Microgrid for Sustainable Lunar Surface Power

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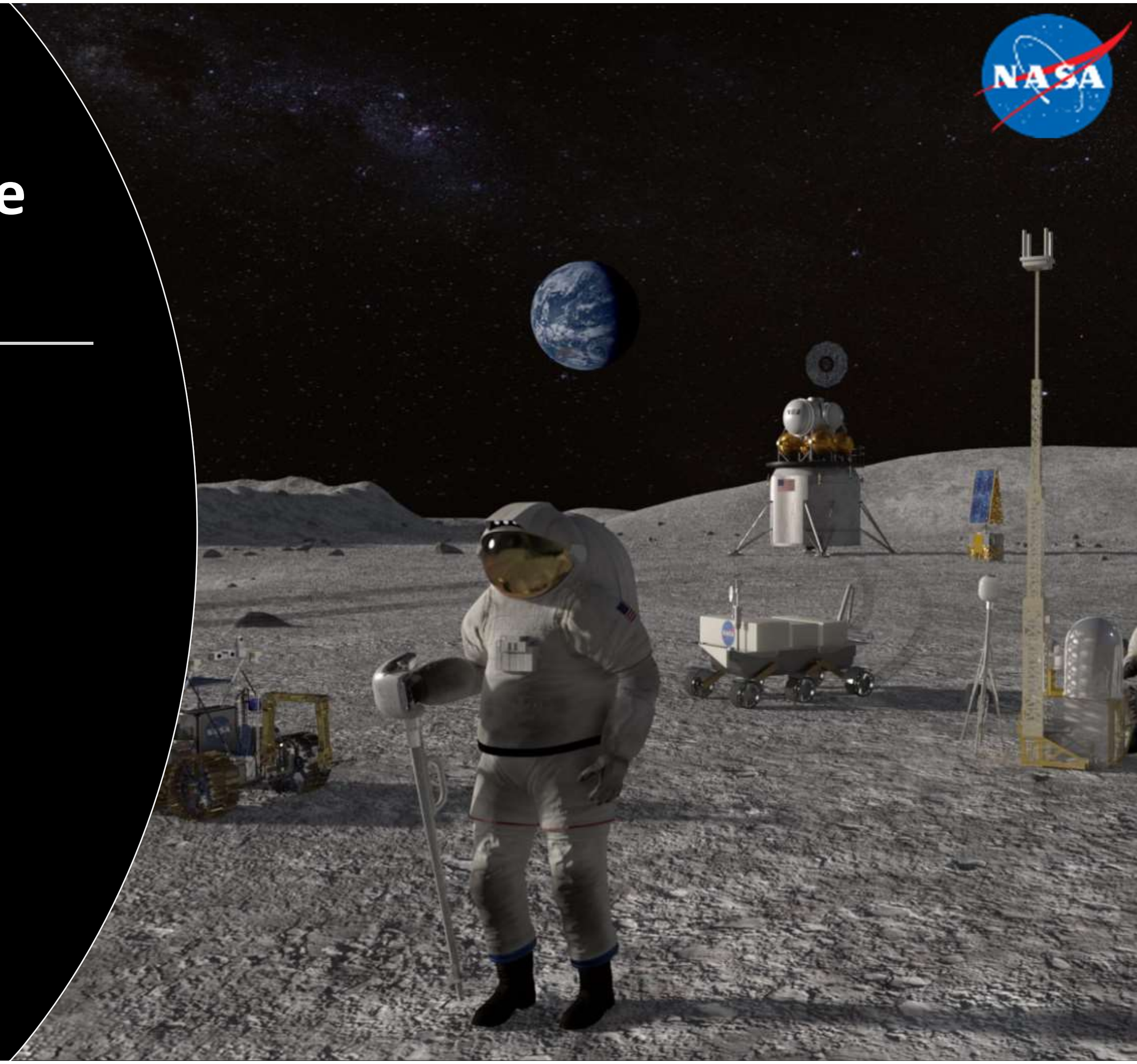
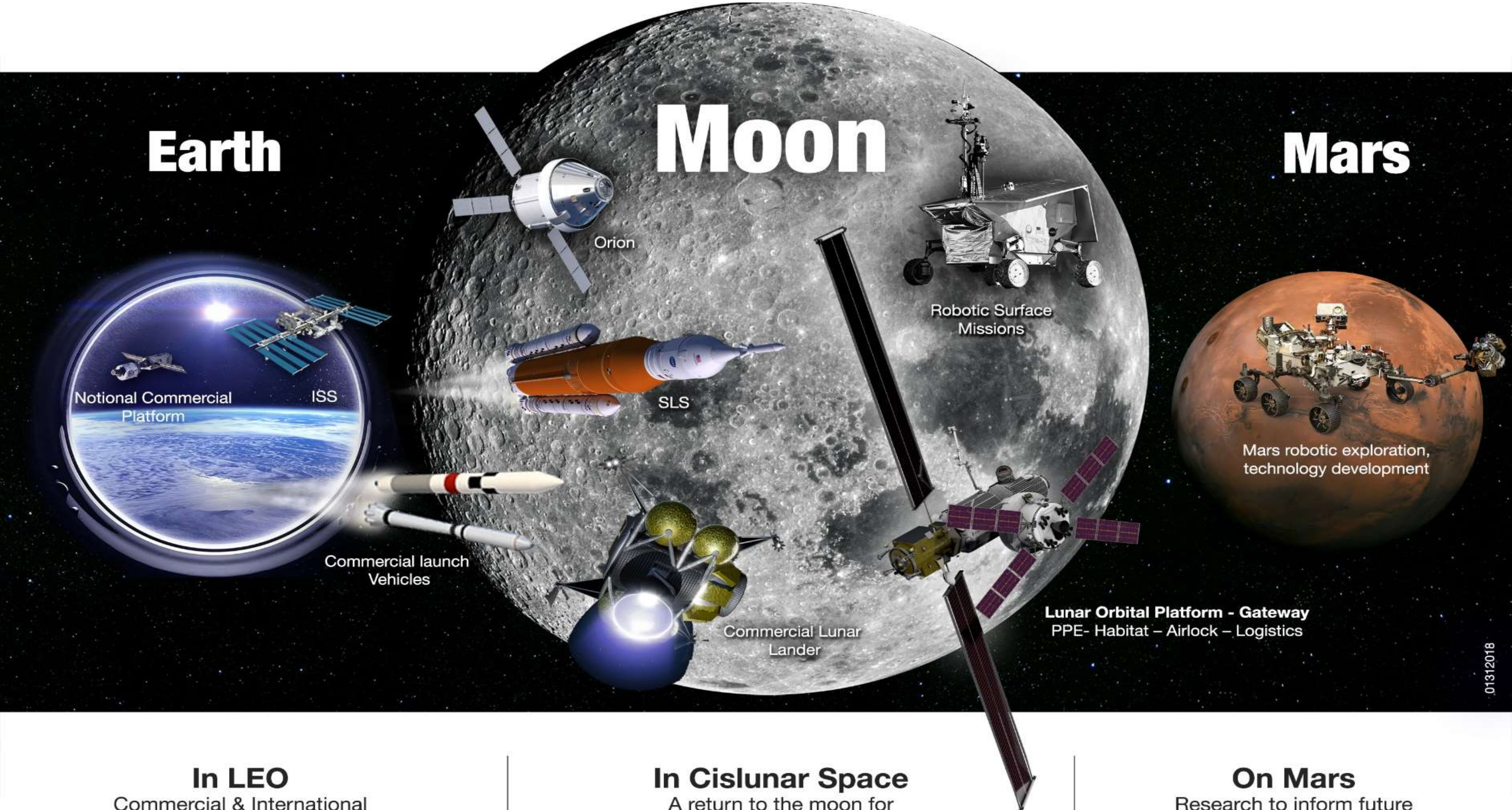




In LEO
Commercial & International partnerships

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

On Mars
Research to inform future crewed missions

The Moon

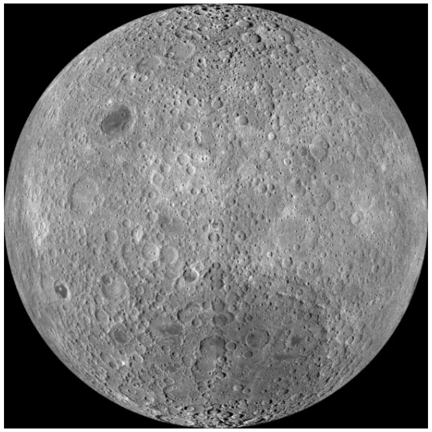
Size:

- 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

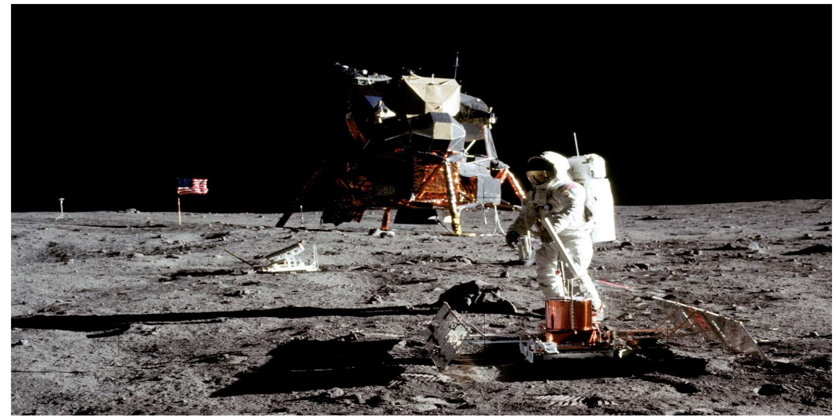
- 27 days
- Earth and moon are tidally-locked
  - Earth will only see one side of the moon
  - Inclination to the Ecliptic is 5.1 degrees
  - Despite what Pink Floyd says – the Far Side of moon gets as much sunlight as the Near Side – There is no “dark side of the moon”

Near Side



Far Side

Lunar Exploration

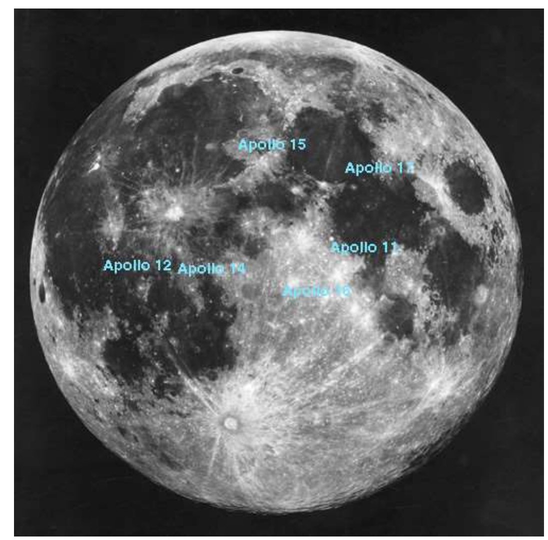


Previous Lunar Exploration

- Mainly scientific
  - More than 105 robotic spacecraft missions
  - Only celestial body beyond Earth visited by Humans
    - 12 Apollo Astronauts have walked on the moon
    - About 10 days on surface (80 hours outside of lander).

Future Human Lunar Missions

- Focused on testing and demonstrating technologies for sustained presence (Lunar and Mars)
  - 30+ day missions on the surface
- Polar Regions have limited temperature swings and more continuous sunlight
  - Eclipse times of 65 to 122 hours requires less energy storage than equatorial regions
  - 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

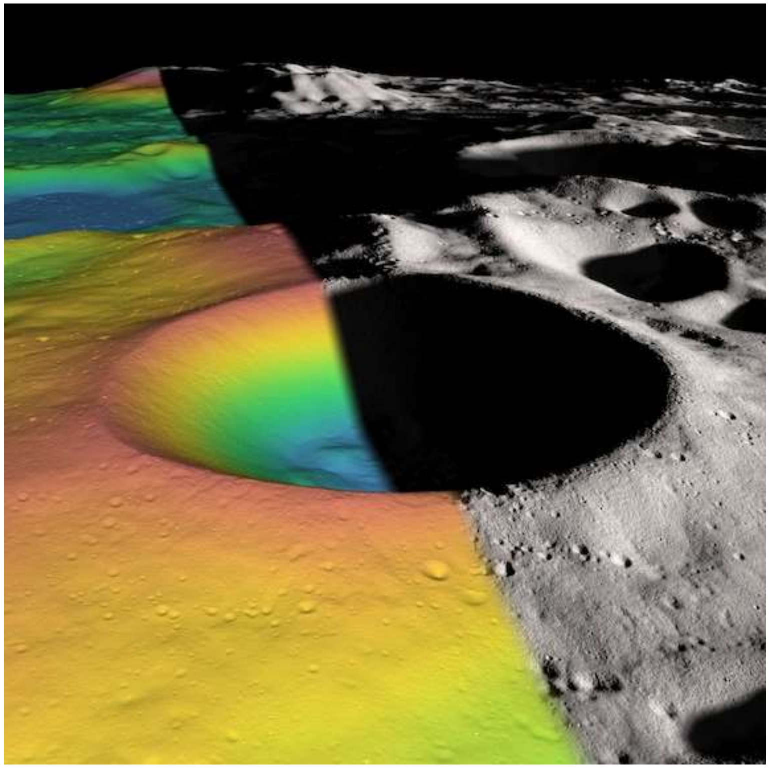
Size:

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

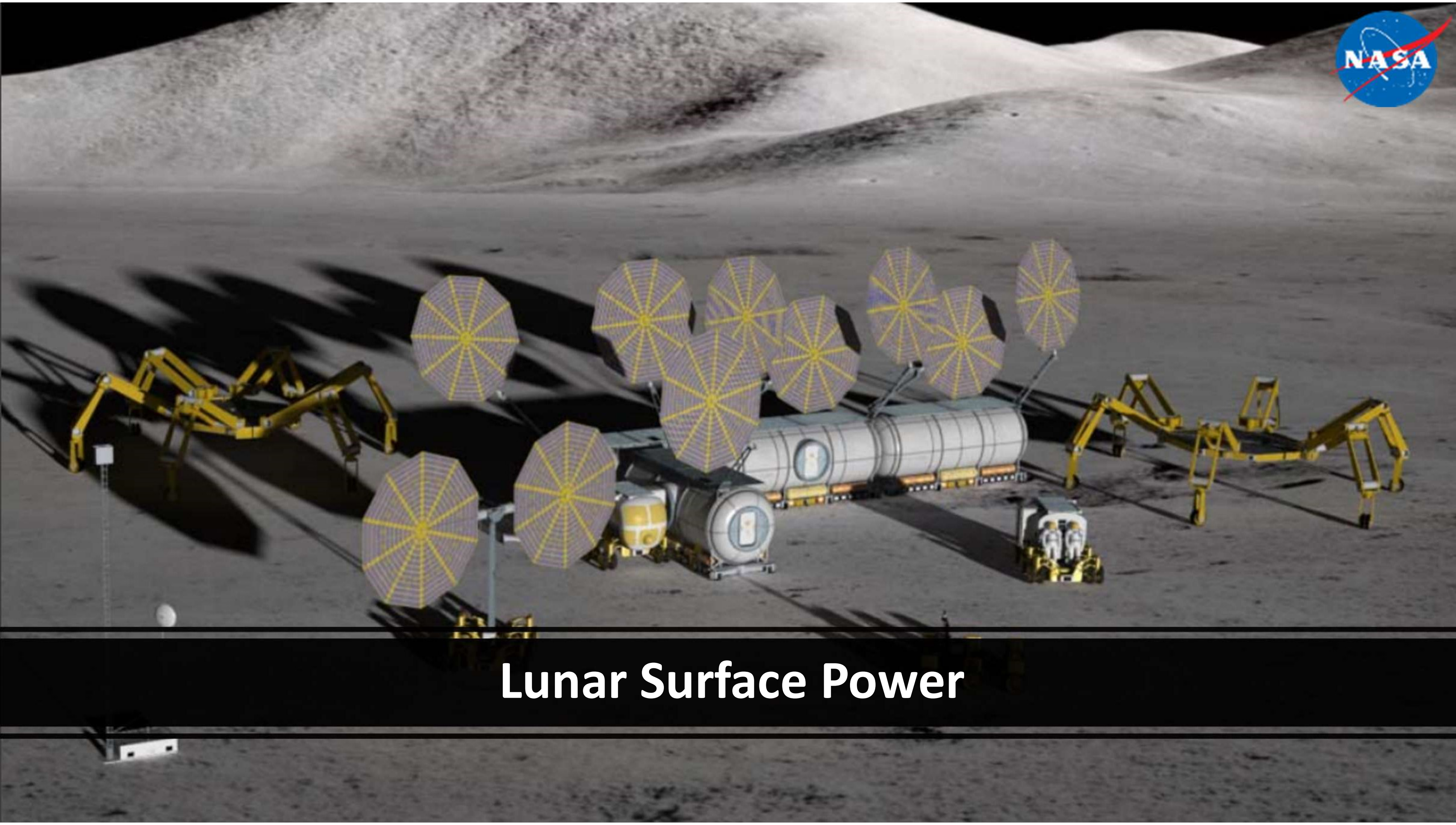
Rims are in almost continuous sunlight

Interior is perpetually in shadow (eternal darkness)

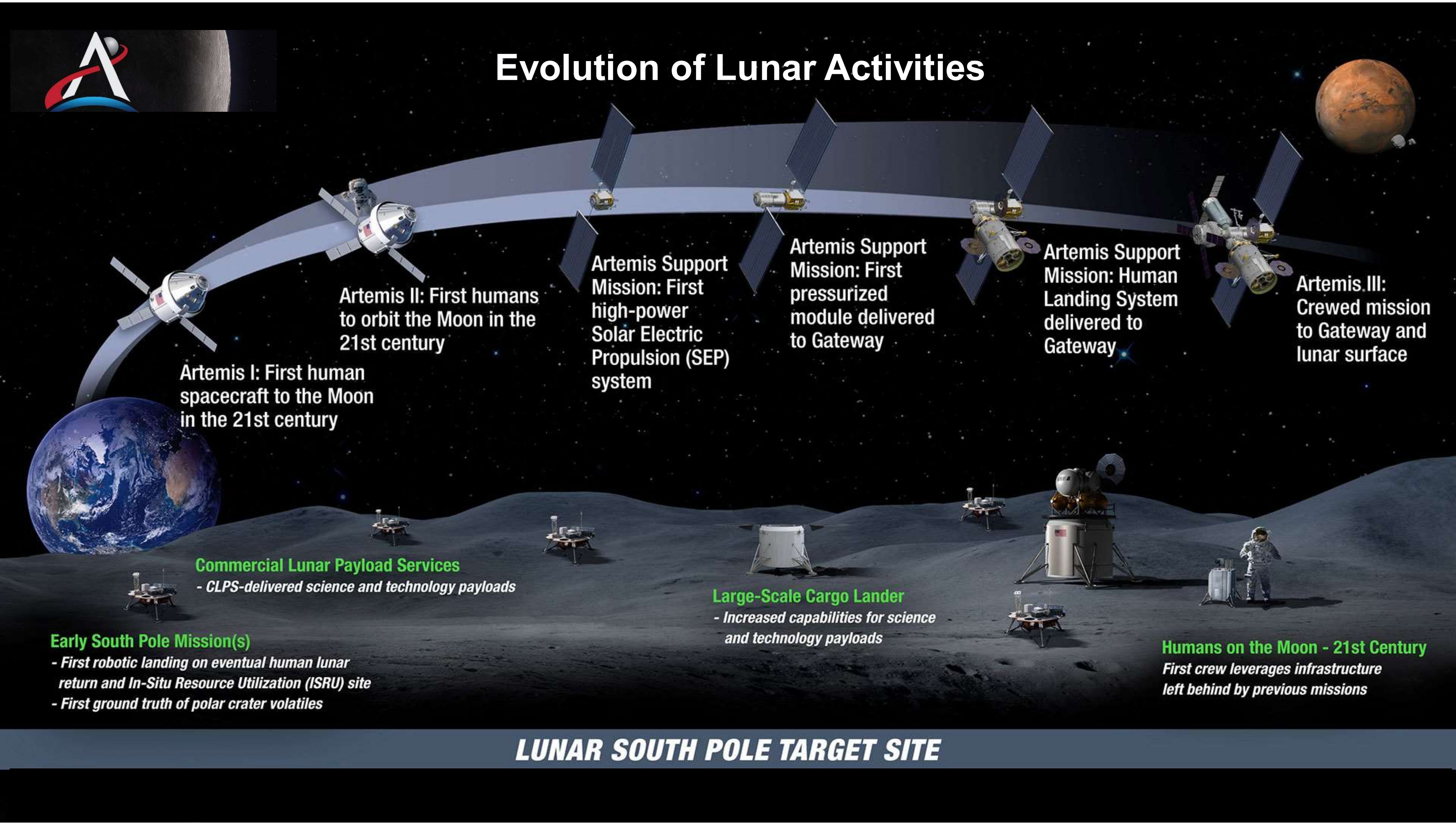
- Average temperature -183 C (90 K)
- Temperature never exceeds -173 ºC (100K / -280 ºF)
- Any water vapor that arrived at the lunar surface from comets or meteorites would have been trapped



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



Lunar Surface Power



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

Sustainable Presence Lunar Surface Activities

Manufacture propellant

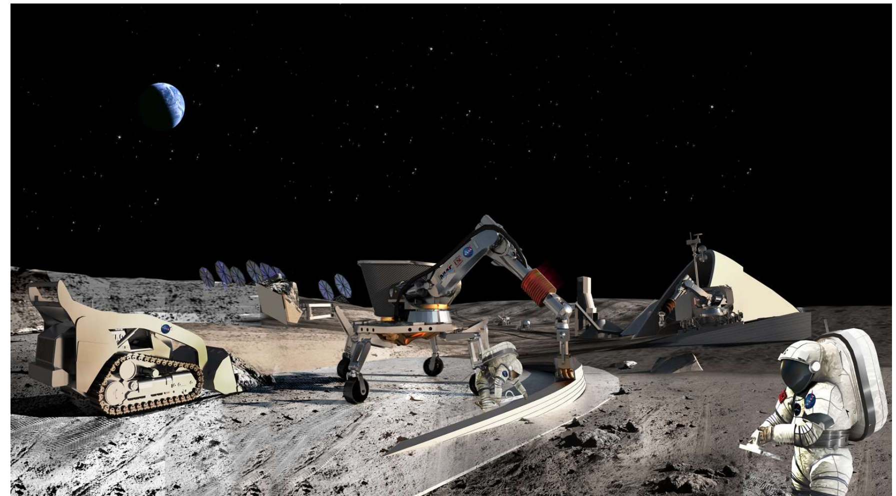
- Fuel landers for round trips between the Lunar surface and Gateway
  - Mining/excavation regolith
  - In-Situ Resource Utilization (ISRU)

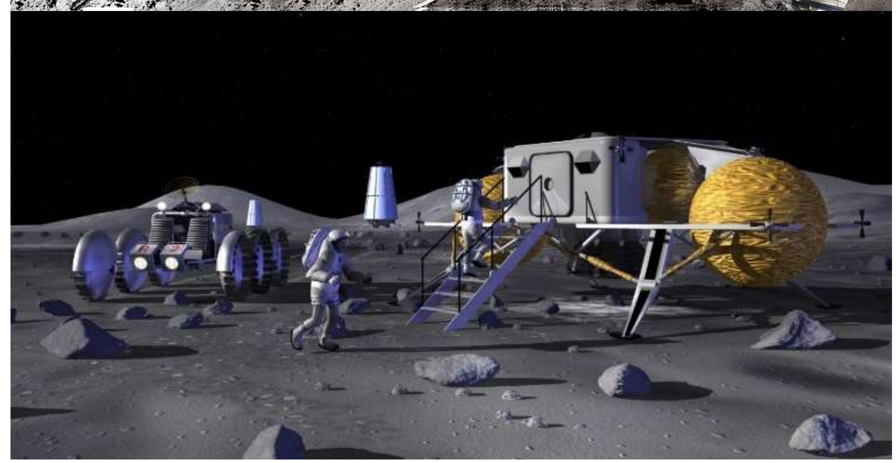
Support a crew / crew operations

- 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 (Earth's Grid)





Lunar Surface Sustainable Power Challenges

Power Demand

- Lunar surface power needs/uses will grow and evolve over time.
- Power strategy (generation / energy storage) will need to evolve over time.
- Accommodate distributed power system resources (mix of generation, storage, and loads)
- Provide power availability regardless of time of lunar day.

Power System Operations

- Autonomous operation for extended periods
- Robotically deployable PMAD / power systems

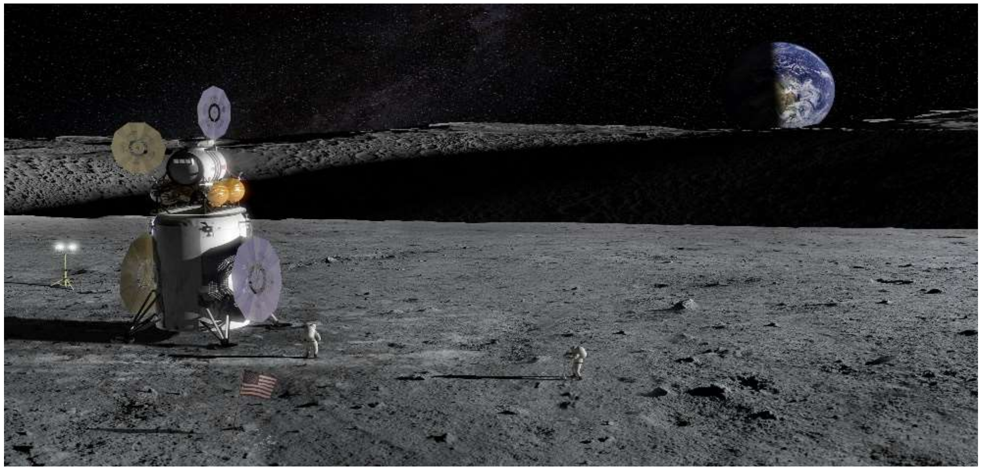
Power Components

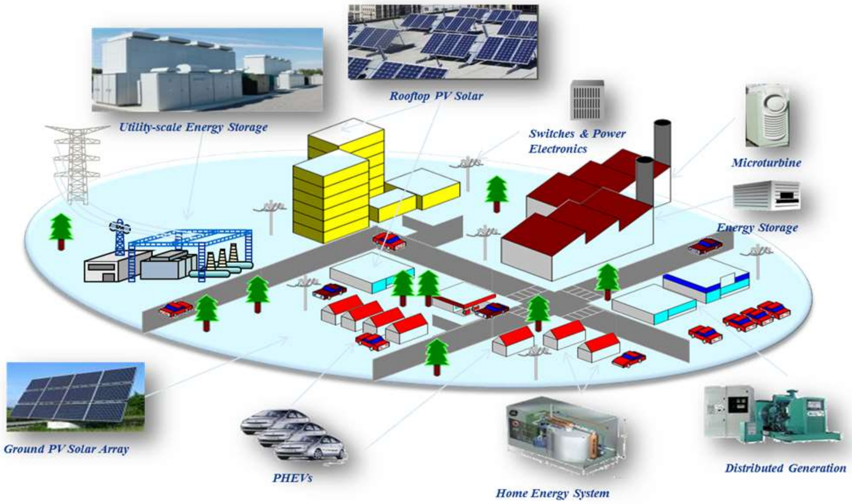
- Mass minimization
- High efficiency generation and transmission
- Ability to survive the lunar environment
  - Cold temperatures / lunar dust / radiation hardening from cosmic rays

Case for a Microgrid

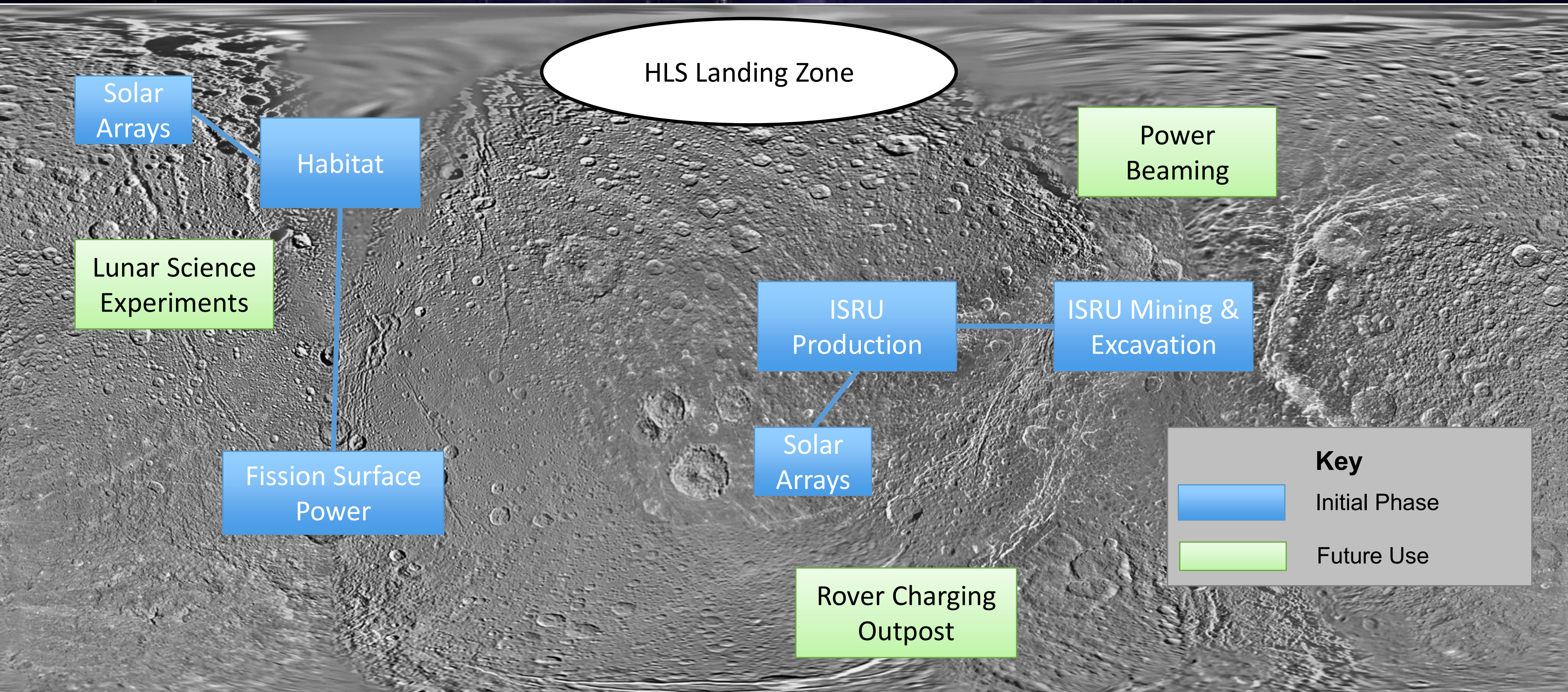
Designing a Lunar microgrid to provide electrical power allows

- Optimal dispatch of power sources / energy storage to service loads
- Addition of dissimilar source and storage methodologies to enhance reliability and availability
- Systematic integration of new sources and loads as the lunar base evolves
- 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



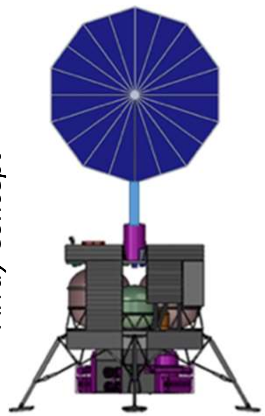


Representative Lunar Surface Operations



Note this is not the actual lunar surface or mapping

Power Generation Technologies



Surface Solar Array Concept

Solar Power (Arrays)

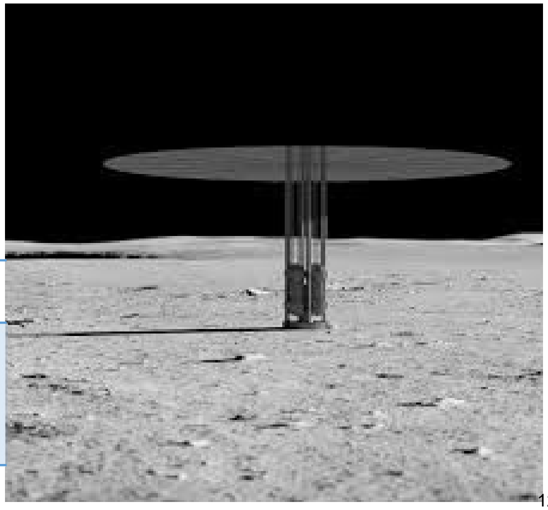
- Lunar south pole has peaks of eternal light (85%+ of the time)
- Sun is low on the horizon
- Still need power during eclipse (<15% of the time)

Primary Fuel Cell

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

Radioisotope

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



Nuclear Fission

- Produce constant power regardless of conditions (sunlight)
- Produces low frequency (~60 Hz) AC power
- Technology is still at a lower TRL

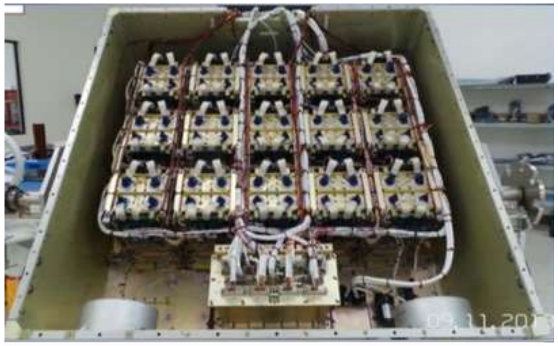
Energy Storage Technologies

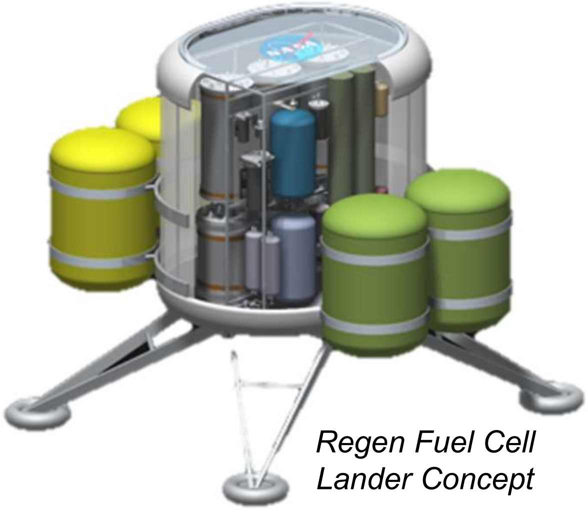
Batteries
• High maturity, low cost, high reliability and efficient • Low energy density and intolerant to extreme temperatures

Regenerative Fuel Cells
• High energy density • Low turn-around efficiency • Complex and lower TRL

Flywheel Energy Storage
• High turn-around efficiency • Accommodates low temperature operation • Energy density TBD for lunar operation • Low TRL Level

New Lithium Ion Batteries for ISS





Regen Fuel Cell Lander Concept

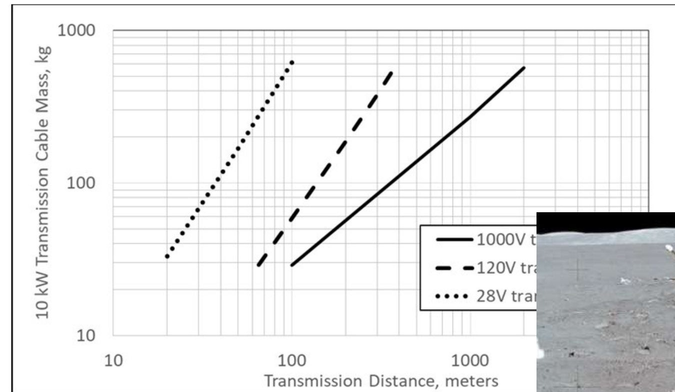
High Voltage Power Transmission

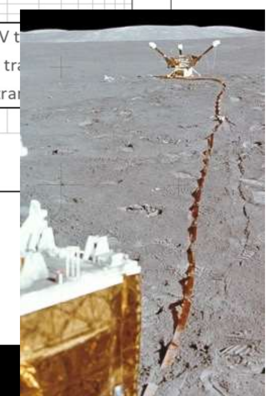
Wired Power Transmission

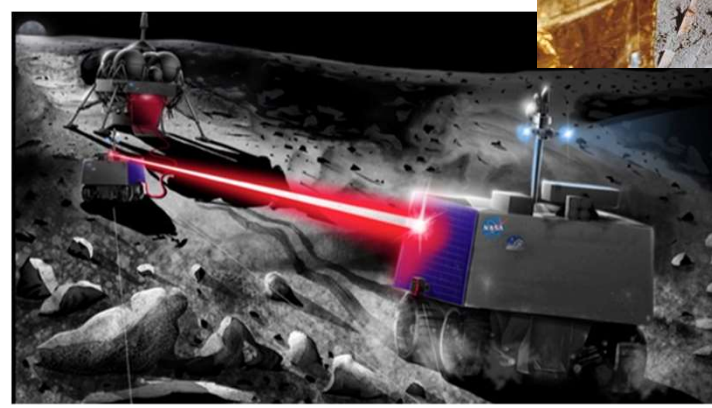
- High efficiency
- Inductive power coupling could mitigate robotic connector & dust issues
- Not limited by line-of-sight (allows for reactor to be hidden by ridge)
- Requires robotic deployment of cable and connectors
- Standard connectors will need to be dust tolerant
- High voltage transmission for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







Power Distribution / Transmission

Traditional Space Power Distribution (120 VDC / 28 VDC)

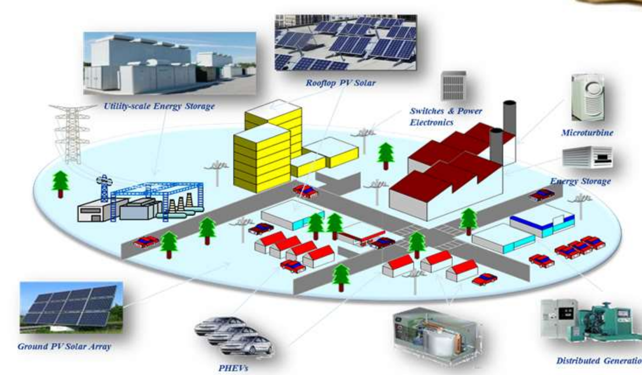
- High TRL & experience in Space Applications
- Mass & loss concerns for long distances (cabling)
- Robotic deployment (cable thickness)

High Power DC

- Lower cable weight with respect to traditional power space power distribution
- Fault control may be challenging
- Low TRL for space applications

AC

- Ease of voltage conversion and fault control
- Resembles terrestrial grid
- AC frequency may have issues with 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



Lunar Surface Power Connectors

Traditional Space Connectors

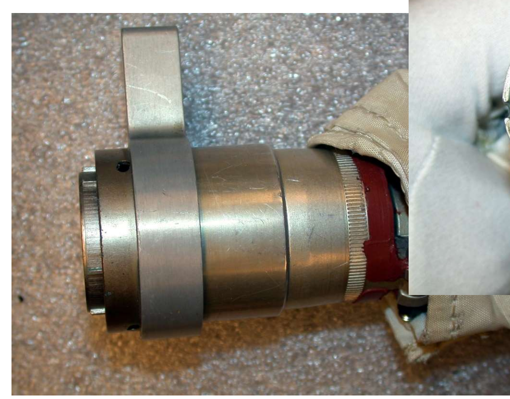
- High power & efficiency
- Lunar dust intolerance
- Mating / De-mating limitations

Dust Tolerant Connectors (in-testing)

- Dust tolerance
- Robotically deployable
- High power & efficiency
- Mass limitations

Inductive Connectors

- Dust tolerant
- Robotically deployable
- Less efficient
- Low maturity, especially for high power applications
- Mass limitations



Summary

Deployment of a Lunar microgrid faces multiple challenges

- Environmental – temperature, dust, radiation
- Need for high efficiency / low mass implementation
- Need for robotic deployment
- Flexibility to evolve over time

Going forward trades need to be made to identify the optimal Grid configuration

- AC Vs DC
- Distribution Voltage
- Connector Strategy
- Grid power interface strategy
- Topology
- Optimal Energy Storage strategy

Utilization of an optimal power microgrid provides best solution for minimizing the amount of delivered mass to moon for power while providing the best service for multitude of users.


Thank you!!
Any Questions?