

Electric Power on the Lunar Surface

National Aeronautics and
Space Administration



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NASA Moon to Mars

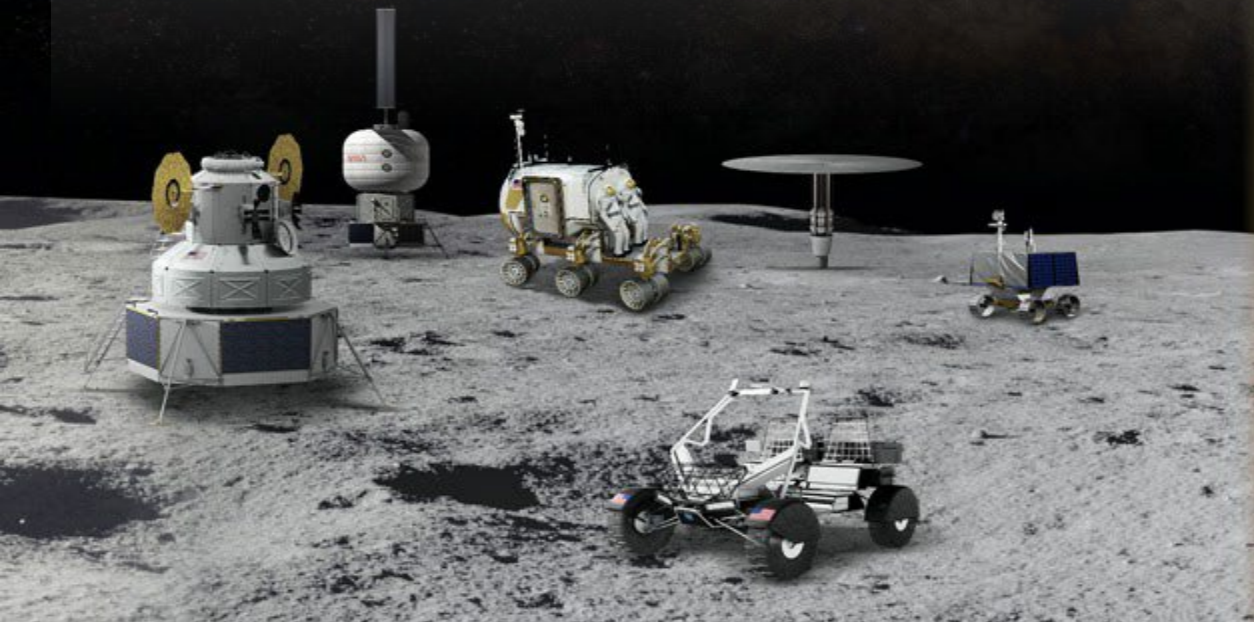
- *NASA will lead an innovative and sustainable program of exploration with commercial and international partners to send humans farther into space and bring back to Earth new knowledge and opportunities*
- **Moon to Mars Objectives (September 2022)**
 - Future long-term vision / Art of the possible
- **Architecture Definition Document (ADD) / Architecture Concept Reviews**
 - Distills agency-developed objectives into operational capabilities and elements that support science and exploration goals.
 - Execution

Moon to Mars (M2M) Objectives - Power



Lunar Infrastructure (LI) Goal: Create an interoperable global lunar utilization infrastructure where U.S. industry and international partners can maintain continuous robotic and human presence on the lunar surface for a robust lunar economy without NASA as the sole user, while accomplishing science objectives and testing for Mars.

- **LI-1L:** Develop an incremental lunar power generation and distribution system that is evolvable to support continuous robotic/human operation and is capable of scaling to global power utilization and industrial power levels.



Mars Infrastructure (MI) Goal: Create essential infrastructure to support initial human Mars exploration campaign.

- **MI-1M:** Develop Mars surface power sufficient for an initial human Mars exploration campaign.



Moon to Mars Architecture Definition Document (ADD)

Moon to Mars Campaign Segments

Human Lunar Return	Initial capabilities, systems, and operations necessary to re-establish human presence and initial utilization (science, etc.) on and around the Moon.	• Self-Sufficiency
Foundational Exploration	Expansion of lunar capabilities, systems, and operations supporting complex orbital and surface missions to conduct utilization (science, etc.) and Mars forward precursor missions.	• Internal Augmentation • External Augmentation • Power Grid
Sustained Lunar Evolution	Enabling capabilities, systems, and operations to support regional and global utilization (science, etc.), economic opportunity, and a steady cadence of human presence on and around the Moon.	• Expanded power for expanded missions
Human to Mars	Initial capabilities, systems, and operations necessary to establish human presence and initial utilization (science, etc.) on Mars and continued exploration.	
Future Segments	<i>Additional segment(s) will be added to enable continued exploration for the Moon, Mars, or beyond as objectives are accomplished and/or added to in the future.</i>	

Power Strategy: Self-Sufficiency



- **Self-Sufficiency Overview**

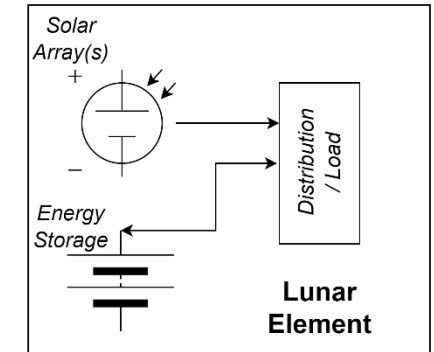
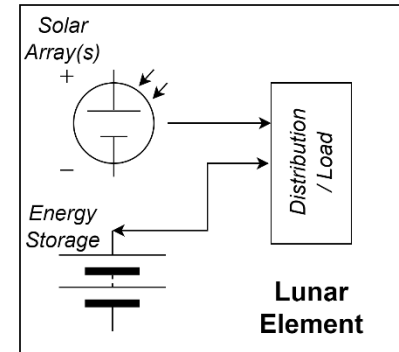
- All power generation / energy storage is self-contained within the lunar element
- Power exchange between lunar elements in certain (contingency) scenarios

- **Moon to Mars Segments**

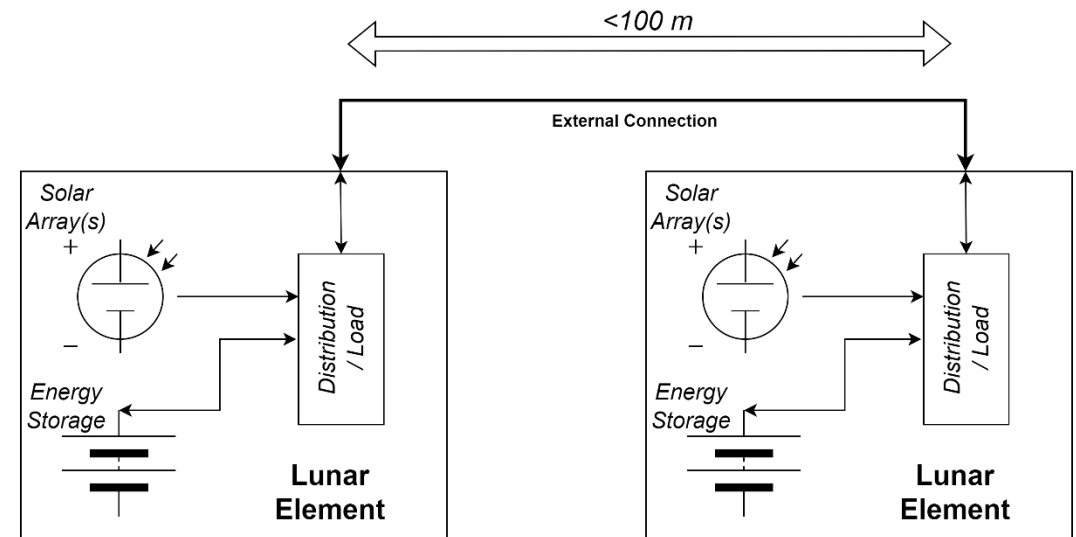
- Human Lunar Return
- Foundational Exploration (Power exchange)

- **Power System Information**

- Power system is designed according to the International Space Power System Interoperability Standard (ISPSIS) - 120/28 VDC power quality standard
- Power exchange must occur at 120 VDC (requirement) and a distance less than 100 m (limitation of 120 VDC).
- Anticipated power demands range from ~100 W to 10 kW+ per element.



Self-Sufficient power system



Self-Sufficient power systems with the capability to exchange (share) power

Power Strategy: Internal Power Augmentation



- **Internal Power Augmentation Overview**

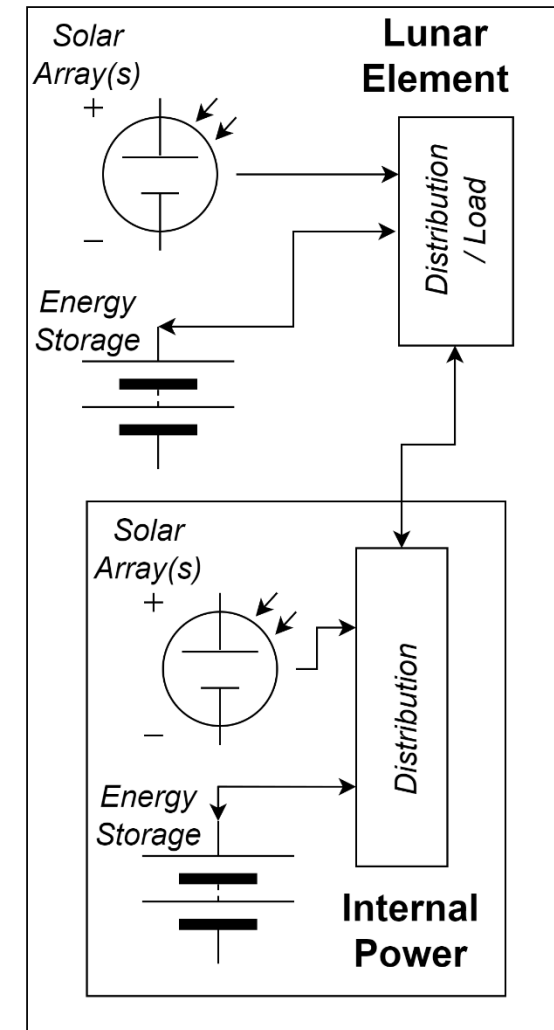
- Original / delivered power system is modified/updated to include additional power sources (generation and/or storage)
- Requires physical installation/modification of lunar element
- Requires Astronaut or robotic assistance

- **Moon to Mars Segments**

- Sustained Lunar Evolution

- **Power System Information**

- Power system is designed according to ISPSIS power quality standard (120/28 VDC)
- Concern and risk associated with modifying the element on the lunar surface.
 - Requires Astronaut/robotic support
 - Lunar dust mitigation

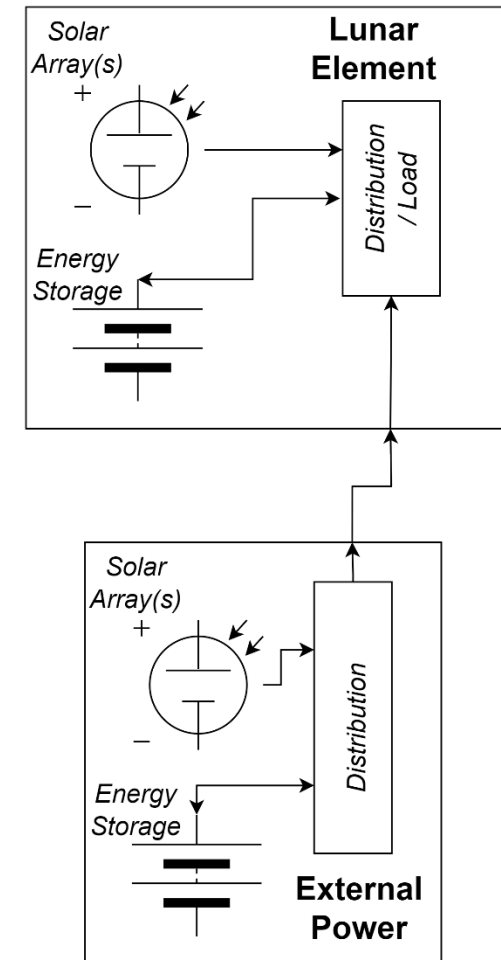


Internal Augmentation power system

Power Strategy: External Power Augmentation



- **External Power Augmentation (EPA) Overview**
 - Dedicated elements are delivered that provide power to extend the survival period
 - Requires mobility to place power source near load(s)
- **Moon to Mars Segments:**
 - Sustained Lunar Evolution
- **Power System Information**
 - Power system is designed according to ISPSIS power quality standard (120/28 VDC)
 - Desired distance between elements less than 100 m (reduce cable mass and complexity)
 - Winter darkness survival is driving factor.
 - Large energy storage is an option to increase winter darkness power availability
 - Longer distance cables maybe required to provide power to multiple assets (*if deemed acceptable*)
 - Helps reduce shadowing during illumination periods
 - Small nuclear generators maybe required to be a distance from other elements/assets

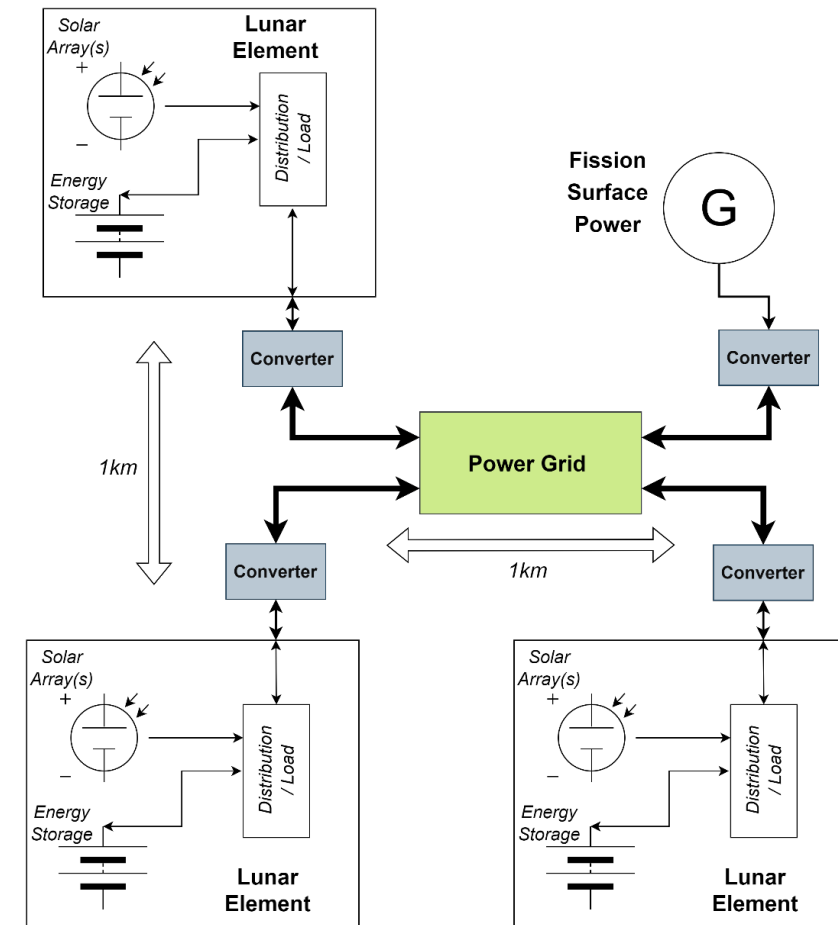


External Power Augmentation is a mobile power source (Element) that can provide power to an existing lunar element

Power Strategy: Regional Power Grid (Site specific)



- **Regional (Site) Power Grid Overview**
 - Make power available over long-distance
 - Provide power during darkness periods
 - Provide power into permanently shadowed regions
- **Moon to Mars Segments:**
 - Sustained Lunar Evolution
- **Power System Information**
 - Distance between elements exceeds 100 m and up to ~10 km (possibly more)
 - Winter darkness survival is driving factor
 - Nuclear power generation (fission surface power) is an option to increase power during winter darkness periods
 - Required to be > 1km from other elements
 - Power grid may increase overall year-round illumination availability



Regional Power Grid where power is transmitted at longer distances

Power Strategy: Lunar Power Grid (Power Utility)



- **Lunar Power Utility Overview**

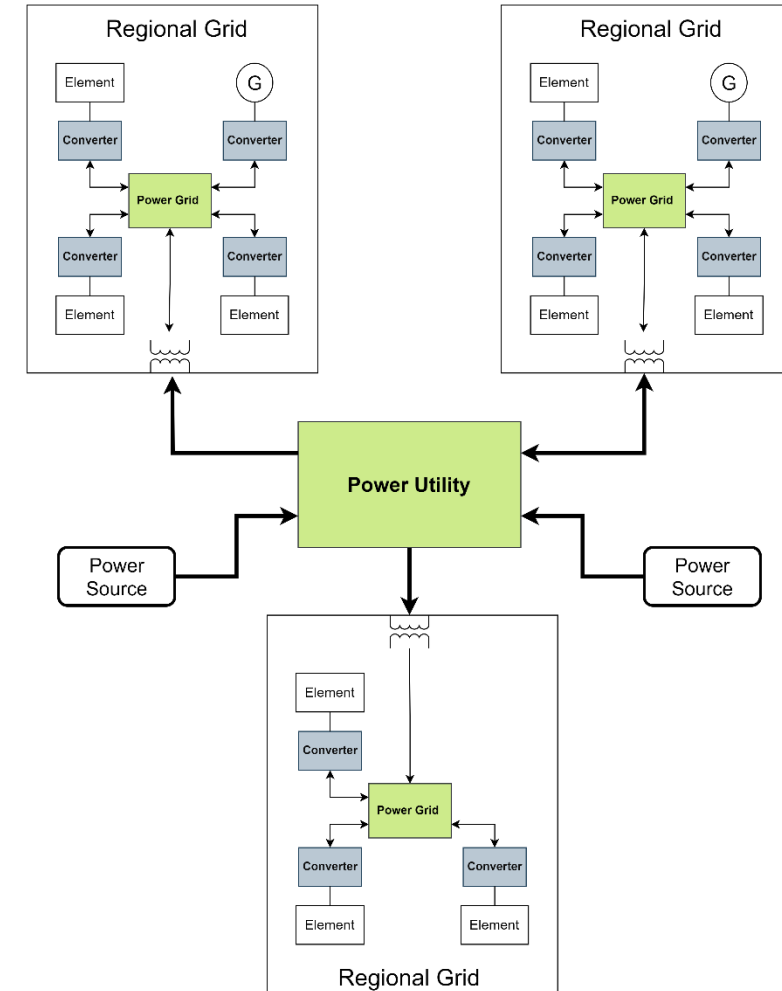
- Power availability beyond a single site / location at the lunar south pole and extend beyond the lunar south pole (towards equatorial region)
- CONOPS to be developed – may include company managing the power grid like the terrestrial power system

- **Moon to Mars Segments:**

- Beyond current Artemis Campaign

- **Power System Information**

- Very long distance between elements (100+ km)
- Maximizing year-round power availability is key driving factor.
- Nuclear power generation (fission surface power) is still an option to increase power during the lunar winter.



Lunar Power Grid (utility) where power can be generated/delivered/used at different locations that extend the lunar south pole

NASA GRC Space Power Projects

Power Generation

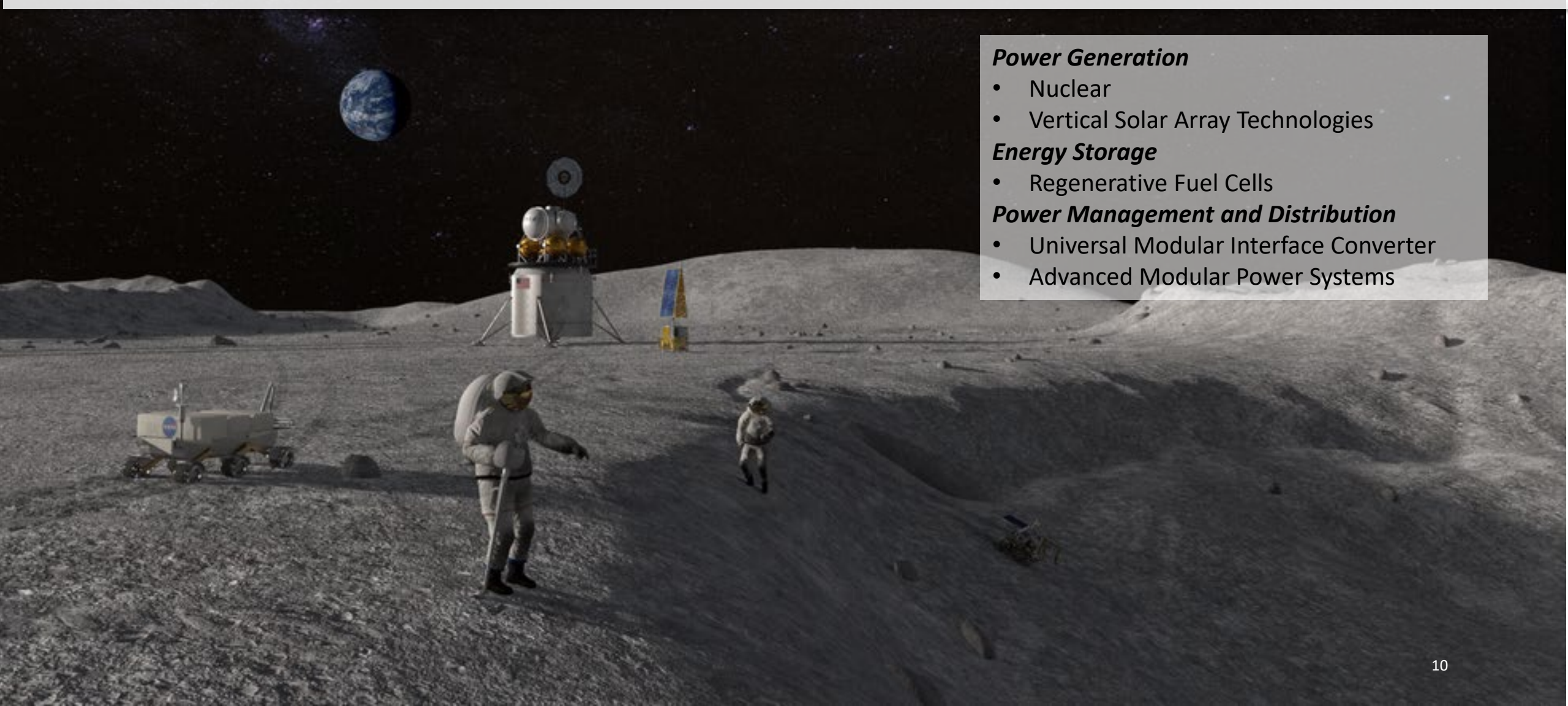
- Nuclear
- Vertical Solar Array Technologies

Energy Storage

- Regenerative Fuel Cells

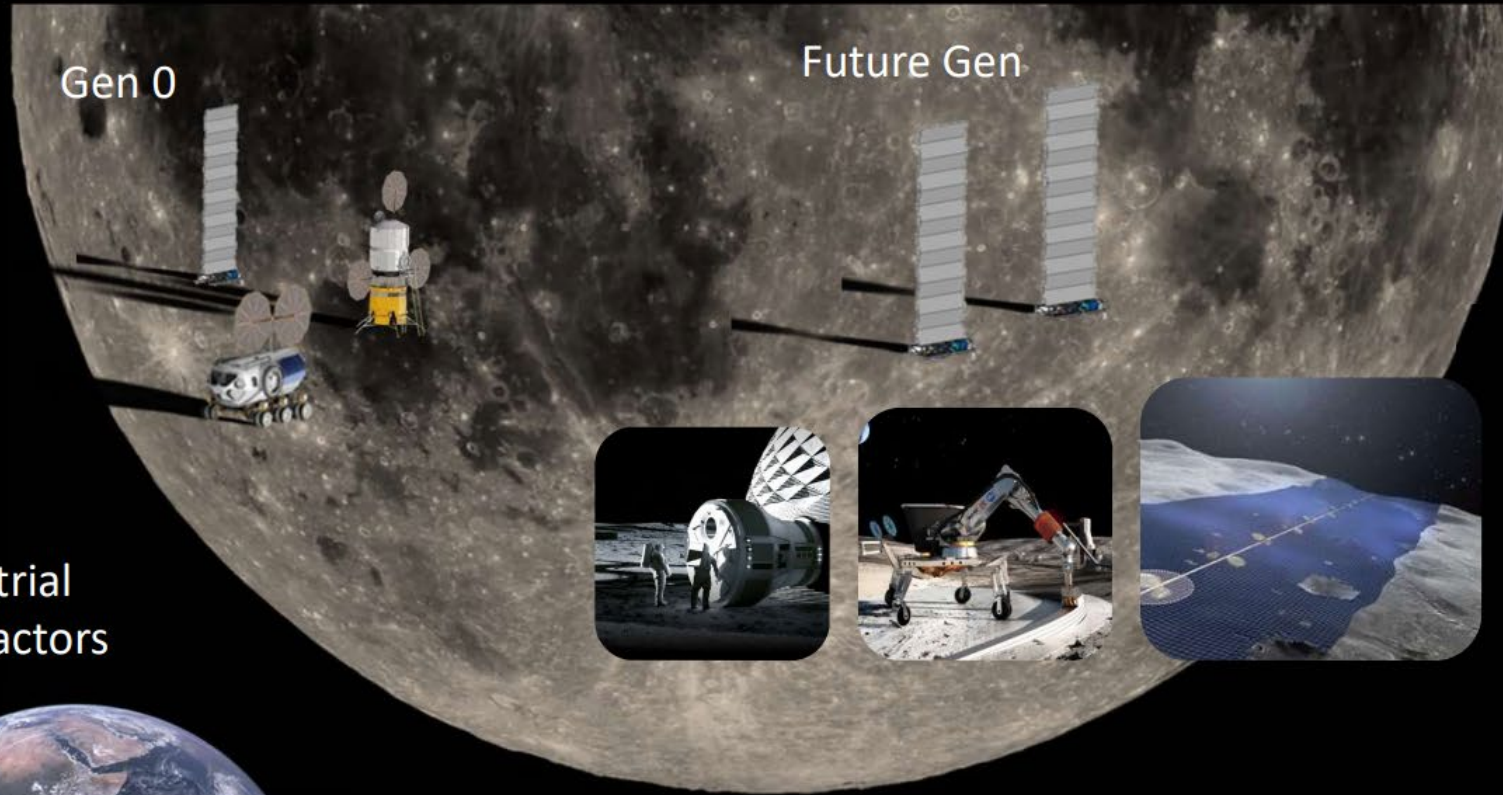
Power Management and Distribution

- Universal Modular Interface Converter
- Advanced Modular Power Systems

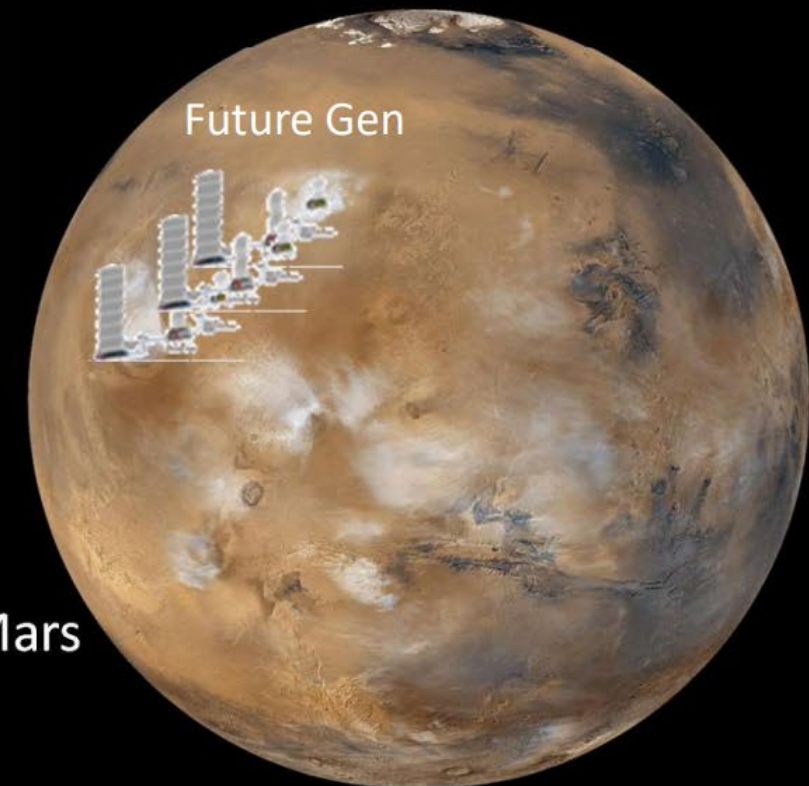


Nuclear Power

The key commodity needed to utilize the Lunar and Martian surface



Terrestrial microreactors



FSP meets/supports STMD civil space shortfalls:

- #1: Survive and operate through the lunar night
- #2: High Power Energy Generation on the Moon/Mars
- #8: NEP for Human Exploration

<https://www.nasa.gov/spacetechnologies/>

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.

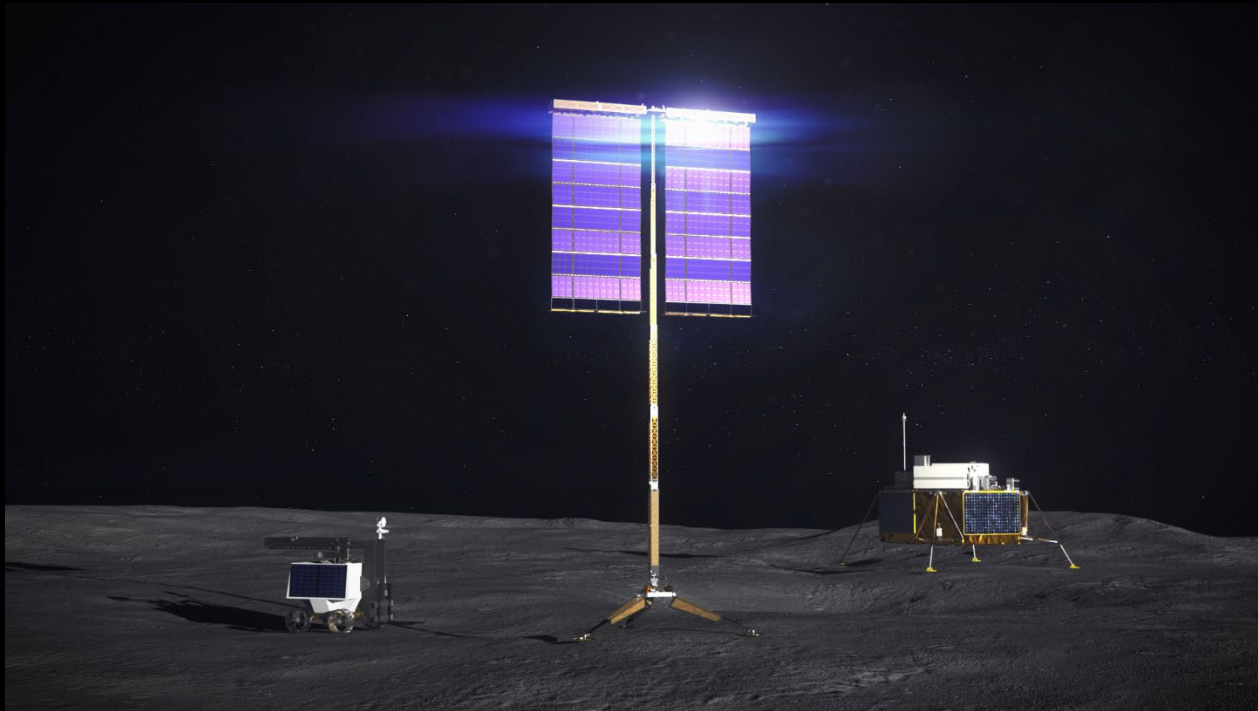
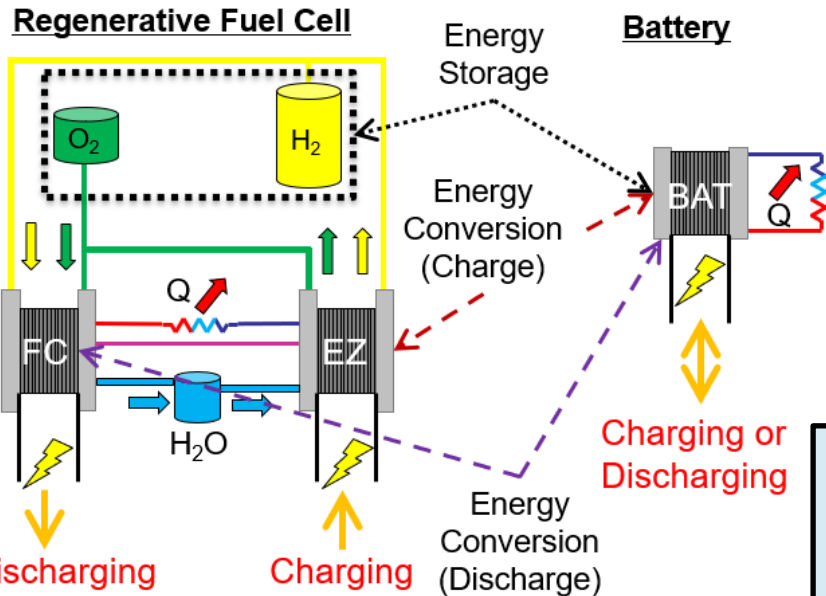
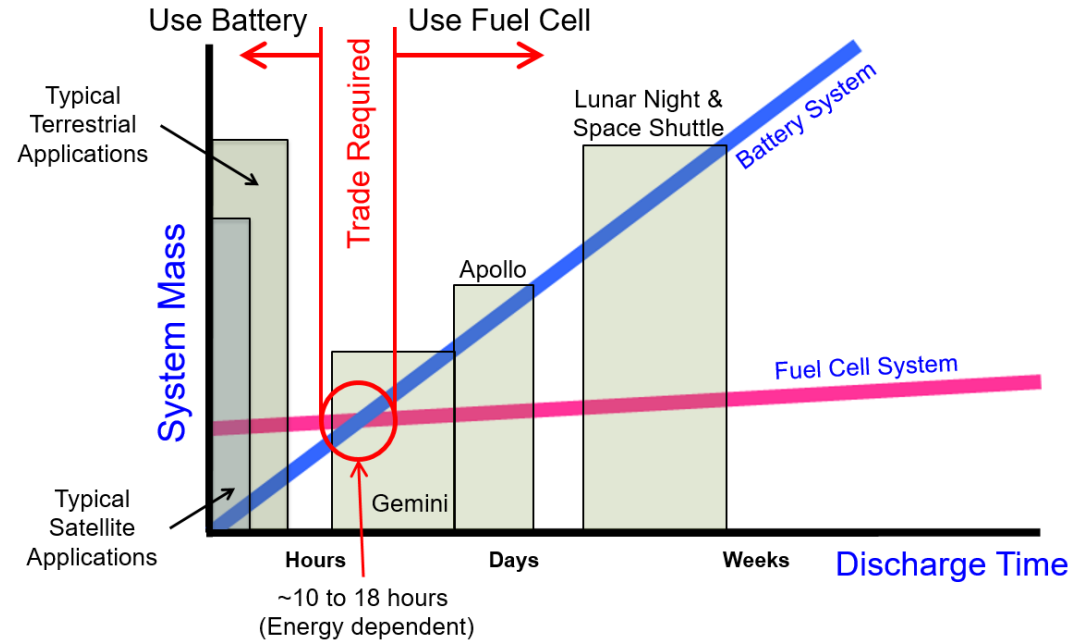


Photo credit: NASA

Regenerative Fuel Cell (RFC) Energy Storage



- **Regenerative Fuel Cells vs Rechargeable Batteries...**
 - Choosing the right solution depends on the application
 - Specific Energy (W·hr/kg)
 - Packaged Li-ion Battery Systems ~160 W·hr/kg
 - RFC Systems range from ~100 to 600 W·hr/kg depending on power level and duration
 - Charge-discharge efficiency
 - Li-ion Batteries ~90%
 - RFC ~50%, results in larger solar array

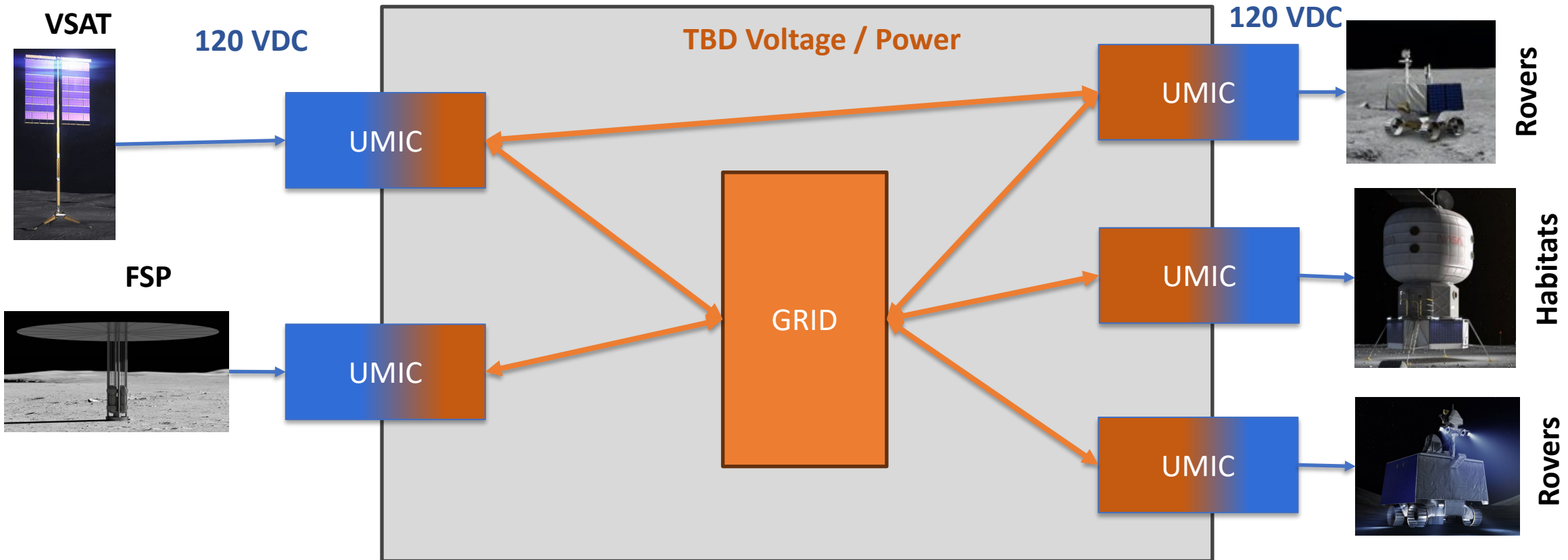


1 kW discharge Power	Discharge Time (h)	System-level Metrics			
		Specific Energy		Mass (kg)	
		Li-Ion	RFC	Li-Ion	RFC
Lunar Polar	120	160	400	750	300
Lunar Equatorial	350	160	550	2200	600
Mars Mid-latitude	13	160	200	80	60

Fuel cells and Batteries Convert and Store Energy differently, thus:

- Different Safety Hazards
- Different Voltage response to State-of-Charge (SoC)
- Different Specific Power and Specific Energy

Universal Modular Interface Converter



- **The UMIC enables long-distance power transmission and a power grid**
 - Connects power sources and loads together over-long distance and allows for a power grid as the system evolves.
 - Source and loads design to current 120 VDC and 28 VDC power standards
 - ISPSIS / HEOMD03-004

Universal Modular Interface Converter



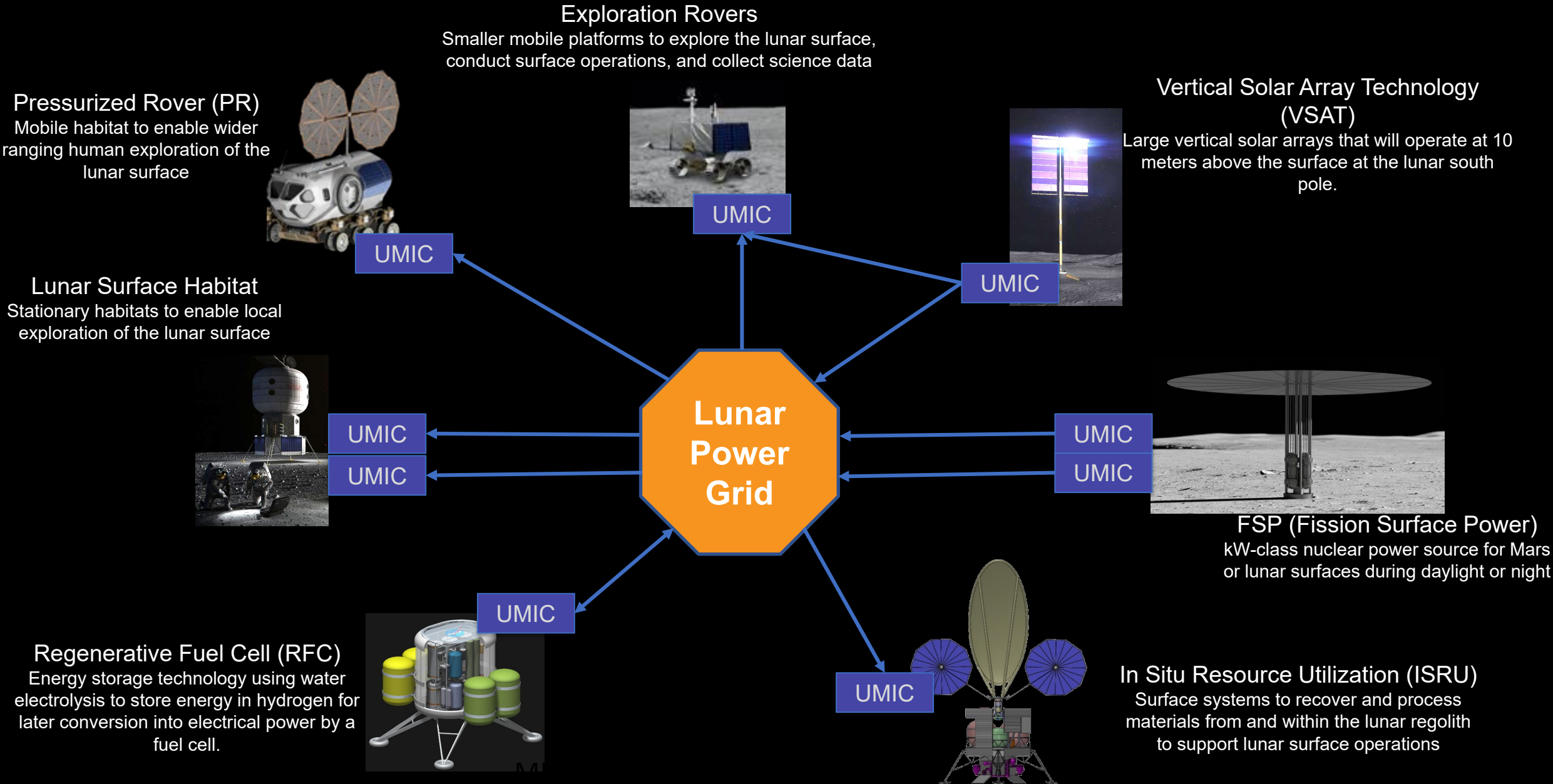
- **Modular, bi-directional converter**
 - Grid side: 3-phase, 3000 VAC, 1000 Hz
 - Load/Source Side: 120 VDC
- **Full rack capable of 10 kW of power (nominal)**
 - 12 kW peak
- **Parallelable - can provide more than 10 kW at single location**
- **Design goals:**
 - >95% efficiency
 - 350 W/kg power density (est. for flight)
- **Capability:**
 - Grid forming
 - Grid syncing



TRL 4 Breadboard Version

Lunar Surface Power

Universal Modular Interface Converter (UMIC)
Enables bi-directional, long-distance power transmission on the lunar surface



Advanced Modular Power Systems (AMPS)



Why is this project important?

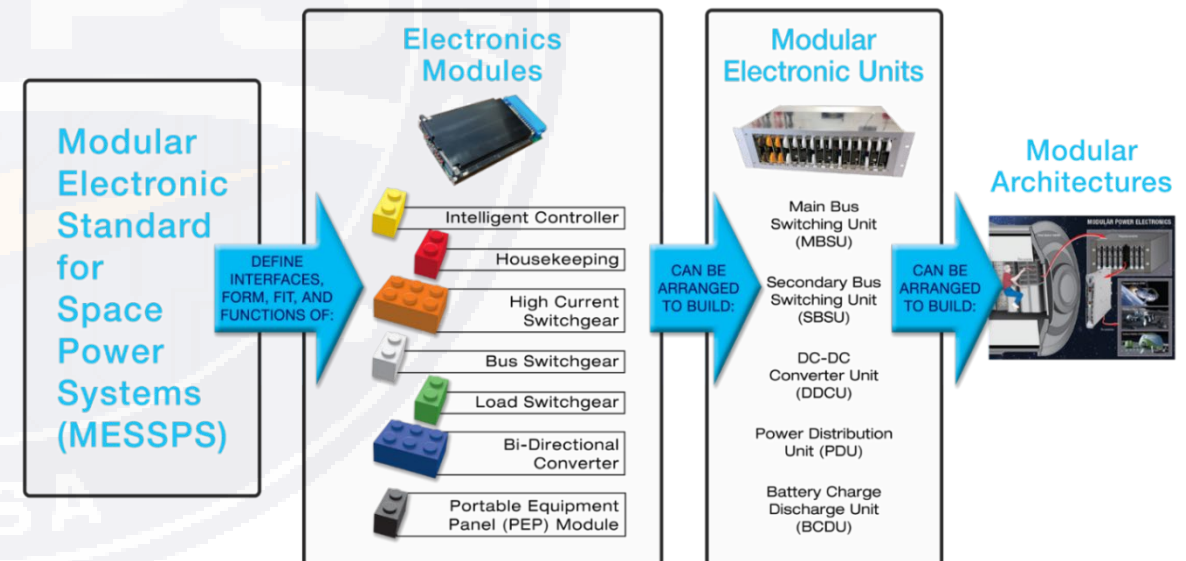
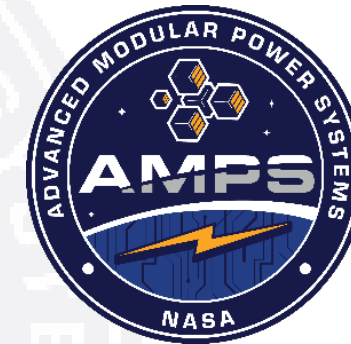
- Modular power systems provide opportunities to minimize maintenance, improve power system availability, and reduce the number of unique spare parts; modularity is an **enabling capability** for sustainable future exploration missions and systems.
- This project matures modular power system technologies, **inclusive of standards**, power electronics, and autonomous power controls, with an emphasis on providing support to future space exploration systems such as the Mars Transit Habitat.

Objectives

- Transform future space power architectures and operations
- Standardize the power system at the electronics module level
- Automate power management, distribution, and control functions

Current Activities

- Assessment for advancing the Technology Readiness Level of the electronic module designs, modular electronic units, and associated standards towards flight and demonstration in a relevant environment.
- Developing and advancing autonomous fault management algorithms to provide crew assistance in resolving unknown / new fault indications:
 - Develop tools to perform fault / anomaly detection and classification
 - Provide recommendations/instructions to vehicle manager and crew to safely handle the scenario.
- Integrating the modular hardware testbed to serve as the common architecture for testing, experimentation, and validation of advanced controls algorithms in support of Earth Independence Operation.



Future of NASA Technology Development / Community Engagement



Prioritizing Space Technology Development – Civil Space Shortfalls



- ***NASA's Space Technology Mission Directorate (STMD) leads the development, demonstration, and infusion of transformational technologies that enhance NASA's efforts to explore the unknown in space, benefit life on Earth, and solve critical stakeholder needs.***
- **STMD's investment strategy informs its portfolio:**
 1. Align with the Administration and the NASA Administrator's priorities that address the Blueprint Objectives (Artemis)
 2. Focus on investments that support science priorities identified in the Decadal Surveys
 3. Foster creation and growth of the space economy through partnering with industry and supporting small business innovation
 4. Engage NASA's workforce to deliver innovative solutions to the nation's toughest technology challenges
 5. Encourage transformative, cross-cutting technologies that benefit NASA as well as other government agencies
 6. Empower a broad community of innovators and academia through emphasis on early-stage investments
- **New Collaborative Process**
 - Released document of 187 shortfalls – technology areas requiring further development to meet future exploration, science, and other mission needs (Spring 2024)
 - Collected feedback and released 2024 Civil Space Shortfall Ranking Document (July 2024)
 - <https://www.nasa.gov/wp-content/uploads/2024/07/civil-space-shortfall-ranking-july-2024.pdf?emrc=671b7467b9c5b>

Prioritizing Space Technology Development – Civil Space Shortfalls



Integrated Shortfall Ranking (1-10)

Integrated Rank	Average Integrated Score	Shortfall ID	Category
1	8.1035	1618: Survive and operate through the lunar night	Thermal Management Systems
2	7.6118	1596: High Power Energy Generation on Moon and Mars Surfaces	Power
3	7.4345	1554: High Performance Onboard Computing to Enable Increasingly Complex Operations	Avionics
4	7.3831	1557: Position, Navigation, and Timing (PNT) for In-Orbit and Surface Applications	Communication and Navigation
5	7.2473	1545: Robotic Actuation, Subsystem Components, and System Architectures for Long-Duration and Extreme Environment Operation	Autonomous Systems and Robotics
6	7.2076	1552: Extreme Environment Avionics	Avionics
7	7.1961	1519: Environmental Monitoring for Habitation	Advanced Habitation Systems
8	7.1679	709: Nuclear Electric Propulsion for Human Exploration	Propulsion: Nuclear
9	7.1145	1304: Robust, High-Progress-Rate, and Long-Distance Autonomous Surface Mobility	Autonomous Systems and Robotics
10	7.0946	1520: Fire Safety for Habitation	Advanced Habitation Systems



- **Integrated Shortfall Ranking – Power**

- **1596: High Power Energy Generation on Moon and Mars Surfaces (#2)**
- **1591: Power Management Systems for Long Duration Lunar and Martian Missions (#12)**
- 1597: Power for Non-Solar-Illuminated Small Systems (#27)
- **1592: High Power, Long Distance Energy Transmission Across Distributed Surface Assets (#32)**
- 1390: Power and Data Transfer in Dusty Environments (#34)
- **1595: Energy Storage to Enable Robust and Long Duration Operations on Moon and Mars (#57)**
- 1593: Lunar Surface Power Generation from ISRU Derived Resources (#178)
- 1594: Martian Surface Power Generation from ISRU Derived Resources (#183)

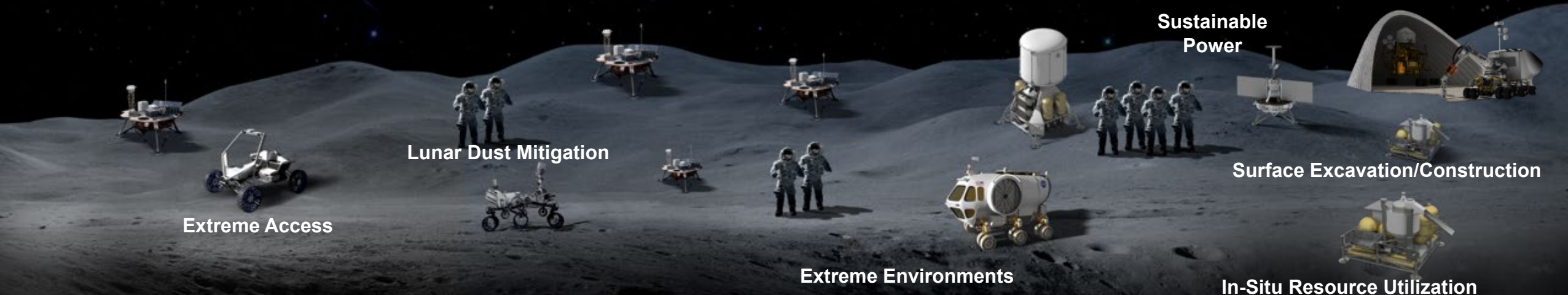


- **STMD will use the integrated ranked shortfall list as a tool**
 - It is one of several factors that will help inform and guide STMD's investments
 - It remains important for STMD to maintain balanced technology development portfolio across all capabilities and readiness levels
- **STMD remains committed to soliciting feedback annually**
 - As a result, the ranked shortfalls may change year to year
 - More information about the next feedback opportunity will be posted to www.nasa.gov/civilspaceshortfalls when available
- **More information regarding NASA Programs**
 - STMD Solicitations and Opportunities:
 - <https://www.nasa.gov/stmd-solicitations-and-opportunities/>
 - NASA Research Opportunities
 - <https://nspires.nasaprs.com/external/>

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



Thank you





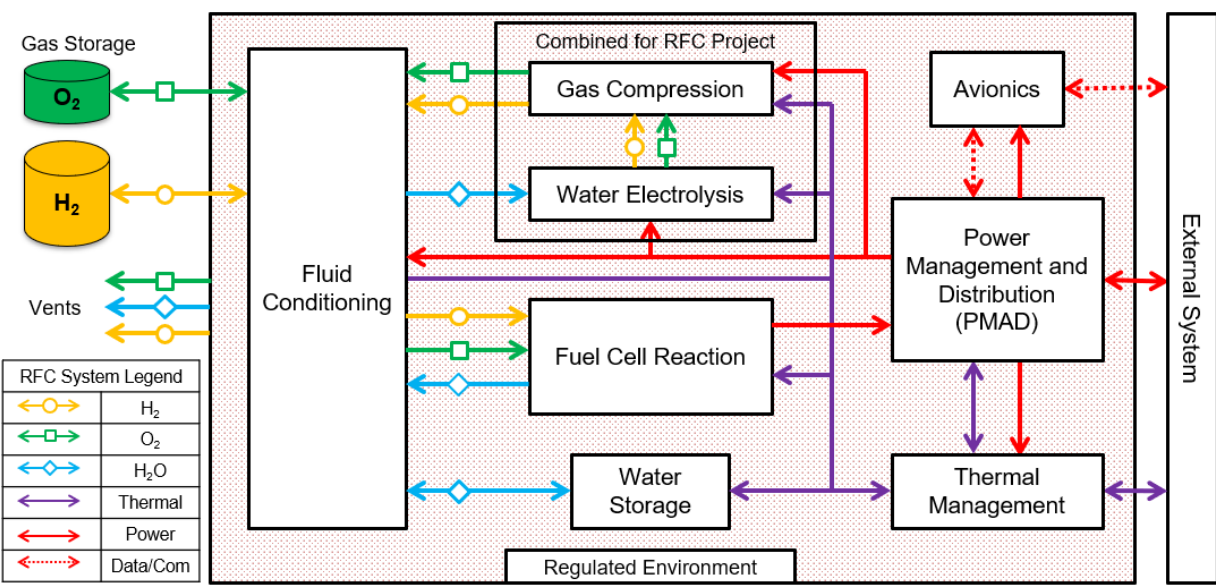
Regenerative Fuel Cell (RFC) Energy Storage

- Available energy storage technologies have low specific energies ($W \cdot \text{hr/kg}$) imposing unacceptable mass onto lunar surface missions
- NASA funds research of multiple technologies to maximize specific energy, including hydrogen (H_2) / oxygen (O_2) regenerative fuel cell (RFC) energy storage technology which offers path specific energy storage of 320 to $\sim 550 W \cdot \text{hr/kg}$
- RFC project to assess viability of optimized discrete [system](#) technology for potential inclusion into lunar surface missions

Regenerative Fuel Cell Project Overview

Design & Build H_2 / O_2 RFC System	• 50 psia Fuel Cell stack (Infinity Fuel Cell and Hydrogen) • 1800 to 2500 psia Electrolyzer (Giner) • Self-supporting sub-systems • Automated control system
≥ 2 month autonomous closed-loop test under laboratory conditions	• Full system pressures and multiple cycles • Open-loop operation for system functional verification • Closed-loop operation for reactant purity verification

Simplified RFC Functional Block Diagram



Open Loop Testing

- Component Verification Testing
- Breadboard System Assembly
- Breadboard System Verification
- Breadboard Open-loop Testing

Closed Loop Testing

- RFC Breadboard System Closed-loop Testing



Lunar Surface Power

Universal Modular Interface Converter (UMIC)

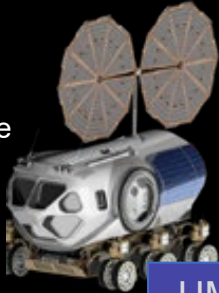
Enables bi-directional, long-distance power transmission on the lunar surface

Exploration Rovers

Smaller mobile platforms to explore the lunar surface, conduct surface operations, and collect science data



Pressurized Rover (PR)
Mobile habitat to enable wider
ranging human exploration of the
lunar surface

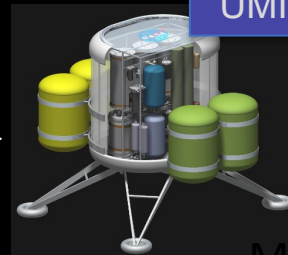


Lunar Surface Habitat

Stationary habitats to enable local exploration of the lunar surface

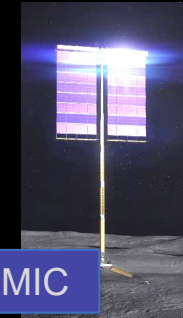


Regenerative Fuel Cell (RFC)
Energy storage technology using water electrolysis to store energy in hydrogen for later conversion into electrical power by a fuel cell.

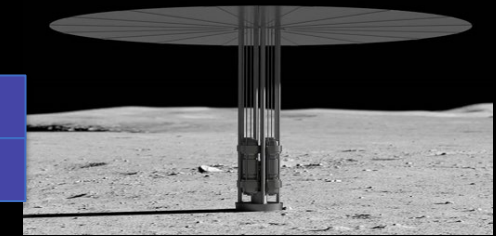


Vertical Solar Array Technology (VSAT)

Large vertical solar arrays that will operate at 10 meters above the surface at the lunar south pole.



FSP (Fission Surface Power)
kW-class nuclear power source for Mars
or lunar surfaces during daylight or night



In Situ Resource Utilization (ISRU)

Surface systems to recover and process materials from and within the lunar regolith to support lunar surface operations

