Electric Power on the Moon

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January 31, 2025
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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

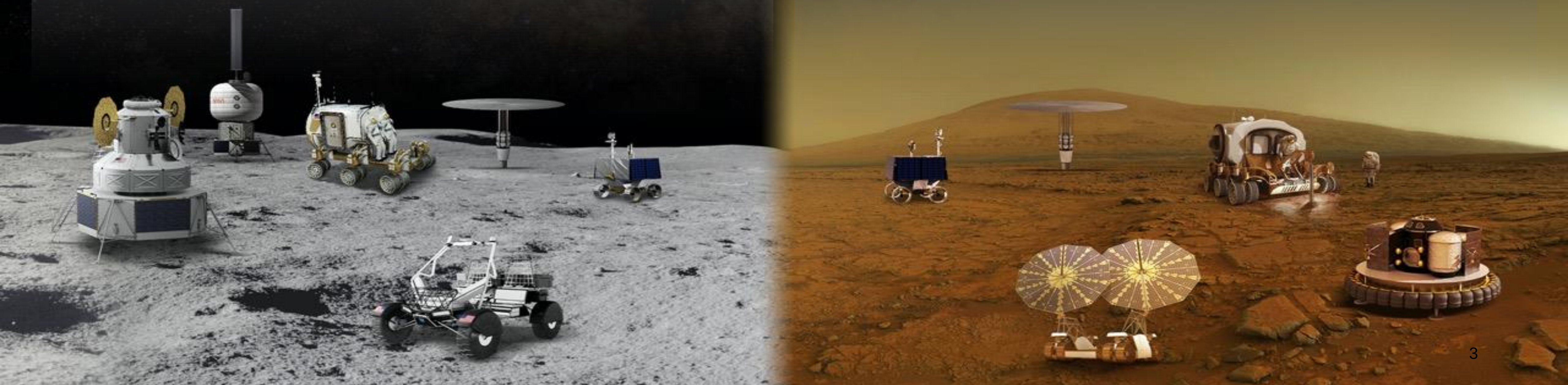
Moon to Mars (M2M) Objectives - Power

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.



Meeting the Lunar Infrastructure Goal – Universal Power

A *global lunar utilization infrastructure* (LI Goal) with a *power generation and distribution system* that *scales to global power utilization and industrial levels* (LI-1L) requires:

- **Access to electric power globally and continuously**
  - Power is available <u>any where</u>
  - Power is <u>continuously</u> available
  - Requires long-distance power transmission
- **Known interface/connection**
  - Standard/well defined connection - like the wall outlet
- **Ensured power quality**
  - Well defined ranges that allow equipment to designed to and protect.

Microgrid Definition and Interface Converter for Planetary Surfaces (MIPS)

- **MIPS project focused on enabling universal access to electric power on the lunar surface.**
  - Long-distance power transmission on the lunar surface
  - Defining an interface to access electric power

- **MIPS project execution:**
  - Identifying power levels and approximate timeline for implementation
  - Performing Trade studies to identify power transmission type (AC/DC) and voltage level
  - Design, build and test prototype converter
  - Create interface definition that can be evaluated and baselined

- **MIPS team created a government reference to baseline power needs and use for the trade study. Assume Artemis VII+ / Design Reference Mission (DRM) 7+**
  - Baselined power system components (sources and loads)
  - Baselined power architecture
    - Identified important characteristics of a lunar power grid

Government Reference Example: Power Needs

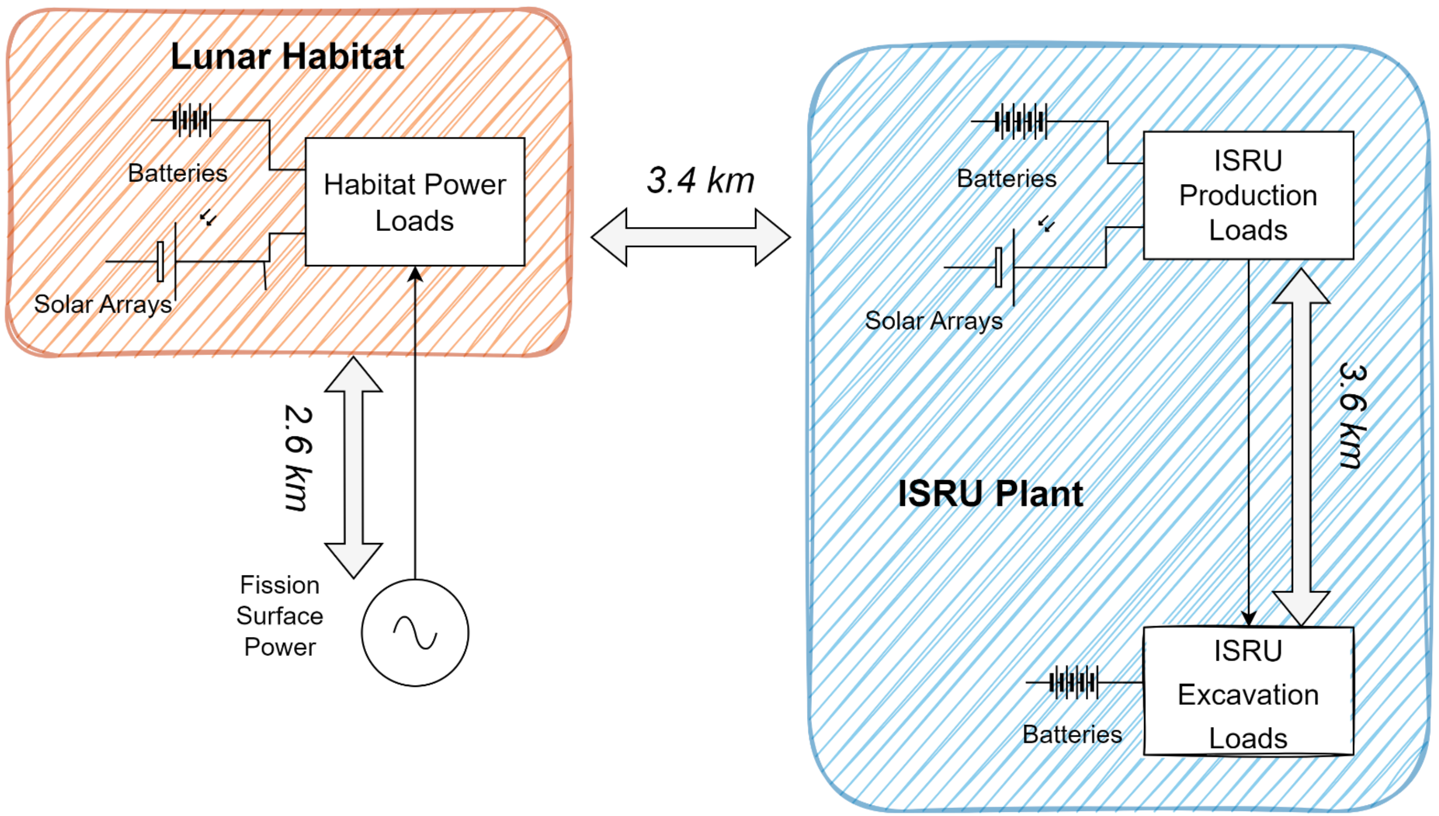
Power Needs (Loads)

- **In-Situ Resource Utilization (ISRU)**
  - Mine regolith and convert into other resources
  - Peak power demand 60 – 70 kW
  - Keep alive power – ~12 kW
  - *Operate during periods of heavy insolation*
- **Lunar Habitat**
  - Power demand during habitation 20 kW
  - Keep alive power - ~2kW
  - *Crew of 4 for 30+ days – 4 times per year*
- **Lunar science / Exploration**
  - Various rovers and lunar science experiments, 500 W to 1000 W

Power Sources (Generation & Storage)

- **Vertical Solar Array Technologies (VSAT)**
  - 10 kW of power @ 100 VDC
  - VSAT at lower TRLs and cannot provide year-round power
- **Fission Surface Power**
  - 40 kW of power @ TBD voltage
  - Low TRL, nuclear restrictions (limited number of units and must be located 1km+ from other assets)
  - Provide power during darkness period
- **Batteries**
  - Heavy and do not operate well at extremely low temperatures
- **Regenerative Fuel Cells**
  - Low TRL

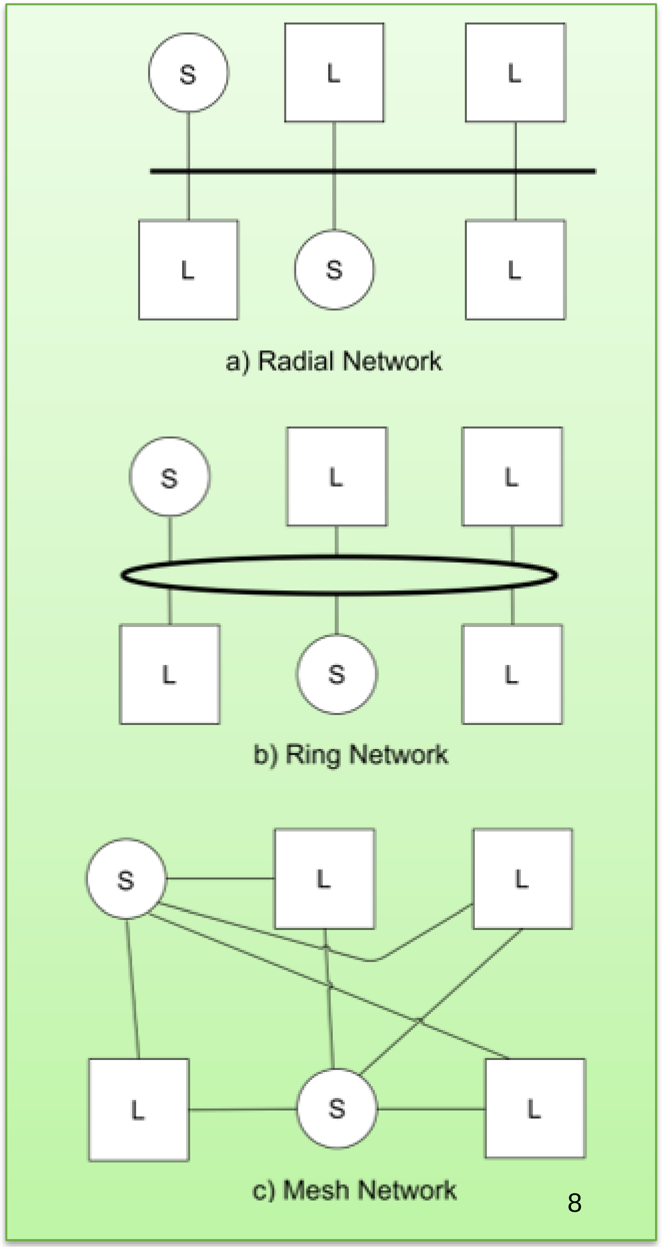
Government Reference Example: Baseline Architecture



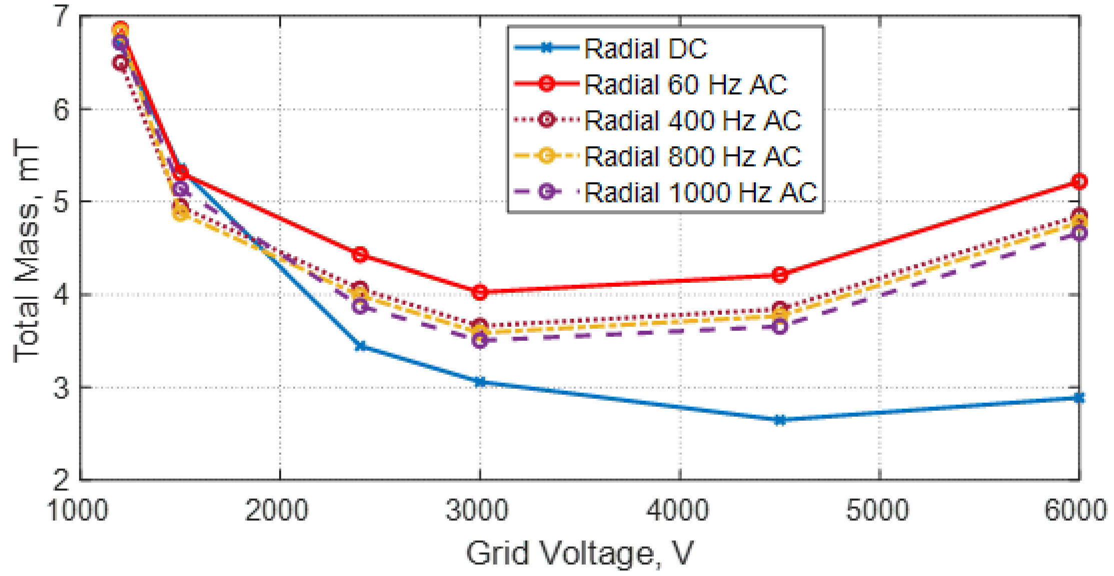
- ***Note: This is not an actual system architecture, rather it is a notional architecture that resembles key characteristics of interest:***
  - *10 km total line distance and ~100 kW of total power*
  - *FSP separated at least 1 km from other assets*
  - *3-5 km distance between ISRU excavation (located in PSR) and ISRU production plant (crater rim, peaks of eternal light)*

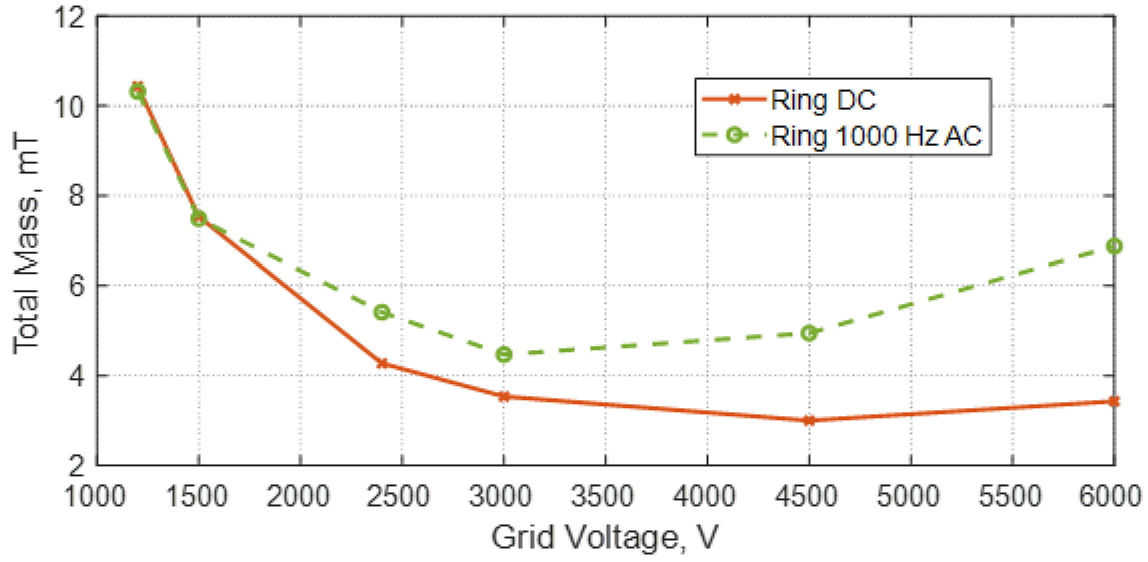
Lunar Surface Power Distribution Trade Study

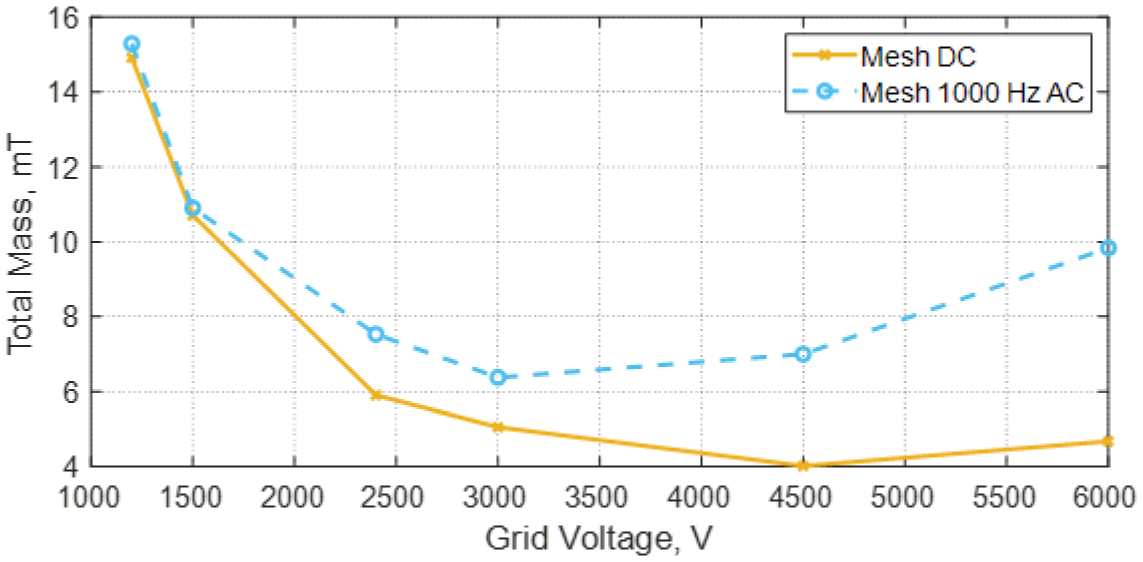
- **Focus of the trade study is on primary power distribution (transmission)**
  - Does not include mass of power sources (solar arrays, FSP, energy storage, etc.)
  - Mass of converters and cable (and connectors)
- **Trades include:**
  - Architecture
    - Trade: Radial, Ring, Mesh
  - Power Type
    - DC, Single-Phase AC, Three-Phase AC
    - AC frequencies range from 60 Hz (terrestrial grid) to 1000 Hz (previous studies recommended based on Brayton generators)
  - Voltage
    - 600 V up to 6000 V



AC vs DC Trade Study Results







<u>Analytical Analysis Data Insights</u>

1. Ring and mesh grids increase reliability with the cost of additional mass. AC/DC mass trends remain consistent.
2. DC mass is lower than AC at higher voltage. Lower voltages slight mass benefit to DC (marginal)
3. Most important factor for decreasing mass is to increase Voltage

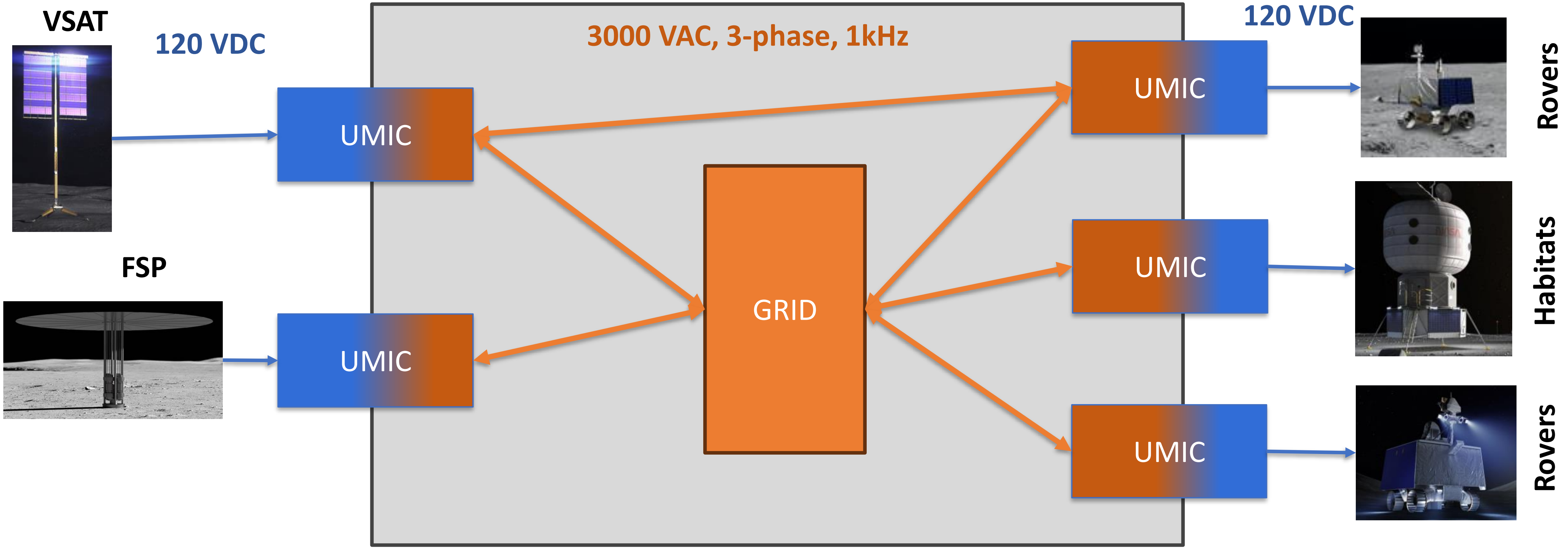
Trade Study Conclusions and Recommendation

- **AC and DC transmission masses comparable over useful voltage range**
  - Ring architecture mass 50% higher than radial, achieves single line fault tolerance
  - Mesh architecture mass 100% higher than radial, achieves dual line fault tolerance
- **DC Transmission**
  - Radiation Hardening constraints limit DC Voltage to 1.5 KV or less
  - 1.5 kV is not sufficient and need to increase voltage beyond this level
- **AC Transmission**
  - AC is lightest solution and best for enabling future growth (to 100s MW–GW range)
  - 3 kV AC is lowest mass solution assuming available cable/converter tech

- **MIPS Recommendation:**
  - Long distance power transmission: 3 kV AC, 3-phase, and frequency of 1 kHz
  - Assume initial grid will be a radial network and expand beyond that.

Any questions related to the Power Trade Studies and Recommendations?

Universal Modular Interface Converter Concept



- **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

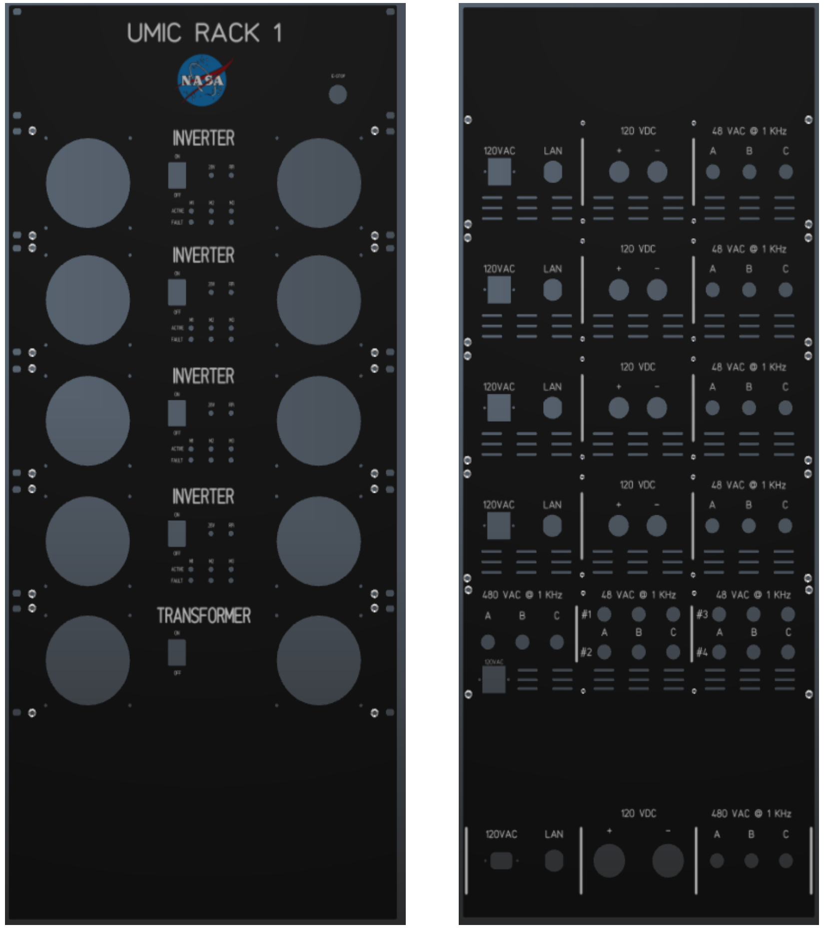
Universal Modular Interface Converter

- **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

10 kW UMIC Rack

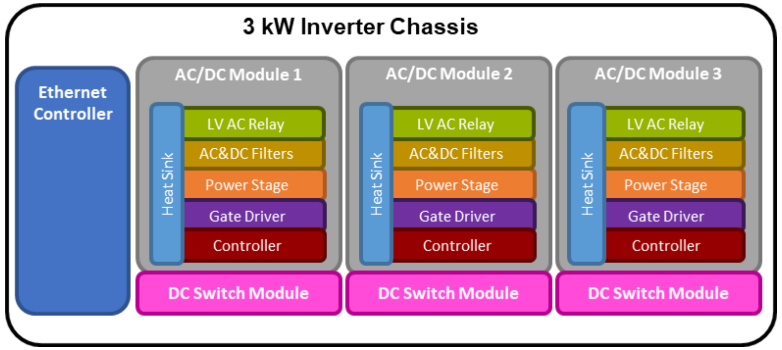
10 kW UMIC Rack



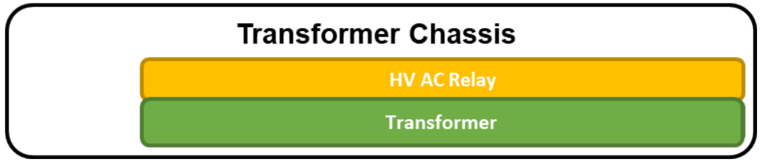
10 kVA continuous with margin, 12 kVA peak

10 kW UMIC Rack

- 4x Inverter Chassis (3 kW each)



1x Transformer Chassis (10 kVA)

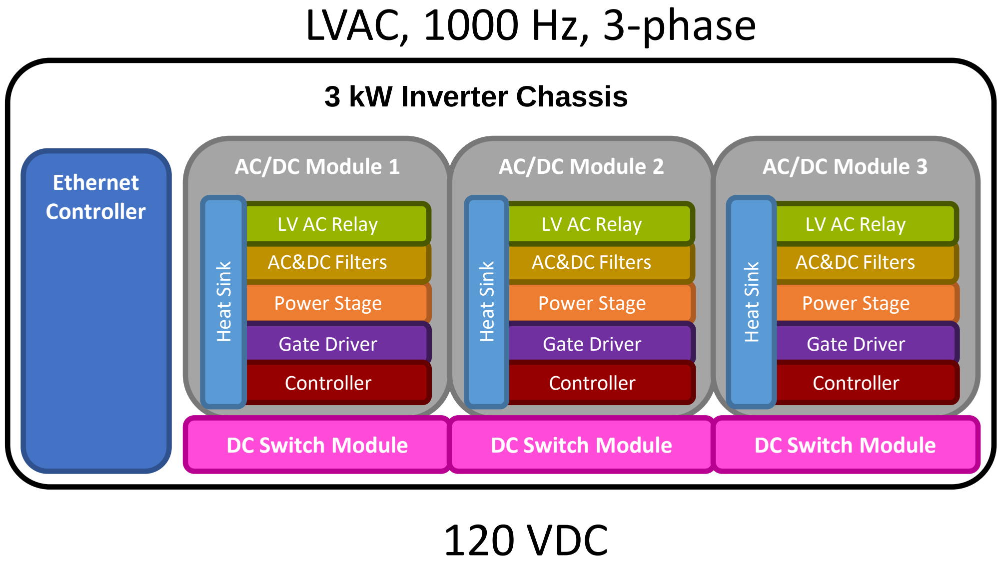


- Interface Rear Panel
  - 120 VDC
  - 3 kV AC
  - Ethernet/LAN
  - 120 VAC mains power (housekeeping/fans)

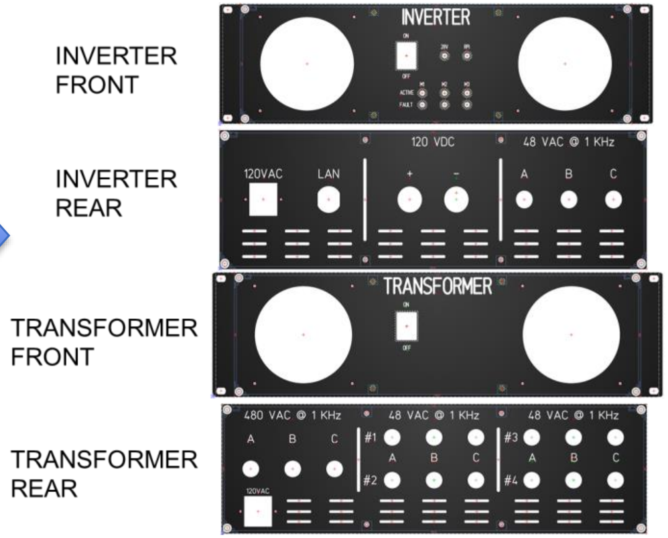
3 kW Inverter/Rectifier Chassis

- **Common 19” rack form factor selected for packaging**
  - Volume enough for 3 kW of inverter modules

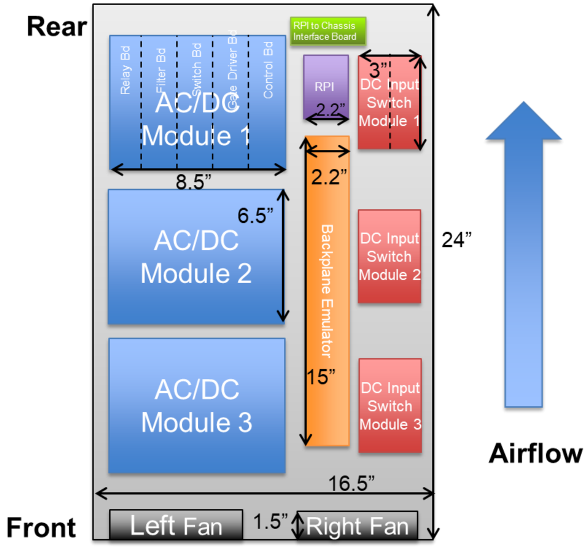
Conceptual Breadboard Chassis Design



Front and Rear Panels

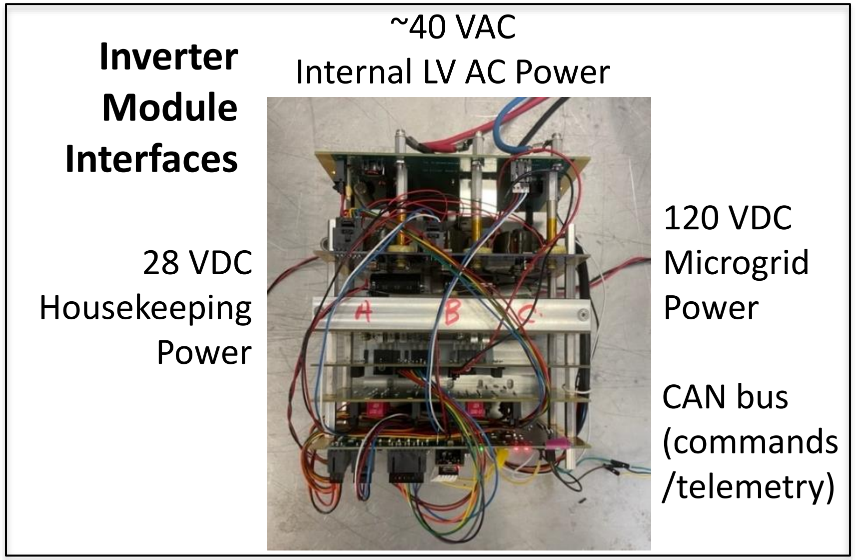


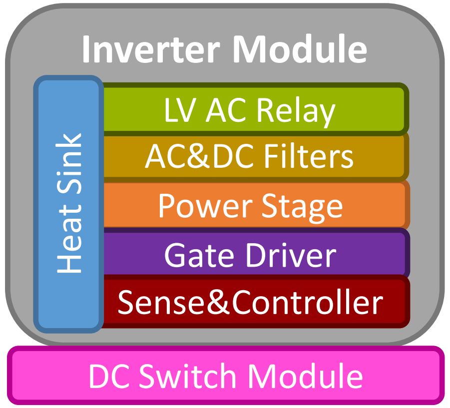
Chassis Top View

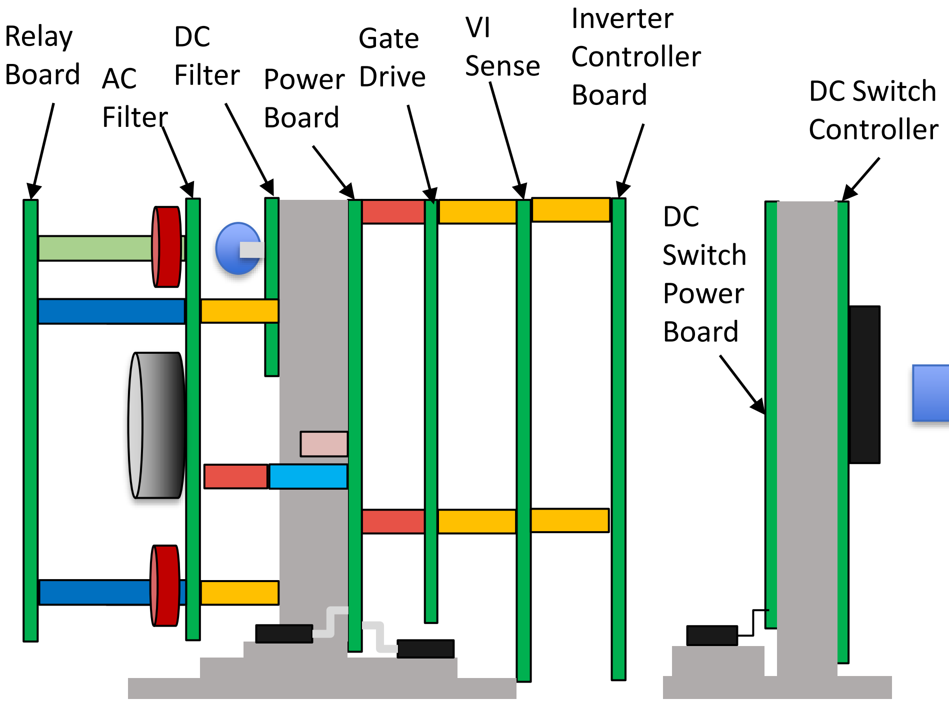


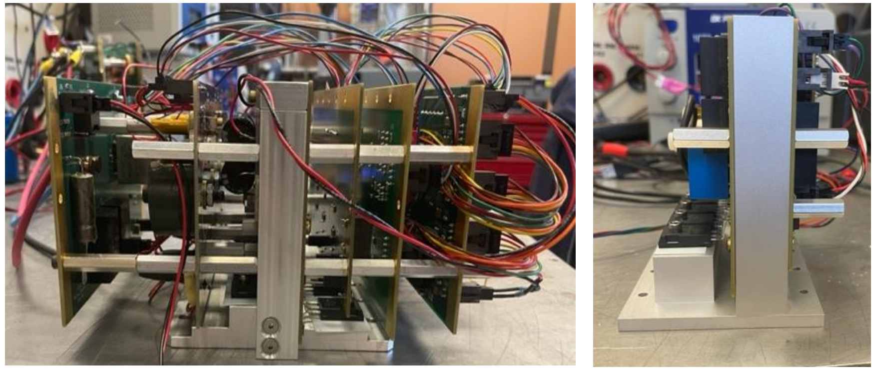
1kW Inverter / Rectifier Modules

- **1 kW Inverter Module plus 1 kW DC Switch Module**
  - Inverter: Converts 120 VDC microgrid bus to UMIC internal low voltage 40 VAC bus
    - Includes filters, power control logic, AC isolation
    - Consists of 5 main subsystems in a stacked card form factor
  - DC Switch: Provides DC-side current limiting & isolation capability









Transformer Chassis

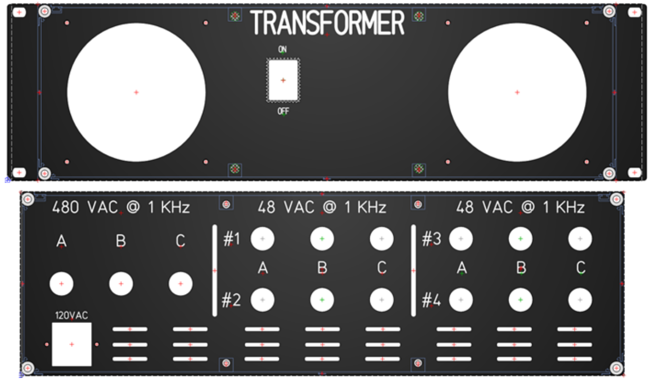
- **Transformer chassis to include all transformers needed at a given site**
  - May shrink or grow based on site power needs

- **Modular (1 kVA) transformers design (both single and 3-phase types)**
  - 10x 1 kVA three phase transformers (10 kVA total)

- **Centralized transformer design (both single-phase type only)**
  - 3x 3.3 kVA single phase transformers (10 kVA total)

TRANSFORMER FRONT

TRANSFORMER REAR

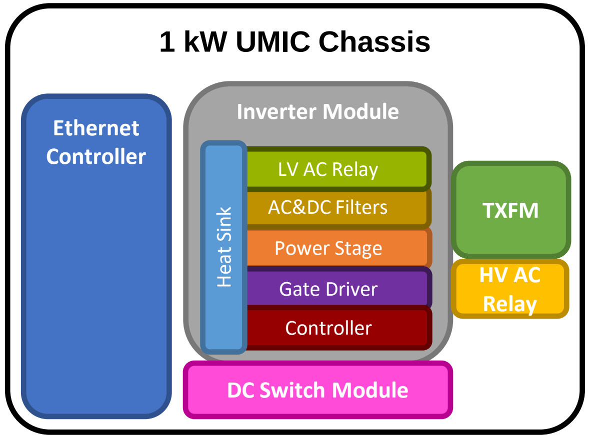


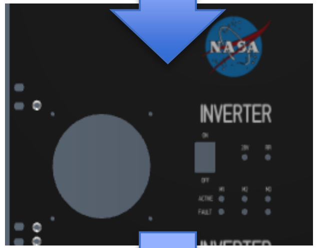
NASA 1 kVA 3-phase design

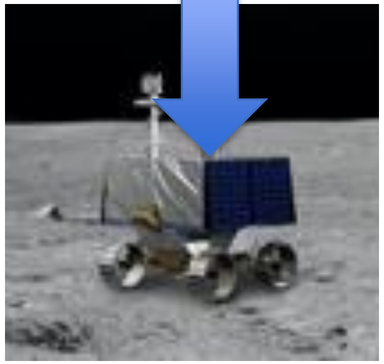
3.3 kVA single-phase design
(3x for 10 kW)

UMIC Scales

1 kW UMIC



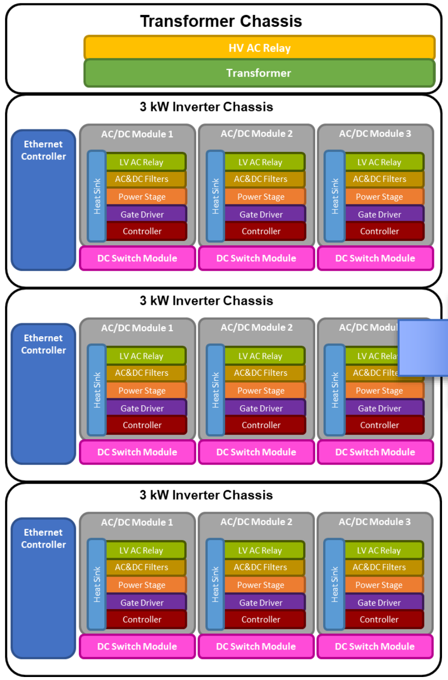


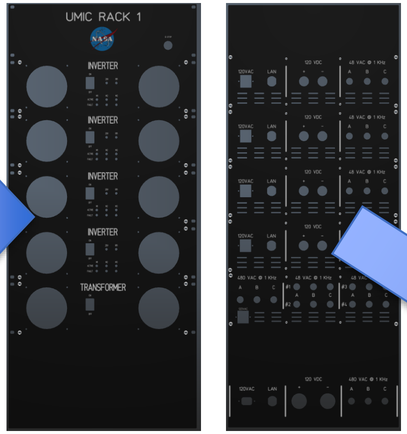


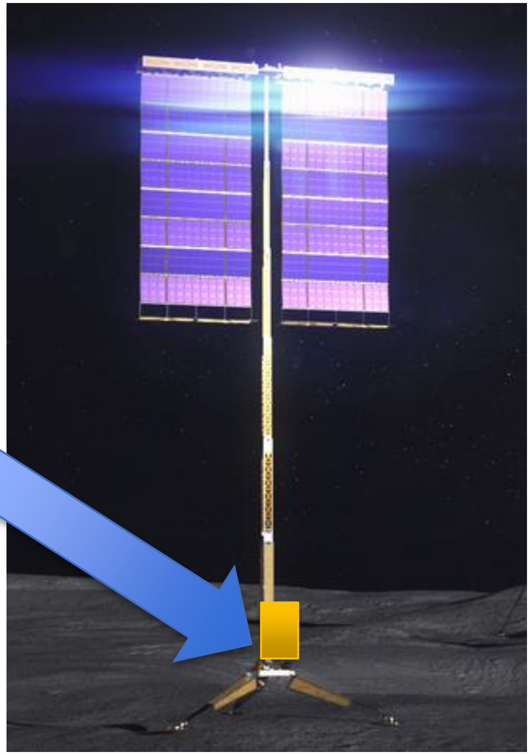
Add modules to go from

Low Power to High Power

10 kW UMIC

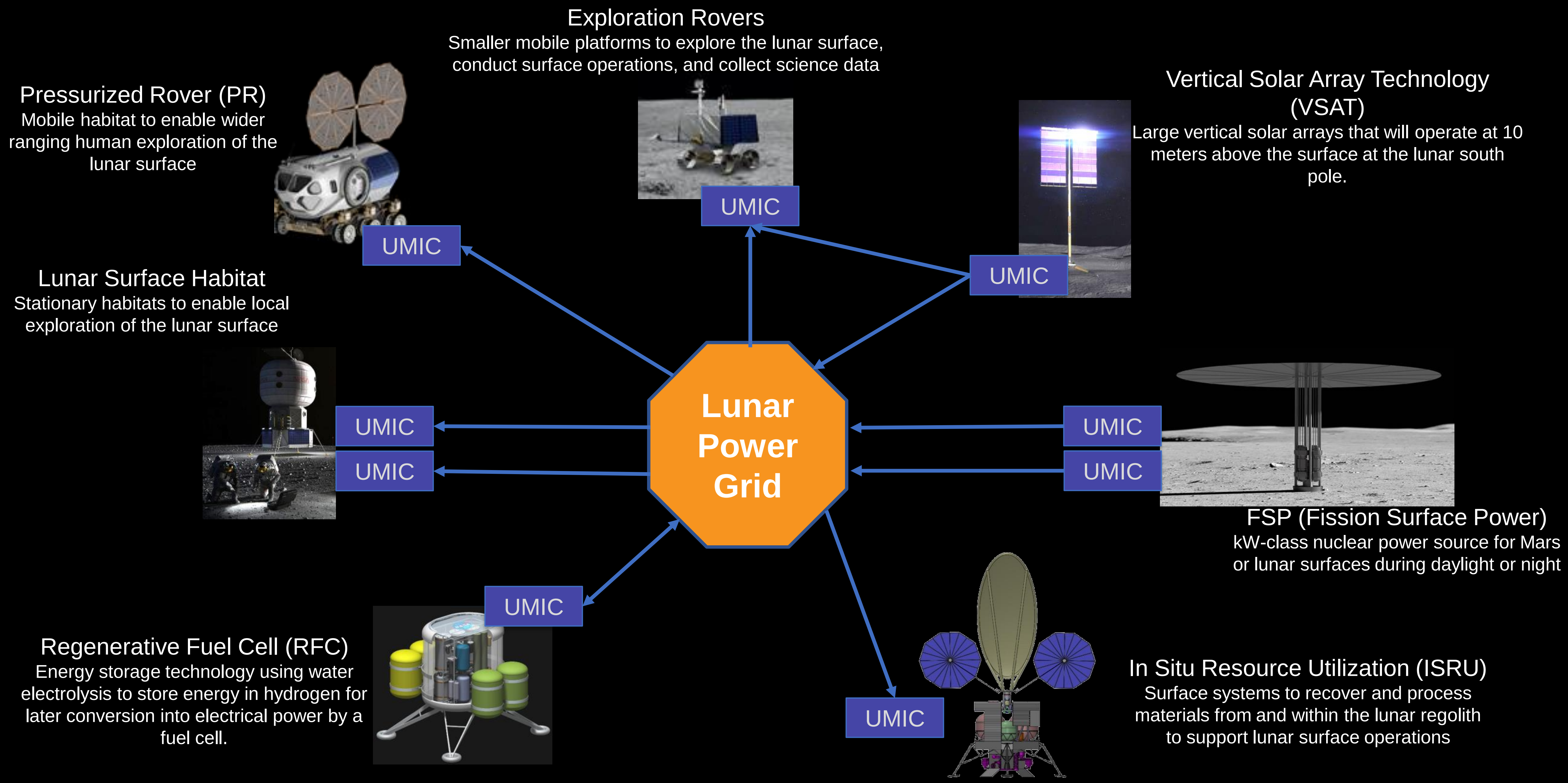






Lunar Surface Power

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



MIPS Related Future Work

- **FY25 Plans**
  - Redesign of the inverter / rectifier modules to process 2kW of power (from 1kW)
  - Investigate and characterize interaction of AC cable and lunar regolith at various frequencies

- **FY26+ Plans**
  - Continue technology development of the converter
  - Continue to develop and advance the converter interface definition
  - Infuse converter into US Industry and International Partners
  - Develop prototype power grid and test UMIC as grid interface

Any questions related to the UMIC and MIPS Project?

NASA Moon to Mars

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- **Moon to Mars Objectives (September 2022)**
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- **Architecture Definition Document (ADD) / Architecture Concept Reviews**
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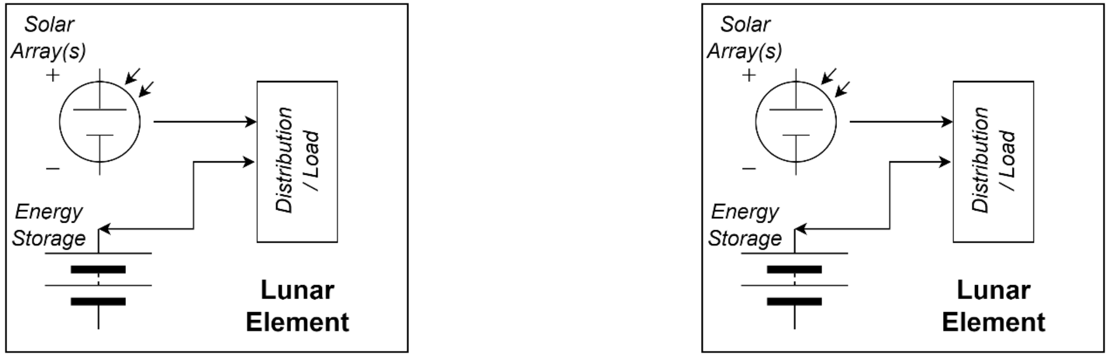
Moon to Mars Architecture Definition Document (ADD)

Moon to Mars Campaign Segments

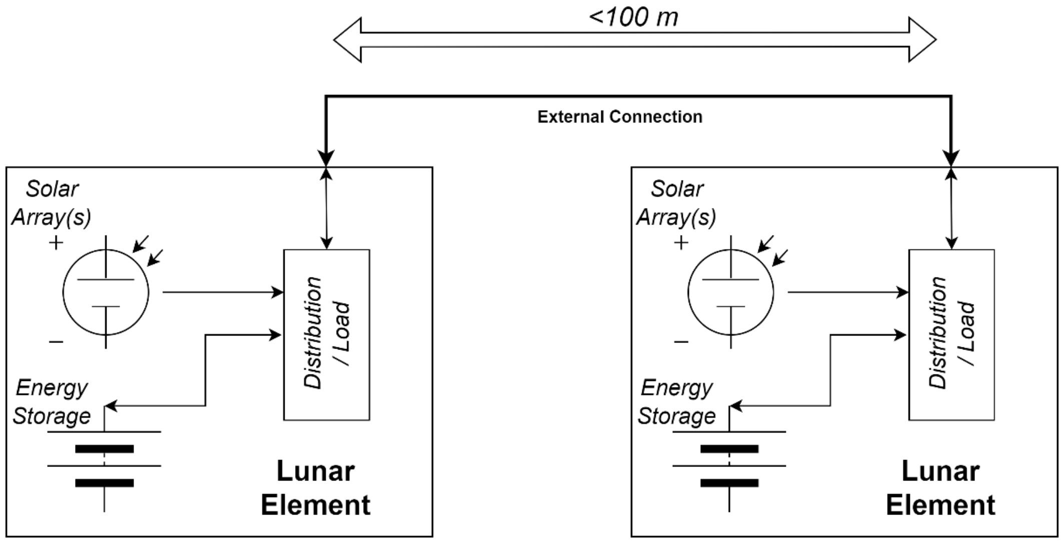
Human Lunar Return	Initial capabilities, systems, and operations necessary to re-establish human presence and initial utilization (science, etc.) on and around the Moon.	• **Self-Sufficiency**
Foundational Exploration	Expansion of lunar capabilities, systems, and operations supporting complex orbital 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	*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.*	

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.



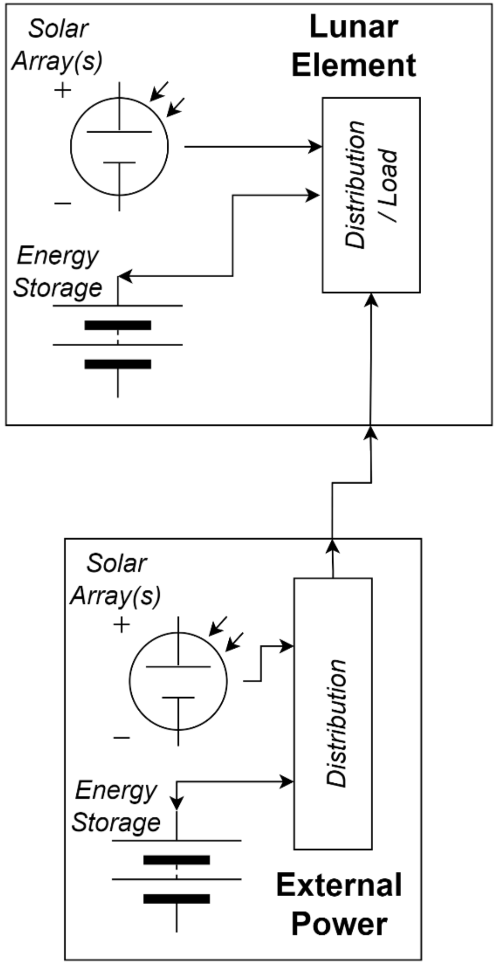
Self-Sufficient power system



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

Power Strategy: External Power Augmentation

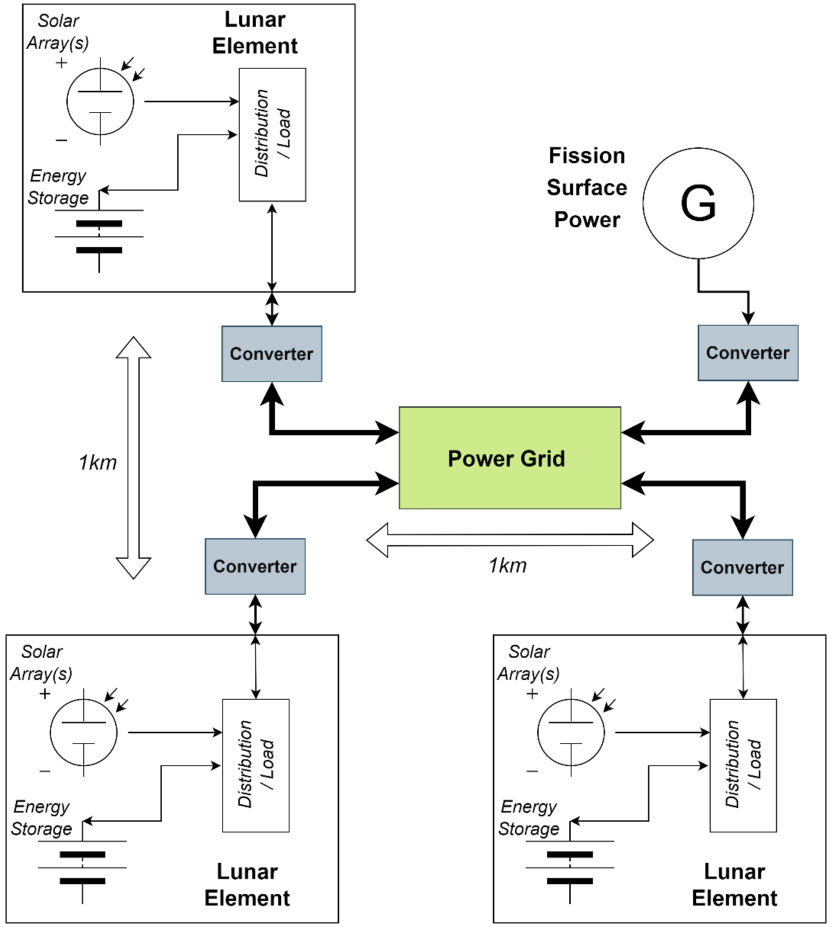
- **External Power Augmentation (EPA) Overview**
  - Dedicated elements are delivered that provide power to extend the survival period
  - May require mobility to place power source near load(s)
- **Moon to Mars Segments:**
  - *Foundational Exploration*
  - Sustained Lunar Evolution
- **Power System 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 (Region specific)

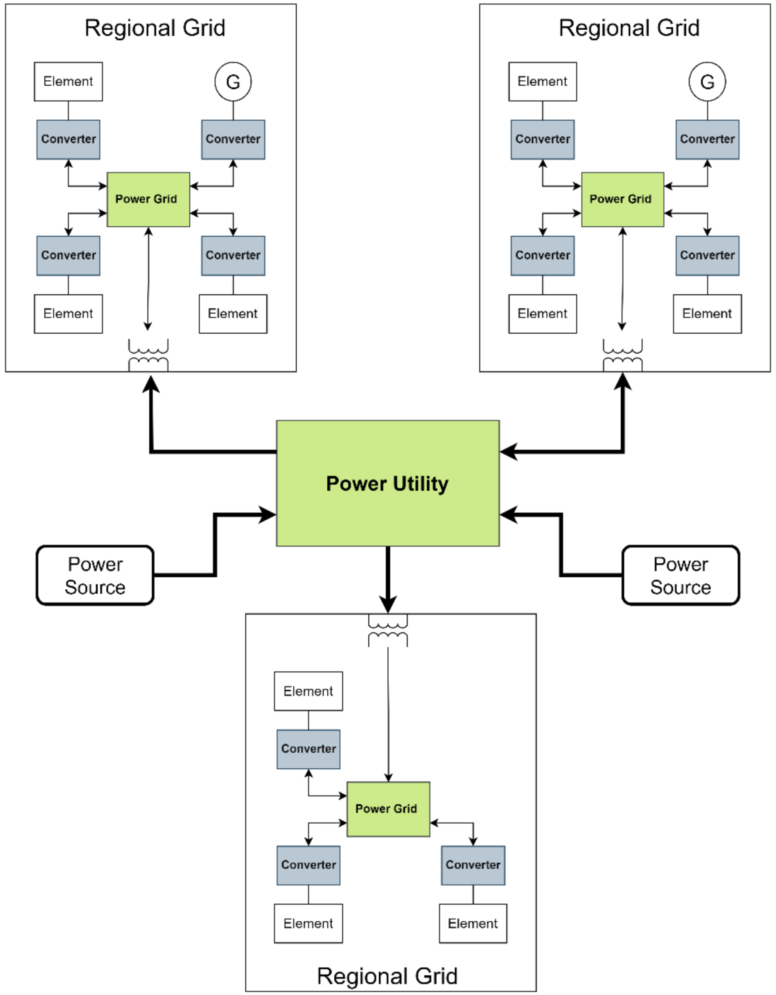
- **Regional (Area/Region) Power Grid Overview**
  - Make power available over long-distance
  - Provide power during darkness periods
  - Provide power into permanently shadowed regions
- **Moon to Mars Segments:**
  - Sustained Lunar Evolution
- **Power System Information**
  - Distance between elements 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

Lunar Power Grid Related Future Work

- **FY26+**
  - Develop lunar power grid concept of operations, governance structure, architecture document, etc.
  - Build grid prototype for testing and document verification
  - Develop an advanced power grid controller to manage electric power on the lunar surface

Any questions related to the Lunar Power Grid?

Advanced Modular Power Systems (AMPS)

National Aeronautics and
Space Administration

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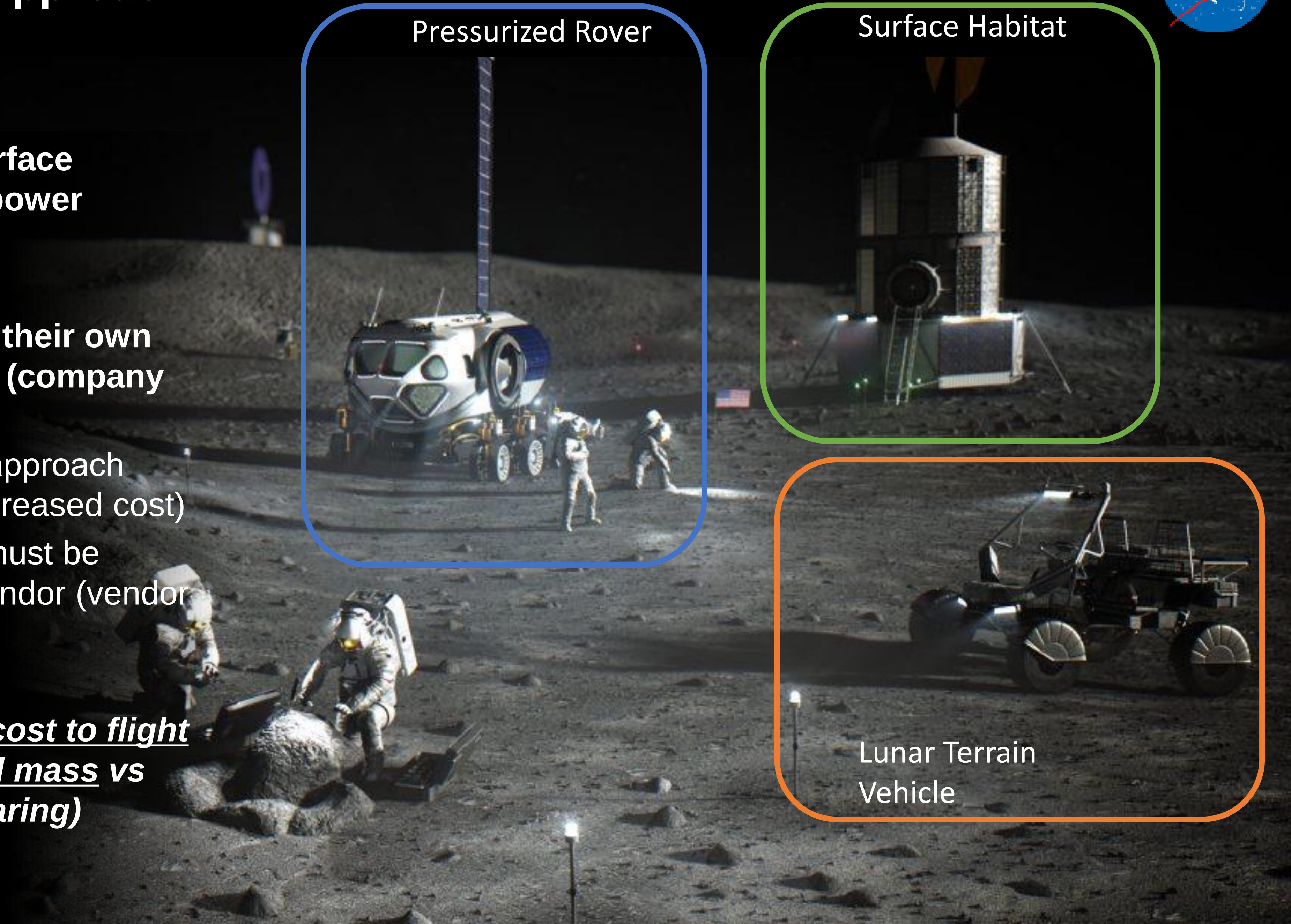
NASA Space Power Approach

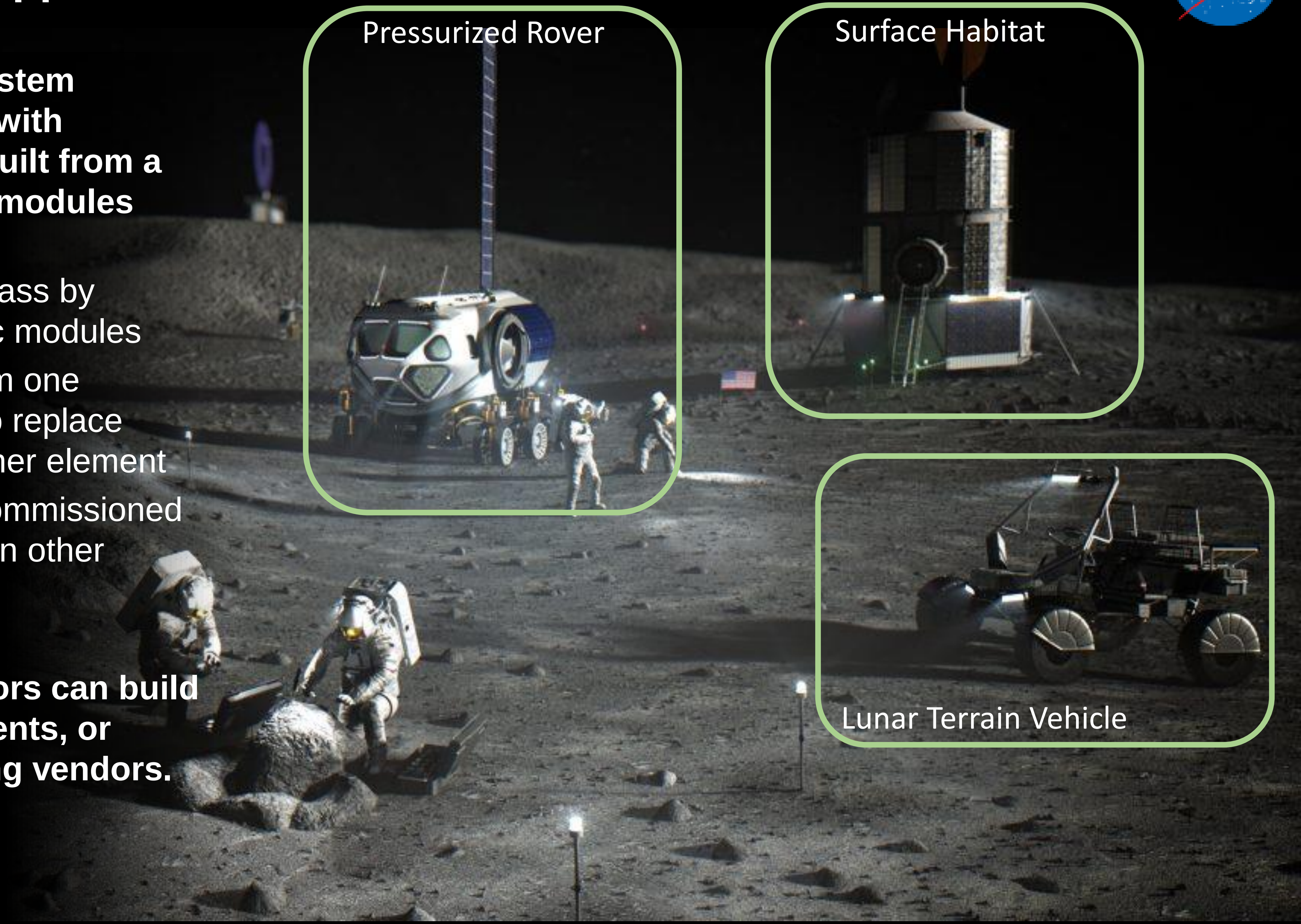
- **Every Lunar or Martian surface element requires electric power (Habitat, LTV, etc.)**
- **Each program/vendor has their own power hardware approach (company specific design)**
  - Each vendor's design/approach have to be certified (increased cost)
  - Spares/replacements must be bought from specific vendor (vendor must stay in business)
- ***This approach prioritizes <u>cost to flight</u> vs long-term and <u>on-board mass</u> vs total mass (on-board + sparing)***



NASA Space Power Approach with a Modular & Common Standard

- **Large traditional power system components are replaced with modular electronic units built from a common set of electronic modules (defined by a standard)**
  - Reduction in sparing mass by sparing small electronic modules
  - Electronic modules from one element can be used to replace components from another element
  - Components from decommissioned elements can be used in other elements.

- **System (element) integrators can build all power system components, or purchase from participating vendors.**



AMPS: NASA Modular Space Power Approach with a Common Standard

Modular Electronics Standard for Space Power Systems (MESSPS)

Define interfaces, form, fit, function

Electronics Modules

- Intelligent Controller
- Housekeeping
- High Current Switchgear
- Bus Switchgear
- Load Switchgear
- Bi-Directional Converter
- Portable Equipment Panel (PEP) Module

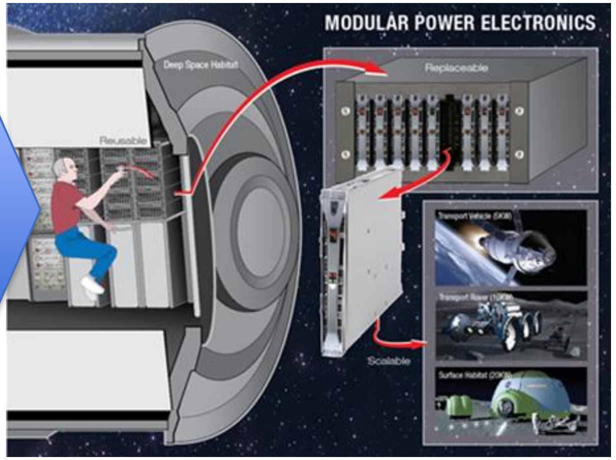
can be arranged to build:

Modular Electronic Units (MEU)

- ***Main Bus Switching Unit (MBSU)***
- ***Secondary Bus Switching Unit (SBSU)***
- ***DC-DC Converter Unit (DDCU)***
- ***Power Distribution Unit (PDU)***
- ***Battery Charge Discharge Unit (BCDU)***

can be arranged to build:

Modular Power System Architecture



Government / Standards Org

Open to all of industry

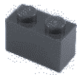
Element / Program Vendor

AMPS Electronic Modules

- **Intelligent Controller**
  - Spacecraft-to-internal network adapter
  - Validates chassis configuration
  - Monitors module status
  - Translates commands & telemetry

- **Housekeeping Module**
  - Generates Housekeeping Power Bus (5VDC) from 120VDC source

- **Bidirectional DC/DC converter**
  - Configurable current & voltage setpoints
  - Configurable, resettable trip
  - Configurable secondary: 120VDC or 28V
  - Synchronized, staggered switching



- **Portable Equipment Panel Module**
  - Variable output, isolating DC/DC converter
  - Load cable or user programmable output
  - Remote voltage sense

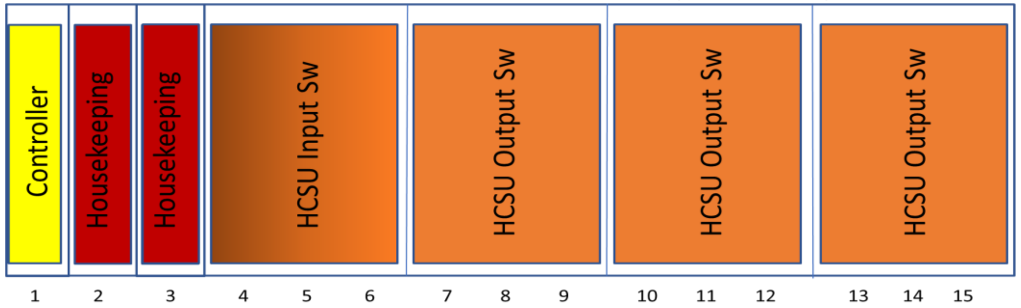
- **Load Switchgear Module**
  - 4-channel unidirectional switch
  - Current-limiting with configurable levels
  - Resettable trip
  - Parallelable channels can form “virtual power channels” (VPCs)
  - Inductive load protection, safe discharge

- **Bus Switch Gear Module**
  - Bidirectional bus switch (supply & return)
  - Bidirectional pre-charge circuit
  - Configurable, resettable trip
  - Transient suppression

- **High Current Switchgear**
  - Bidirectional supply-side switch
  - Bidirectional pre-charge circuit*
  - Configurable, resettable trip
  - Transient suppression*

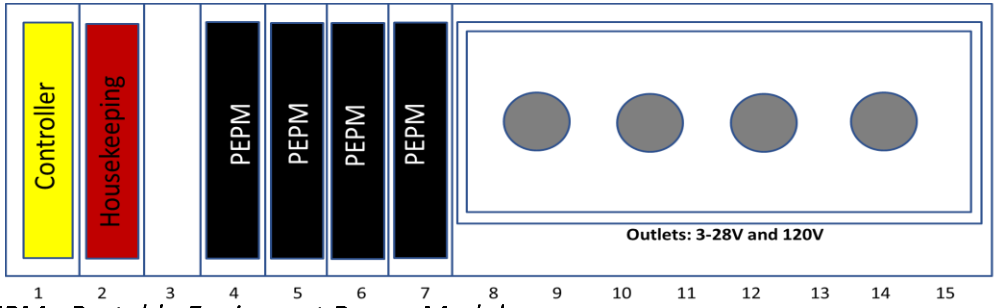
AMPS Modular Electronic Units (MEUs)

Main Bus Switch Unit (MBSU)



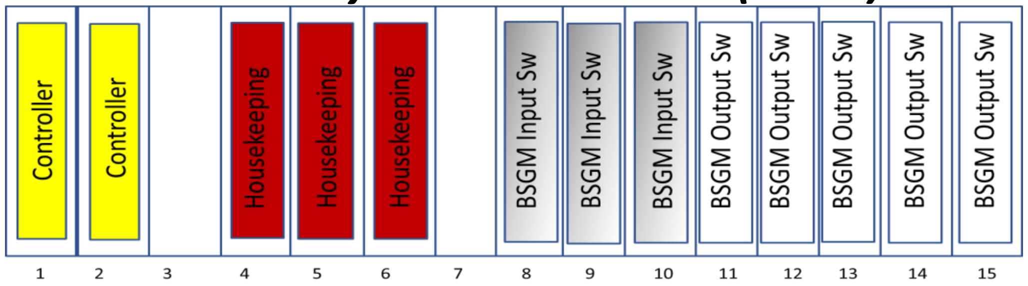
HCSU: High Current Switching Unit

Portable Equipment Panel (PEP)



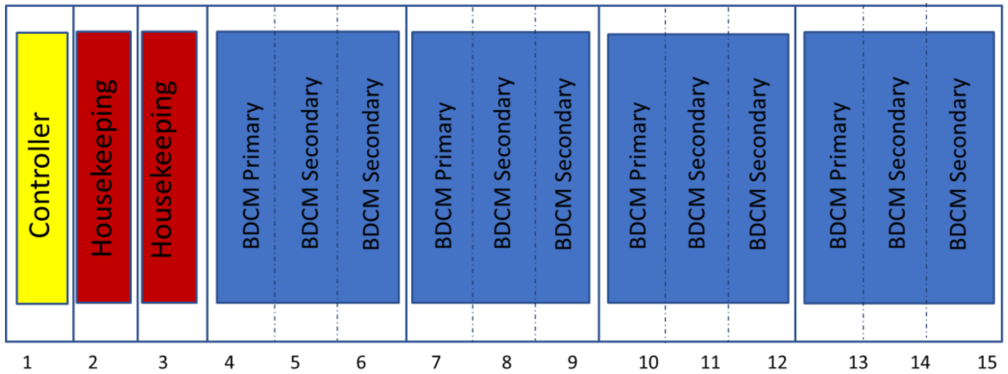
PEPM: Portable Equipment Power Module

Secondary Bus Switch Unit (SBSU)



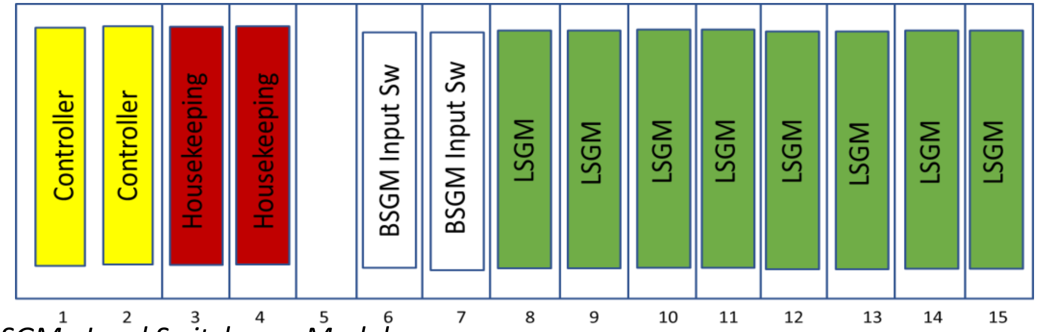
BSGM: Bus Switchgear Modul

DC to DC Converter Unit (DDCU)
Battery Charge Discharge Unit (BCDU)
Bidirectional Converter Unit (BDDCU)



BDCM : Bidirectional Converter Module

Power Distribution Unit (PDU)



LSGM: Load Switchgear Module

Current State of AMPS Modular Hardware

- **“String” of Modular Electronic Units have achieved TRL 4+ (Brass-board)**
  - *DC to DC Converter Unit (DDCU)*
  - *Secondary Bus Switch Unit (SBSU)*
  - *Power Distribution Unit (PDU)*
  - *Portable Equipment Panel (PEP)* Module

- **A string of AMPS hardware have been used to validate the *International Space Power System Interoperability Standards (ISPSIS)* 120 VDC Standard**

- **Modular Electronics Standard for Space Power Systems (MESSPS),** *GRC-AES-AMPS-006*
  - Draft released and is available from the NASA Techport site: https://techport.nasa.gov/view/10759
  - Includes CANopen Profile for Modular Power Electronics, *GRC-AES-AMPS-008*

AMPS Modular Hardware Related Future Work

- **FY25**
  - Assess current state of the modular hardware designs and standards
  - Identify existing technology gaps that need to be addressed
  - Determine cost and plan to advance the TRL of the hardware designs and associated standards to TRL 6 and infuse into US Industry and International Partners.

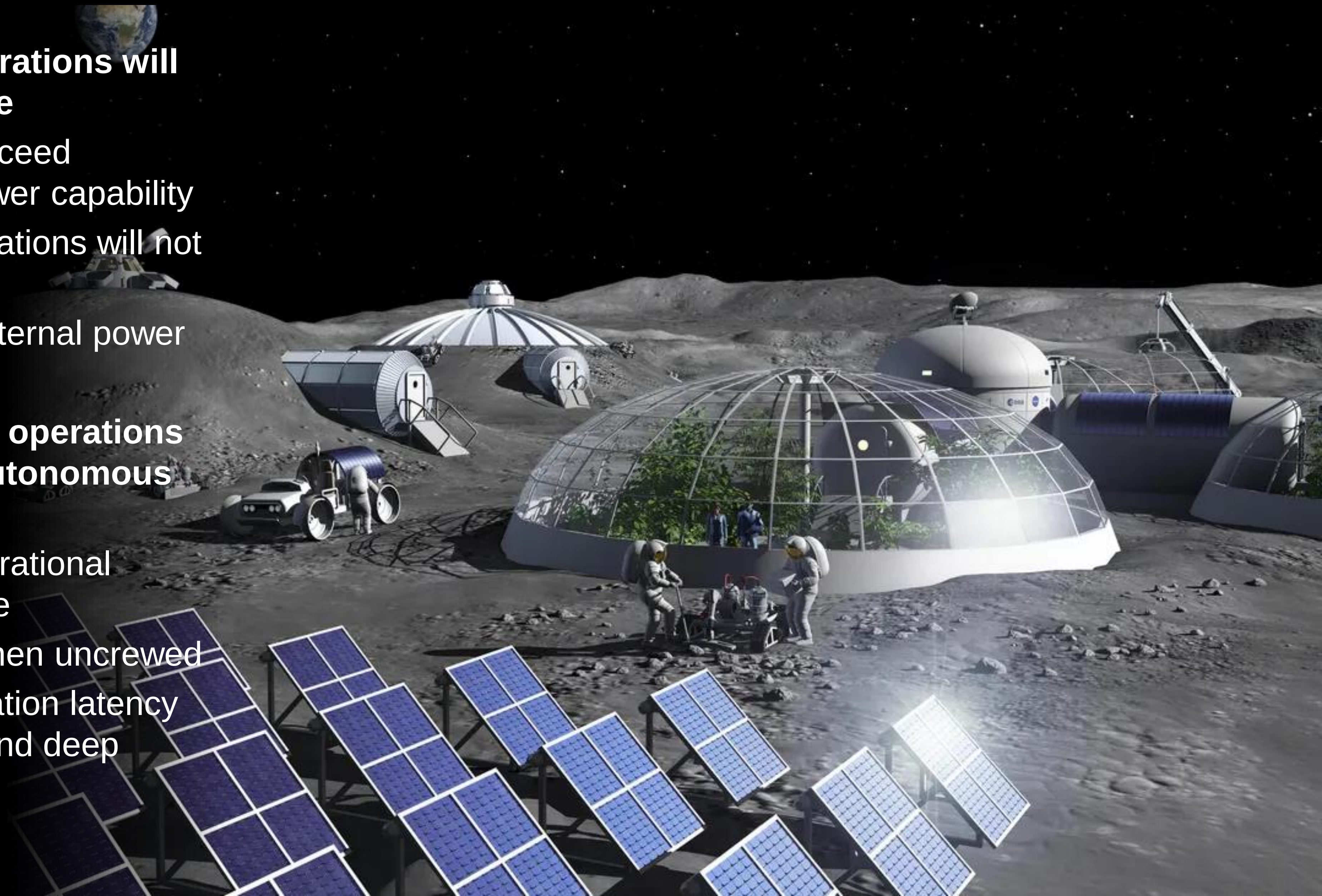
- **FY26+**
  - Advance the hardware (or select an alternative open-source standard) and push for adoption in M2M program

Any questions related to AMPS Modular Hardware?

The Growing and Evolving Lunar Surface Power System

- **Lunar/Martian surface operations will grow and expand over time**
  - Power demands will exceed individual elements power capability
    - Self sufficient operations will not be viable
  - Systems will require external power

- **Lunar and Martian surface operations will require intelligent & autonomous operation**
  - Allow system to be operational before Astronauts arrive
  - Continue operations when uncrewed
  - Account for communication latency associated with Mars and deep space travel.

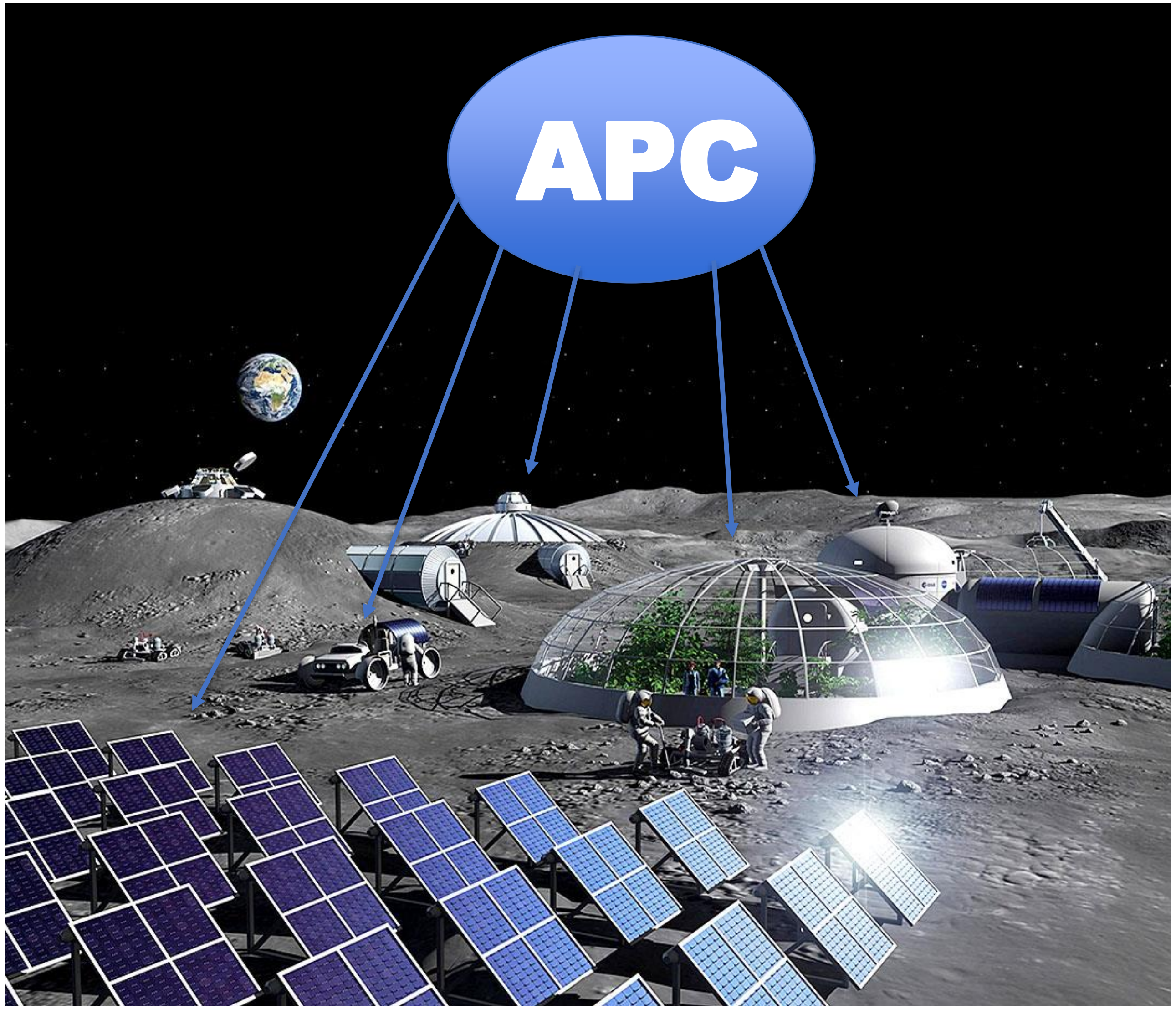


Autonomous Power Controller (APC)

What is it?

The APC is a comprehensive Energy Management System designed to minimize the need for human interaction and oversight of ~~dc~~ microgrids in space.

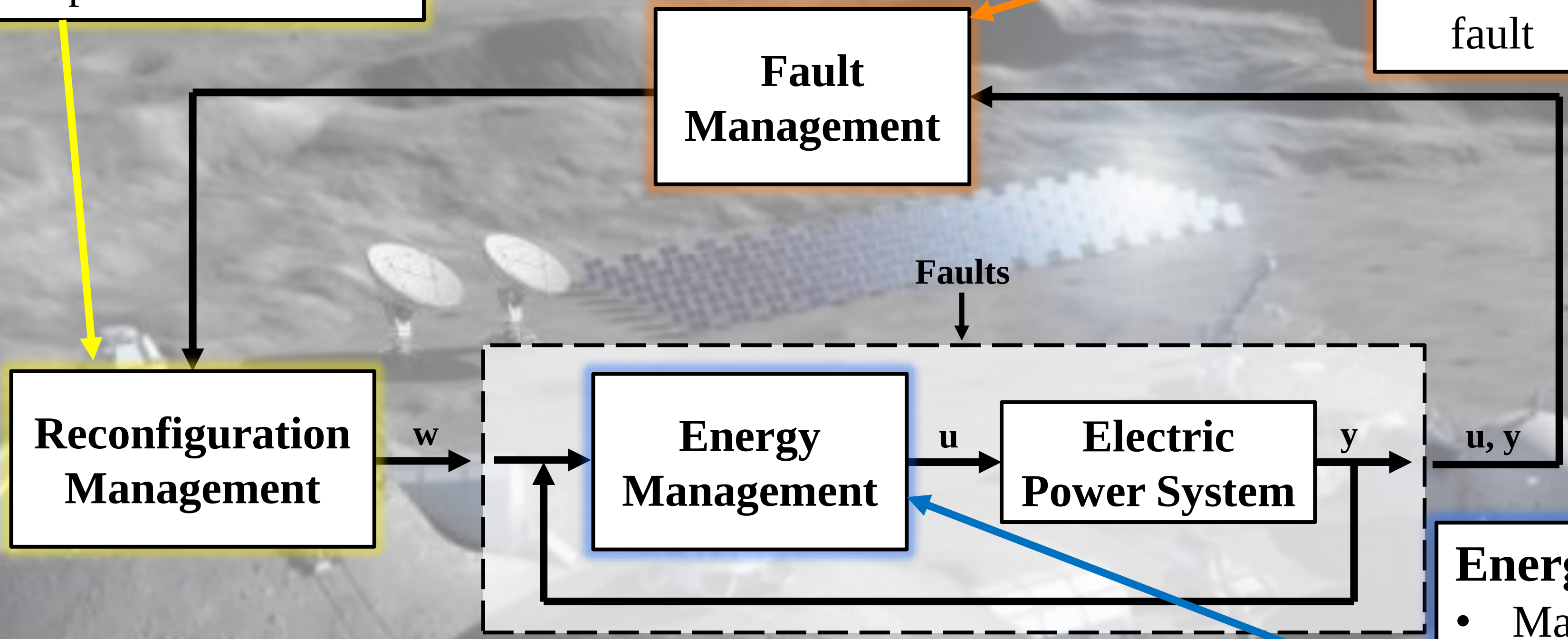
- Increase the *reliability*, and *resilience*
  - Minimize downtime and load sheds
  - Prioritize mission critical loads
- Develop control strategies to achieve *autonomy*
  - Reduce the need for operator intervention
  - Quickly react to unplanned outages & failures
- Increase *interoperability*
  - System agnostic controller
  - Enable power system growth over time
  - Introduce plug-n-play components



Autonomous Power Controller

Reconfiguration Management:
- Determine corrective actions after a fault
- Provide maintenance shutdown/startup services

Fault Management:
- Detect, isolate, and diagnose system faults
- Identify the fault type, location, and magnitude of the fault

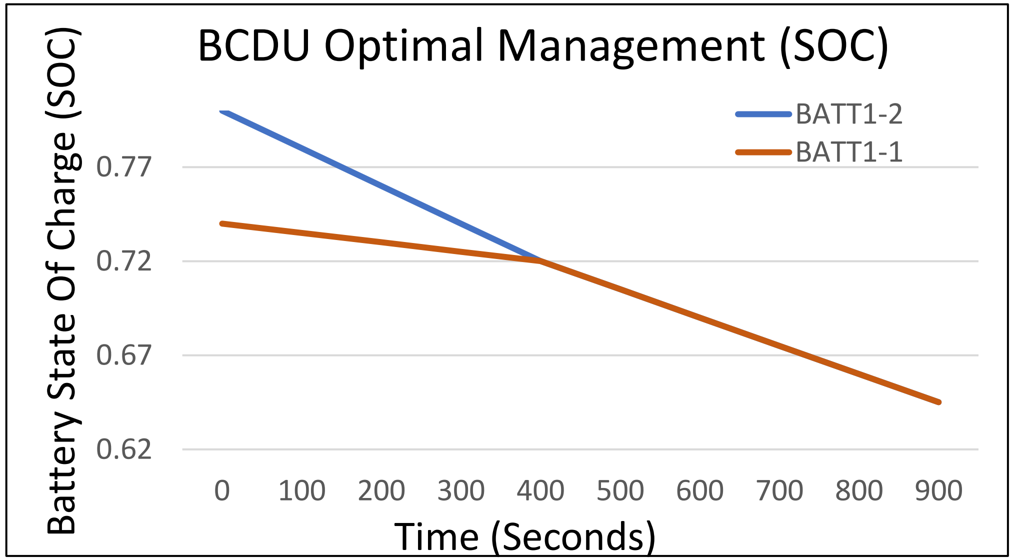


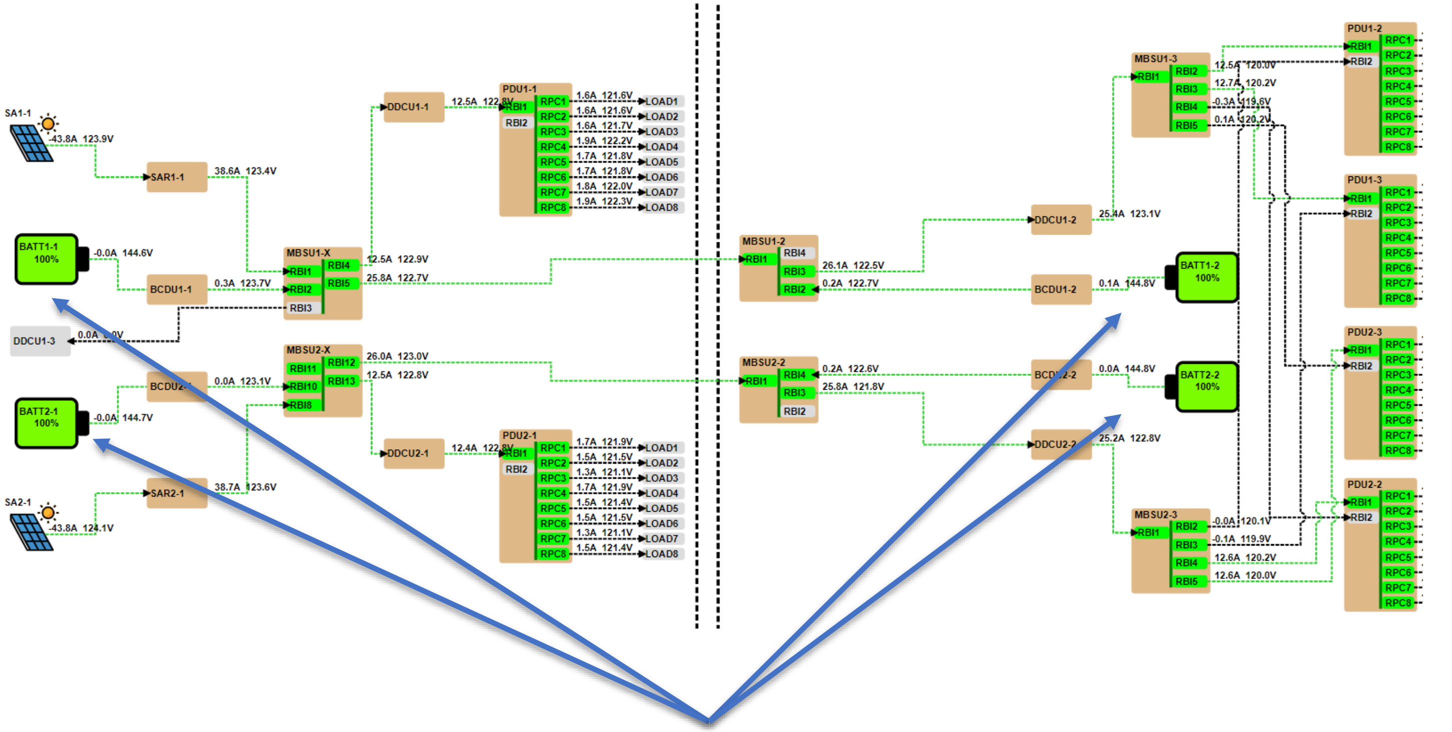
Autonomous Power Controller Functional Block Diagram

Energy Management:
- Manage distributed energy sources, loads and storage
- Maintain system stability
- Perform look-ahead analysis for power system planning

Energy Management: Distributed Energy Storage Control

- **Uniformly discharge the distributed batteries in the power system**
  - Maximizes peak power availability during eclipse.
- **Three-level control solution**
  1. Reactive layer controls (BCDU)
     - Droop control regulates bus voltage
  2. Secondary control (central APC)
     - Balances current between batteries
  3. Tertiary control (central APC)
     - Balances SoC between batteries





Distributed battery energy storage systems

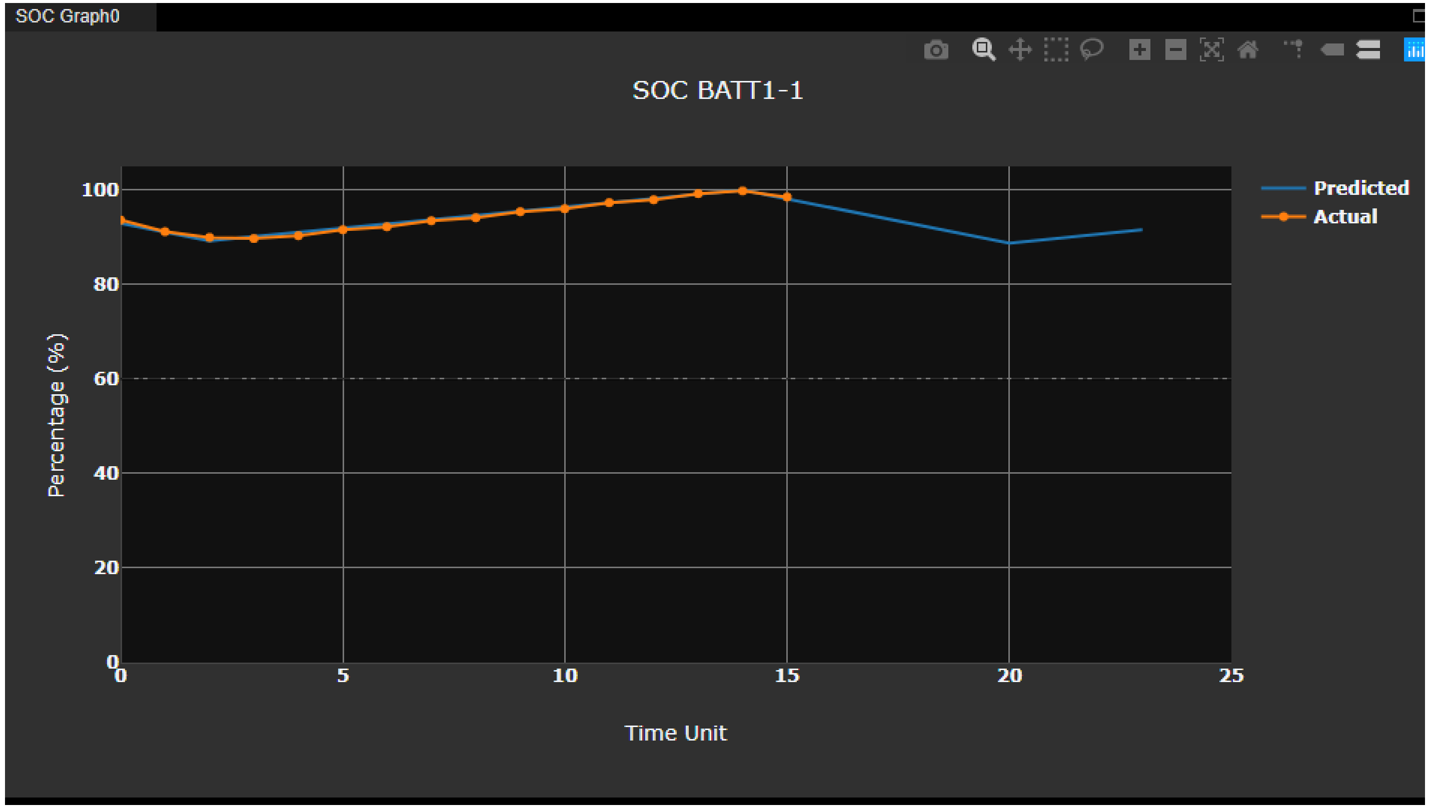
Zhang, Jing, Jeffrey T. Csank, and James F. Soeder. "Hierarchical control of distributed battery energy storage system in a DC microgrid." *2021 IEEE Fourth International Conference on DC Microgrids (ICDCM)*. IEEE, 2021.

Energy Management: Energy Planning and Forecasting

- **Use dynamic model of the EPS (load flow) to determine the max power that can be delivered to the loads during insolation and eclipse**
  - Constrains include device ratings, PV/battery capability, line losses, etc.

- **Perform load flow calculation for a given load schedule and check for violations**
  - E.g., battery depth-of-discharge, bus voltage, etc.

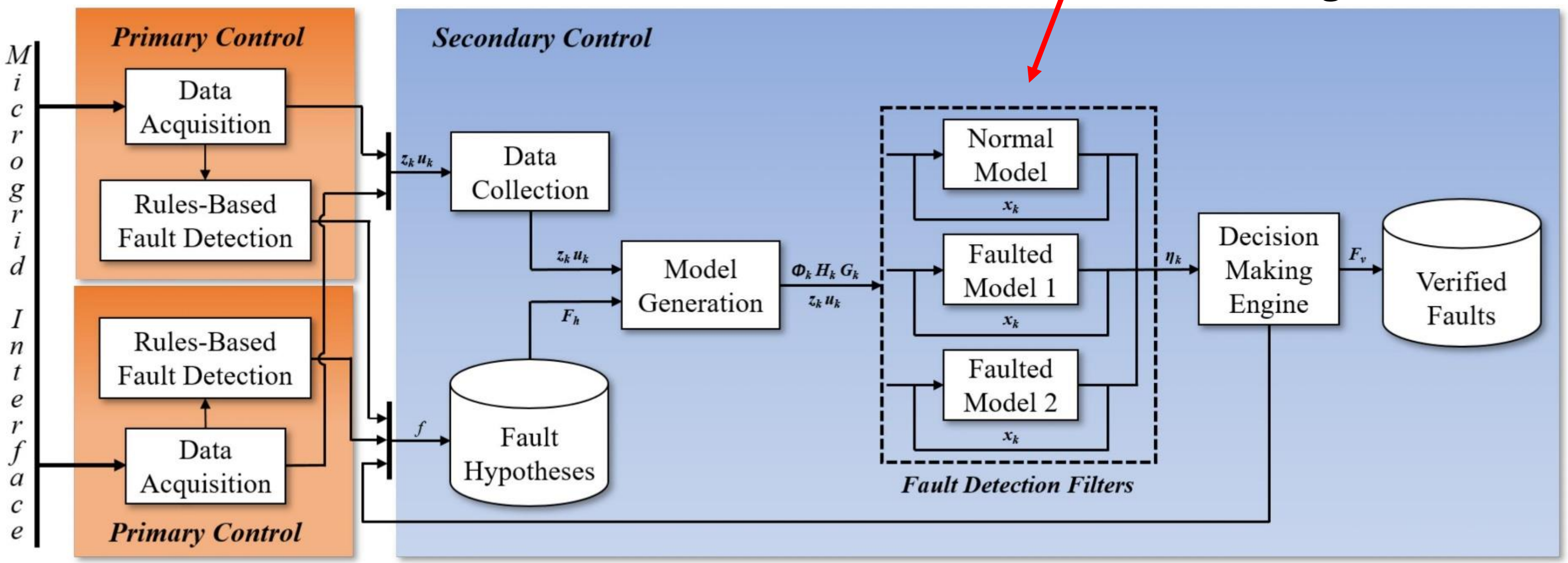
- **Implements load shedding based on available generation capability**
  - Sheds lowest priority loads when demand greater than available energy

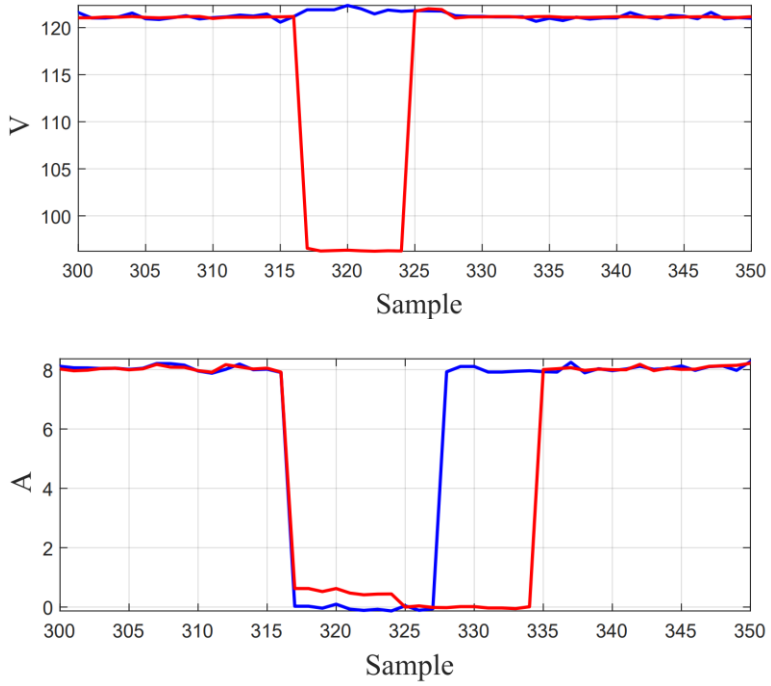


Predicted vs. measured State-Of-Charge of a battery over a rolling time horizon

Fault Management: Fault Detection and Diagnosis Using State Estimation

Bank of state estimators for fault diagnosis



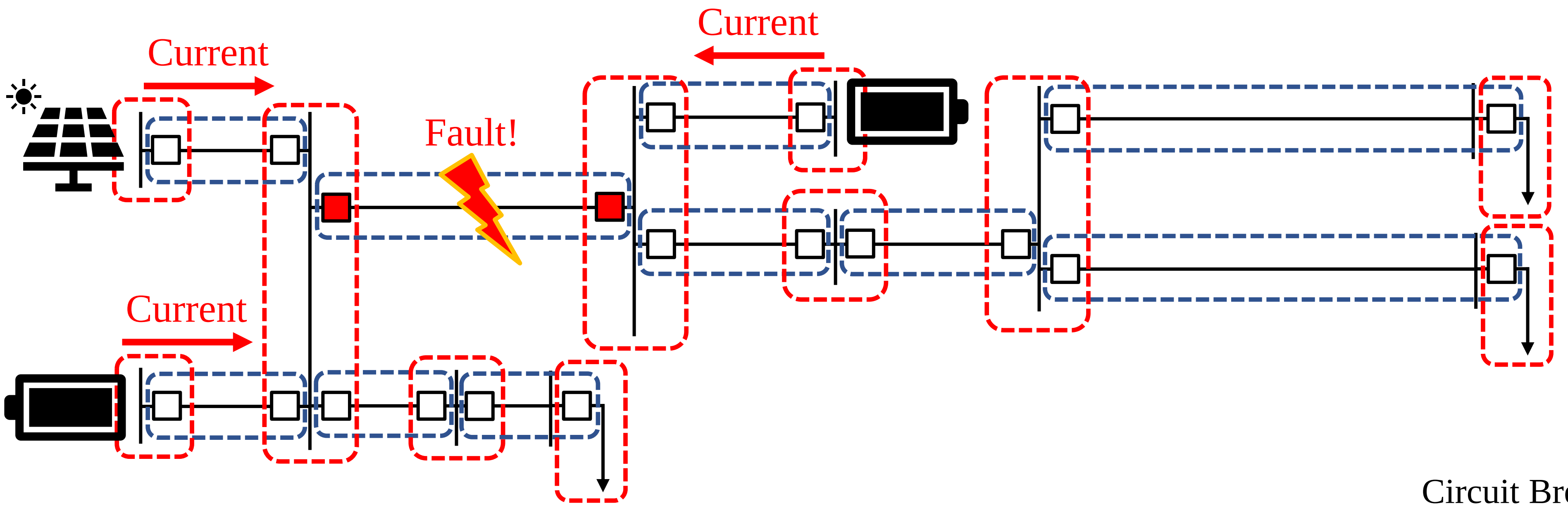


Measurements (red) and state estimates (blue) during a distribution switch failure

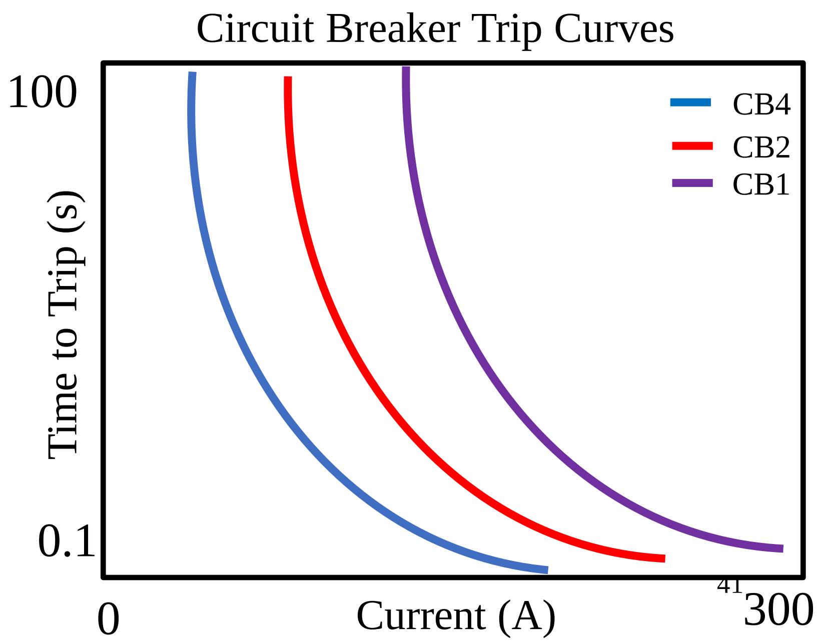
- **The APC Fault Manager service uses parallel state estimators to diagnose EPS faults**
  - Rules-based (limit checking) fault diagnosis occurs at the primary level
  - The secondary controller compares measured data to the models of the power system under varying conditions
  - The faulted model that matches the incoming data allows us to diagnose the fault

Carbone, M., and Loparo, K., “*Fault Detection and Diagnosis in Spacecraft Electrical Power Systems,” AIAA Journal of Aerospace Information Systems, 2023*

Fault Management: Coordinated Fault Protection

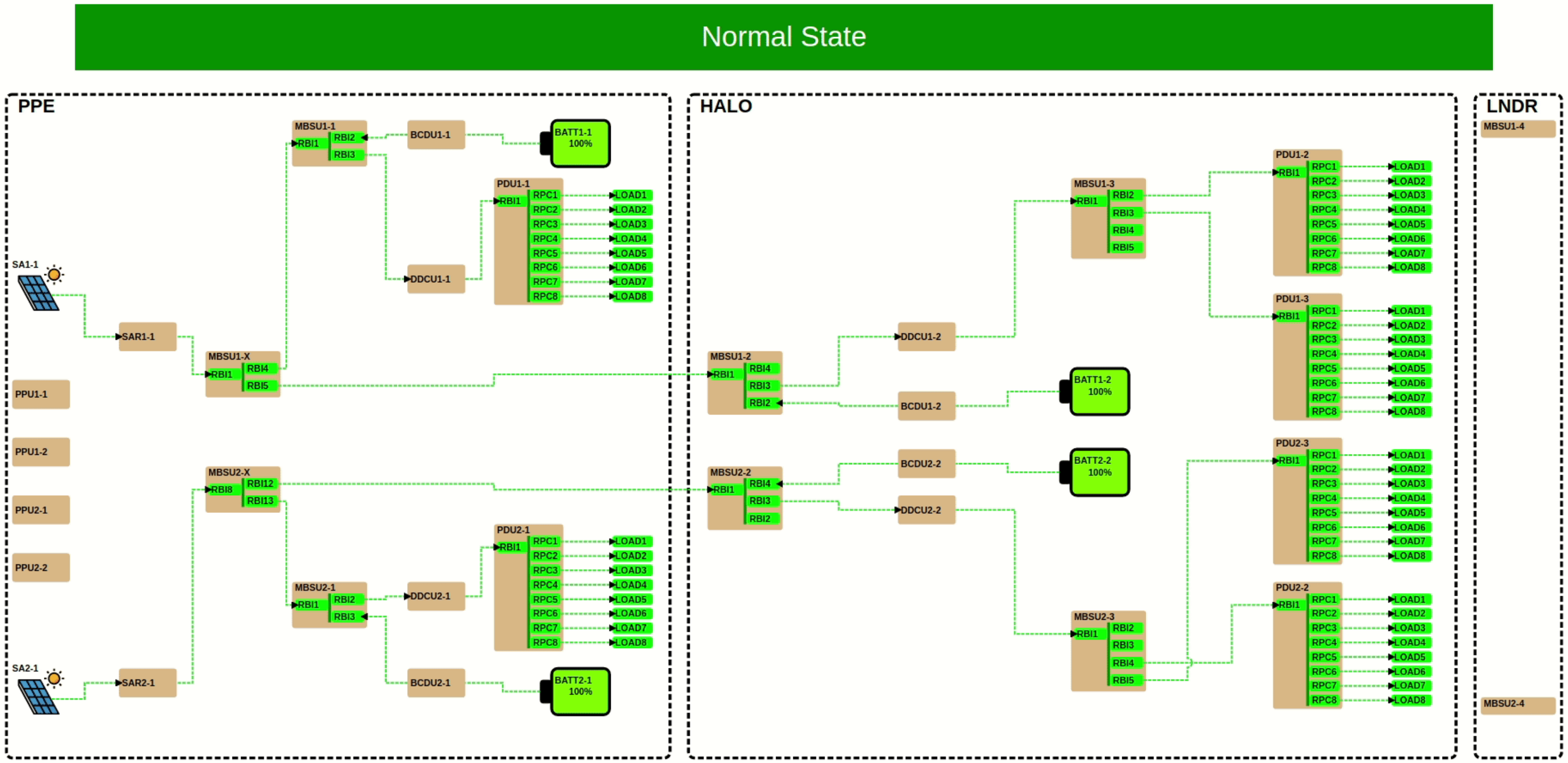


- **Prevent cascading failures due to improper protection settings and minimize power disruptions**
- **Achieve "zonal protection" to the EPS**
  - Nearest circuit breakers to the fault should trip to isolate fault and maximize available EPS components
- **Use an algorithmic approach to automatically assign trip-times and current limits for all circuit breakers**



Reconfiguration Management: Autonomous Network Reconfiguration

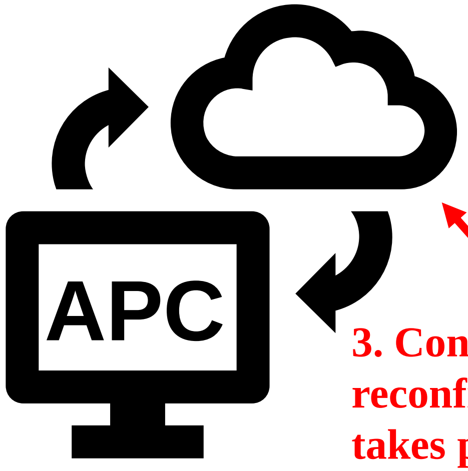
- **After a fault, the electrical network is determined based on a modified Dijkstra's shortest path algorithm**
  - Finds a near optimal topology based on the given fault information
  - Computes quickly (<100ms) to minimize load outages
  - The algorithm can also be used to re-configure the power system to allow for maintenance and repair of components



Power system simulation of a conceptual Phase I Gateway

Device Discovery

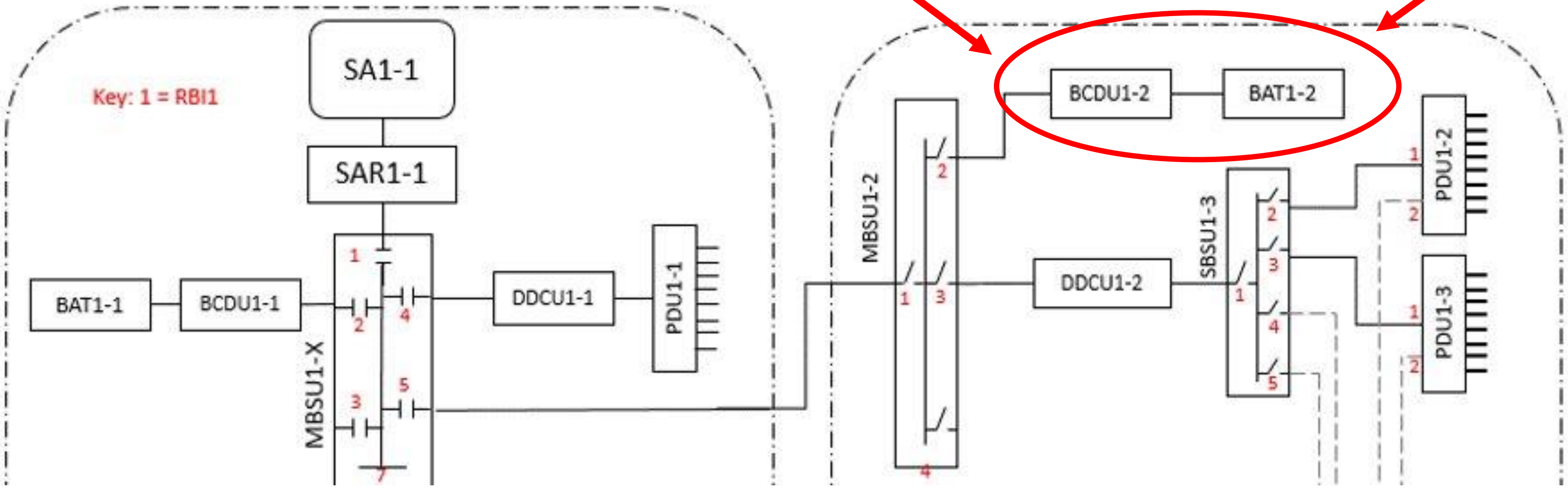
- **Add the ability to detect when a device is added to the EPS**
  - New components send messages with the necessary device information to the central controller
  - Controller automatically adapts to handle the new architecture
  - Allow EPS to grow and adapt over time
  - Handle unique scenarios such as docking events and visiting vehicles



1. New devices added to EPS

2. Communication established between device and APC

3. Controller reconfiguration takes place to account for the new components



Prognostics and Health Management Society 2025

- **Asked to host the Prognostics and Health Management Society 2025 (PHSM 2025) Data Challenge**
- **Data Challenge:**
  - Estimate the health of a spacecraft electrical power system (EPS). This is a classification problem focused on estimating the fault state of the EPS as well as a measure confidence of the algorithm’s predictions.
  - Teams will be provided:
    - Training dataset
    - Unlabeled testing dataset which will need to be classified based on the predicted health state of the system and used to improve their approach.
    - Validation set will be released in which teams will be released for a one-time assessment.
- **Data for this test is being generated using the integrated AMPS Modular Hardware and Autonomous Power Controller (APC).**

Autonomous Power Control Related Work

- **FY25**
  - Continue to advance power system fault management focused on handling anomalies (observing unknown indications/failures)
  - Incorporate/leverage Artificial Intelligence and Machine Learning into the fault management approach

- **FY26+**
  - Lunar surface power management and developing a lunar power grid controller

Any questions related to the Autonomous Power Controller?

Summary

- **NASA Glenn Research Center is committed to developing technologies/capabilities to advance lunar surface power and enabling Universal Power on the Lunar Surface.**
  - Lunar Power Grid
    - Provide continuous power on the lunar surface
  - Universal Modular Interface Converter
    - Long-distance power transmission and standard interface to a power grid
  - AMPS Modular Hardware
    - Common modular power standard
  - Autonomous Power Controller
    - Power system management for elements and the lunar surface

Thank you!
Any questions?

Modular Power Approach for Commonality

- **Promotes power system commonality across vehicles, elements, and/or modules**
  - Provides a compatible set of common electronics modules (i.e. circuit boards or cards) that, when combined with a chassis and backplane, can be built up into a variety of modular electronic units (MEUs)
    - MEUs are the equivalent of International Space Station (ISS) Orbital Replacement Units (ORUs)
  - Provides NASA the ability to implement a common integrated power architecture across Exploration system, thus simplifying the integration and verification testing of the power system

- **Reduces the cost of hardware development and testing**
  - Once the Electronic Modules (i.e. circuit boards) are developed, they can be reused to develop multiple Modular Electronic Units (MEUs) within a single vehicle, or across vehicles, elements, or modules.
    - Reduction in non-recurring engineering costs as the electronics modules can be utilized for multiple modular electronic units (MEUs)
    - Reduction in build costs as a result of standardized interfaces between the electronics modules and the modular electronics units (MEU’s)

Modular Power Approach for Commonality

- **Improves sparing and logistics up-mass impacts by making components interchangeable**
  - Power distribution and power converter electronic modules would be common across all future exploration vehicles or systems, thus reducing number of unique types of spares and the up-mass needed
    - Individual spare power modules can be shared between docked systems
    - Reduces storage volume needed for on-orbit power module spares
  - Sparing would be done at the electronic module level vs. the ISS-like ORU level
    - For example, if a single RPC switch fails:
      - ISS-like RPCM Switch Spare Mass: 4.7 kg
      - AMPS Approach Switchgear Module Spare Mass: 0.5 kg

- **Provides a common vendor(s) that can be certified for long term supply of electronics modules and their supporting components (FETs, Drivers etc.)**
  - Reliable source of spares for multiple program customers
  - Support new builds for follow-on new vehicles (i.e. Lunar Surface Habitat, Mars Transit Habitat)