain Vehicle | 1750 | 300 | 15,000 | • Solar/battery design<br>• Energy storage limited by CLPS payload capacity (500kg)<br>• Requires extra 20,000 W-hr prior to Habitable Mobility Platform arrival for 4-day eclipse survival |
| Foundational Habitat | 10,000 | 2,000 | ? | • Solar design<br>• Entire survival energy storage not desired in landed payload due to lander limits |
| Habitable Mobility Platform | 3500 | 500 | 70,000 | • Solar/battery design<br>• No extra energy storage required for 4-day survival period<br>• Extra water thermal heat available |
| ISRU Plants | 8,000-37,000 | 400 | ? | • Design dependent: a mix of nuclear reactors and/or solar electric and solar electric/solar thermal/RFC |
| HLS | NA | NA | NA | • Power sources selected for in-space operation & <30-day surface stay in sunlight only & independent operation<br>• Power level/designs contractor dependent |

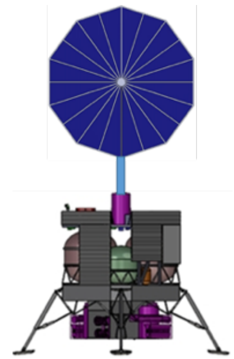
*J. Fincannon, Lunar Surface Power Architecture, 5/4/2020

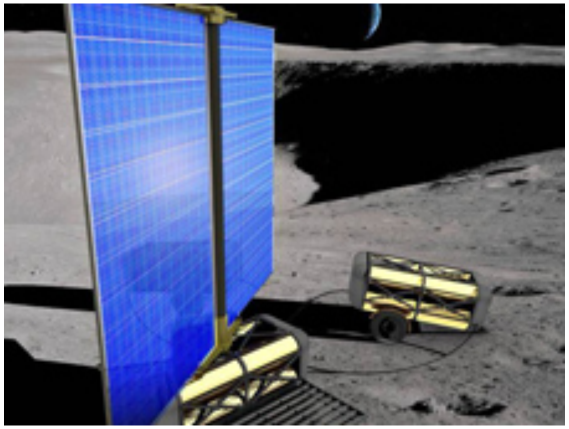
# Power Generation

## Solar Power (Arrays)

- Lunar south pole has peaks of eternal light (85%+ of the time)
- Sun is low on the horizon
    - To maximize power arrays need to be tilted
    - Requires additional arrays to cover the horizon or be movable
- Still need power during eclipse (<15% of the time)

*Surface Solar Array Concept*





## Primary Fuel Cell

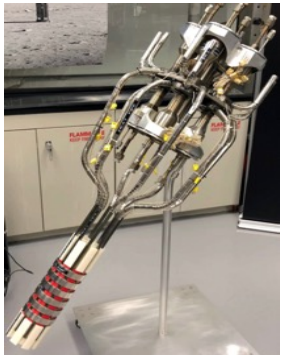
- Produce constant power regardless of conditions (sunlight)
- Heat & water byproducts
- No flight hardware
- Lower TRL

*Recent ground demo of a new PEM fuel cell for space*

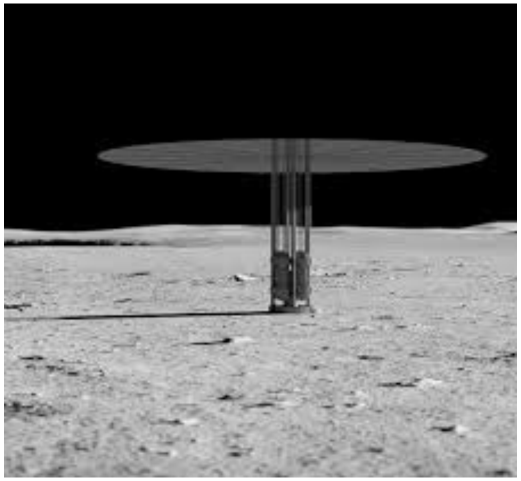
# Power Generation

## Nuclear Fission

- Produce constant power regardless of conditions (sunlight)
- Protective shielding is very heavy
  - Alternatively nuclear sources can be placed a safe distance from Lunar operations (1+ km)
- Current design produces low frequency (~60 Hz) AC power
  - Traditional space power is DC
- Technology is still at a lower TRL

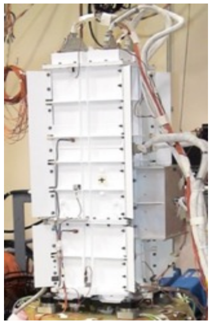


*1kW Nuclear Fission Power 2018 Ground Demo*



## Radioisotope

- Produce constant power regardless of conditions (sunlight)
  - Low power 0.1 to 1.0 kW
- Low radiation
- Higher TRL (already in  use in many applications)
- Fuel availability is limited



*125W Multi-mission RTG (MMRTG)*

# Energy Storage

**Batteries**

- Energy stored in electrochemical cells
- High maturity, low cost, high reliability and efficient
- Low energy density and intolerant to extreme temperatures

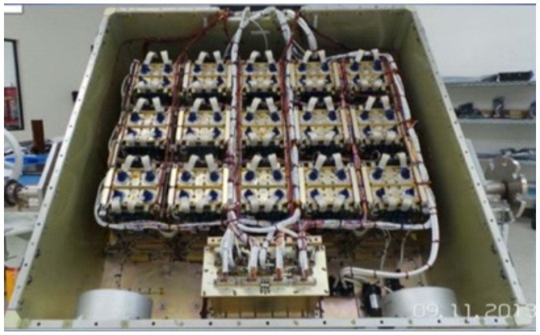
**Regenerative Fuel Cells**

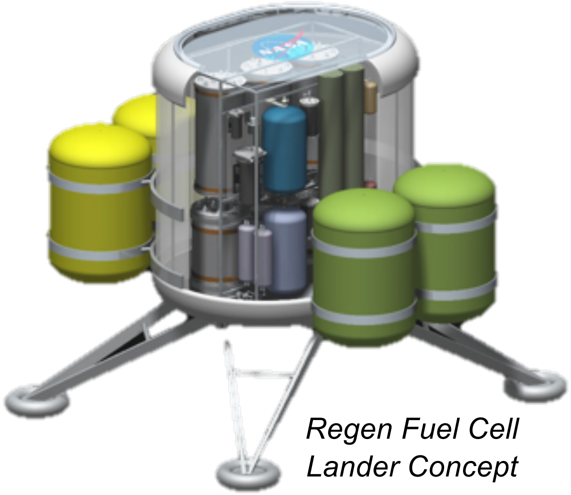
- Insolation (charge): Electrolyzer splits water into H2 and O2
- Eclipse (discharge): Create electricity + water + heat
- High energy density
- Complex and lower TRL

**Advanced Concepts**

- Flywheel: mechanical energy storage
- Superconducting Magnetic Energy Storage (SMES)

*New Lithium Ion Batteries for ISS*



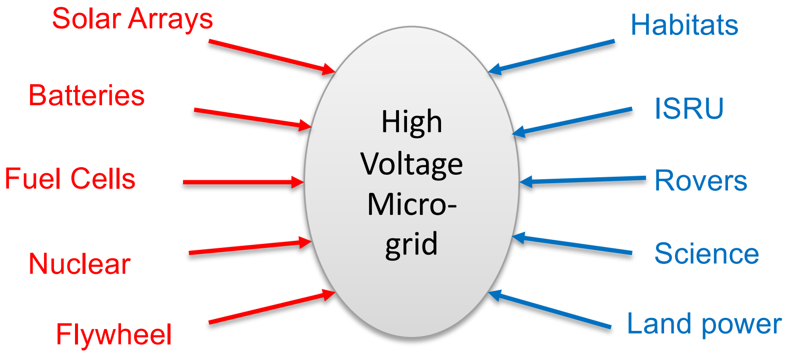


*Regen Fuel Cell Lander Concept*

# Lunar Micro-grid

**Lunar Micro-grid**

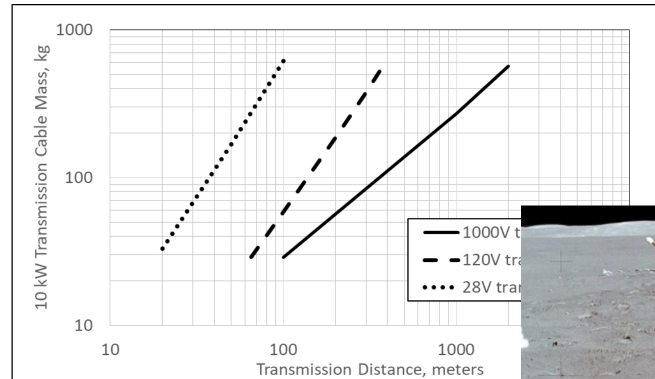
- Ability to integrate dissimilar power sources
  - Allows for sharing power between sources (generation/storage)
  - Increase overall reliability and availability of power
- Adds redundancy (distribution / generation)
- Evolvable / scalable / reconfigurable
  - Allows for evolution from a point to point – on power source per load to integrated system of multiple power sources serving multiple loads
  - Allows for consumers to grow and change over time.
- Micro-grid challenges
  - Standard interface for both power producers and consumers
  - System stability / power quality
  - Design parameters (voltage, etc) to maximize efficiency
  - Accommodates long term unattended operation

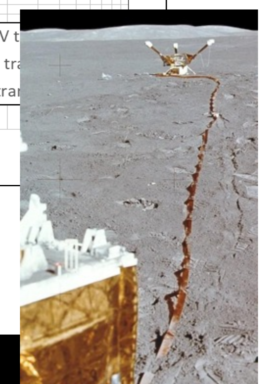


# High Voltage Power Transmission

### Wired Power Transmission

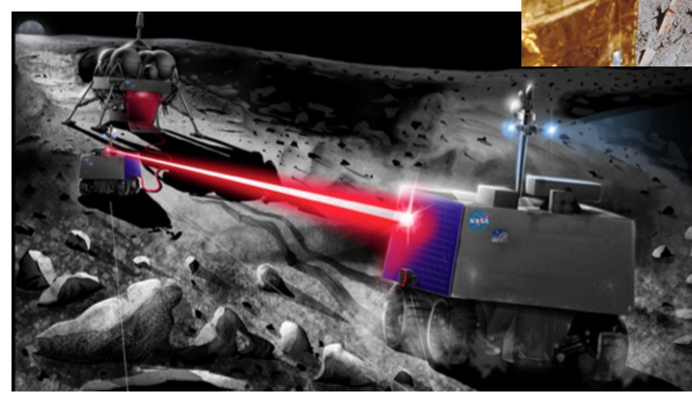
- High efficiency
- Inductive power coupling could mitigate robotic connector & dust issues
- Not limited by line-of-sight (allows for reactor to be hidden by ridge)
- Requires robotic deployment of cable and connectors
- Standard connectors will need to be dust tolerant
- High voltage transmission for space applications is low TRL



### Wireless Power Transmission

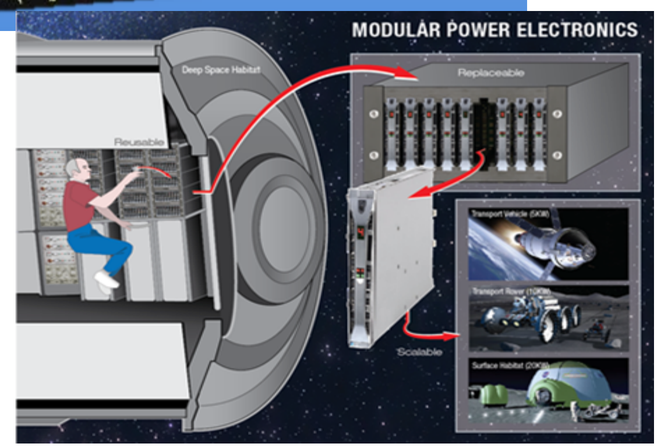
- Convert source electricity to laser or microwave energy & transmit wirelessly (beam)
- No need for robotic deployment of cables and connectors
- Effective distance is line-of-sight with no degradation in power
  - Allows for exploration/operations in difficult terrain
- Requires active tracking for acceptable performance
- Low end-to-end efficiency (~25%) results in increase power source
- Components and systems are low maturity



## Universal Modular Interface Converter (UMIC)

### UMIC

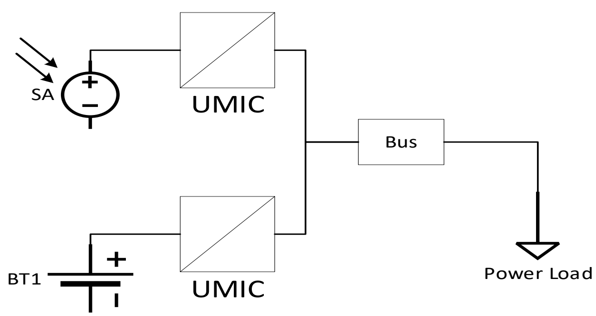
- Standardize interface to connect stationary power sources – Solar Arrays / Fission to mission loads through the micro-grid
    - Power Source to micro-grid
    - Micro-grid to loads
- Modular Converter to service loads and sources at different power levels
    - Source Voltage to Micro-grid voltage
    - Micro-grid voltage to Load voltage
    - Be power scalable based on the size of the source / load
    - Minimized spare mass (hardware can be scavenged & re-purposed)
- Must incorporate a connector that:
    - Can survive the harsh lunar environment (cold, dust)
    - EVA/EVR capable



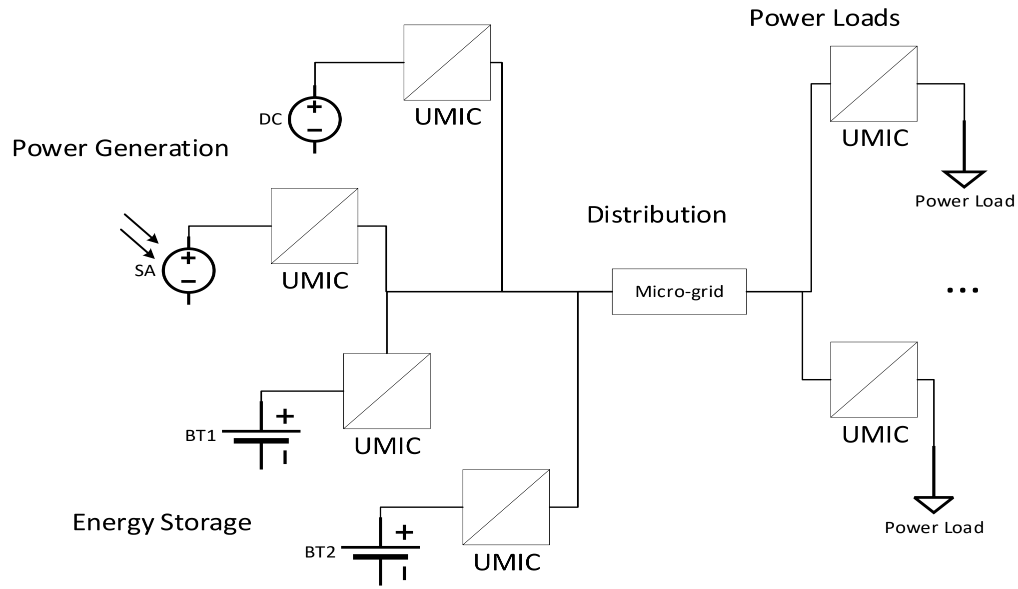
# Evolvable Lunar Surface Power System

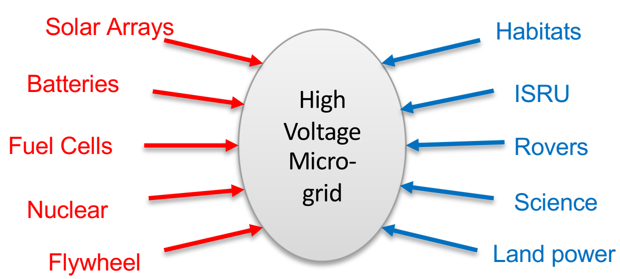
**Leverage early science mission payloads to increase the power generation / energy storage capability of the Lunar Surface power system**

Single Load Example




Lunar Surface Micro-grid Example



# STMD Collaboration Opportunities

https://www.nasa.gov/directorates/spacetech/solicitations

**Open Solicitations**

- NASA Space Technology Graduate Research Opportunities - Fall 2021 (NSTGRO21) (Nov 2, 2020)
- Lunar Vertical Solar Array Technology (Nov 16, 2020)

**Recently Closed Solicitations**

- Lunar Surface Technology Research (LuSTR) Opportunities

**Upcoming Solicitations**

- Nuclear Thermal Propulsion Industry Solicitation (DOE) – September/October 2020
- Fission Surface Power System Design Solicitation (DOE) – October 2020
- 2021 SBIR/STTR Phase I solicitation – November 2020
- 2021 Early Career Faculty solicitation – February 2021
- 2021 Early Stage Innovations solicitation – April 2021
- 2022 NASA Innovative Advanced Concepts Phase I solicitation – June 2021

# Summary

**NASA has an increasing focus on returning to the Moon to test and demonstrate technology for Mars**

- Major step towards getting humans on Mars (Moon2Mars)

**Sustainable power for the Lunar surface has some very unique challenges.**

- Ability for the lunar surface power system to grow and evolve over time.
- Ability to survive the lunar environment

**Key features of the Lunar surface power system will include:**

- Dissimilar power sources to deliver the required power
- Growth from a point-to-point system to a Lunar power utility
- Robotically deployable, modular, and reconfigurable power systems
- A highly distributive design that spans large distances
    - Allow for Lunar activities to occur where needed:

**To deliver will require an investment in power related technologies**

- Autonomous control, robotics, and Autonomous power management
- Modular power systems
- Power source devices, such as Nuclear Fission and Fuel Cell


Thank you!!
Any Questions?

# Power Electronics (PMAD)

**Modular (AMPS / MUSTANG)**

- Small suite of common component replaceable power system building blocks
- Reduced time development time and cost
- Minimized spare mass (hardware can be scavenged & re-purposed)
- Higher initial mass/volume
- Medium TRL
- Standards & industry adoption is ongoing

**Custom / Dedicated**

- Current standard for space components
- Lowest initial mass
- Highest performance & maturity
- Higher development cost
- Higher total system mass for crewed missions