NASA Lunar Surface Power Approach

National Aeronautics and Space Administration

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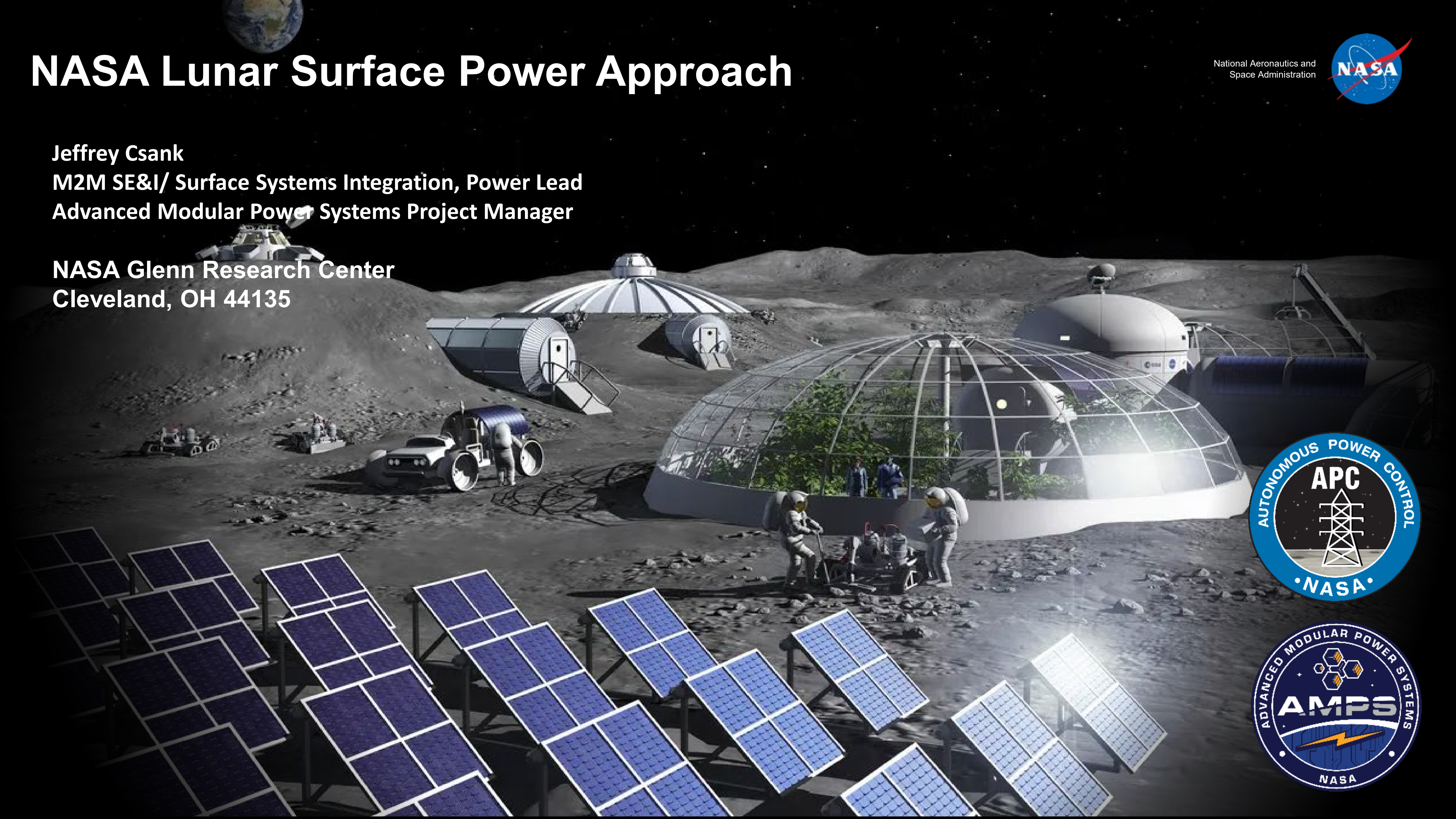


Moon to Mars (M2M) Objectives

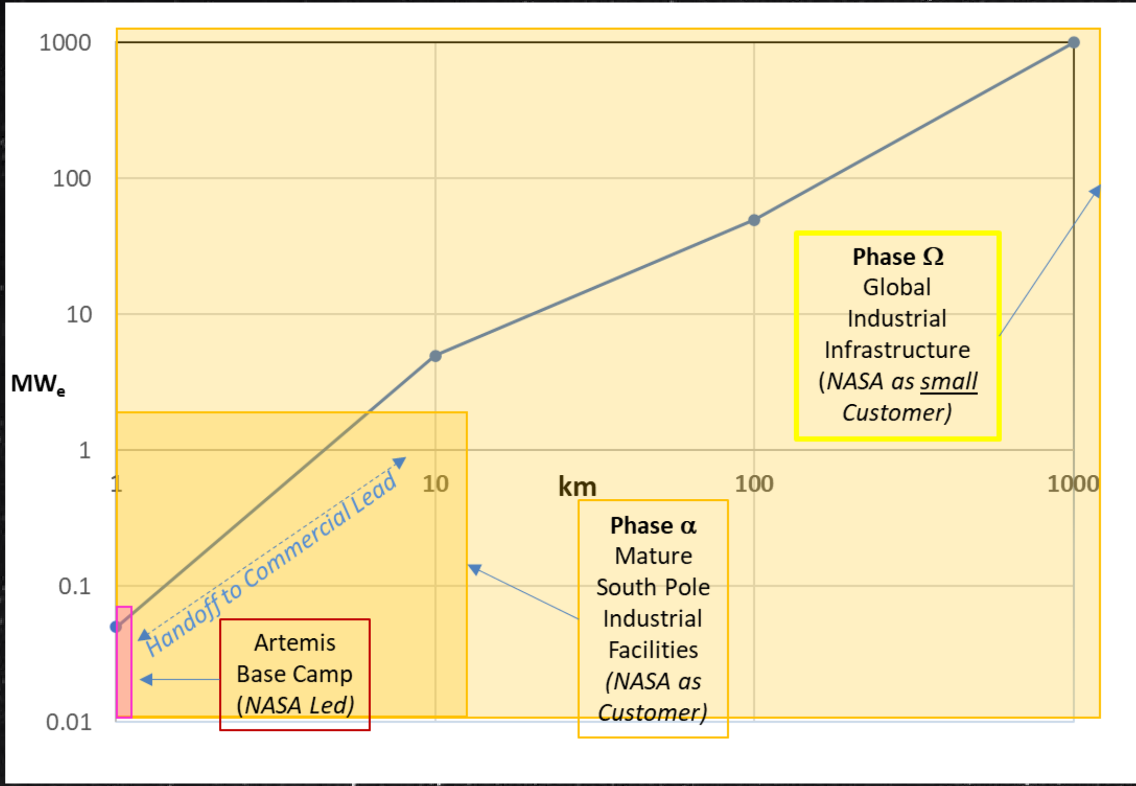
Lunar Infrastructure (LI) Goal: Create an interoperable global lunar utilization infrastructure where U.S. industry and international partners can maintain continuous robotic and human presence on the lunar surface for a robust lunar economy without NASA as the sole user, while accomplishing science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

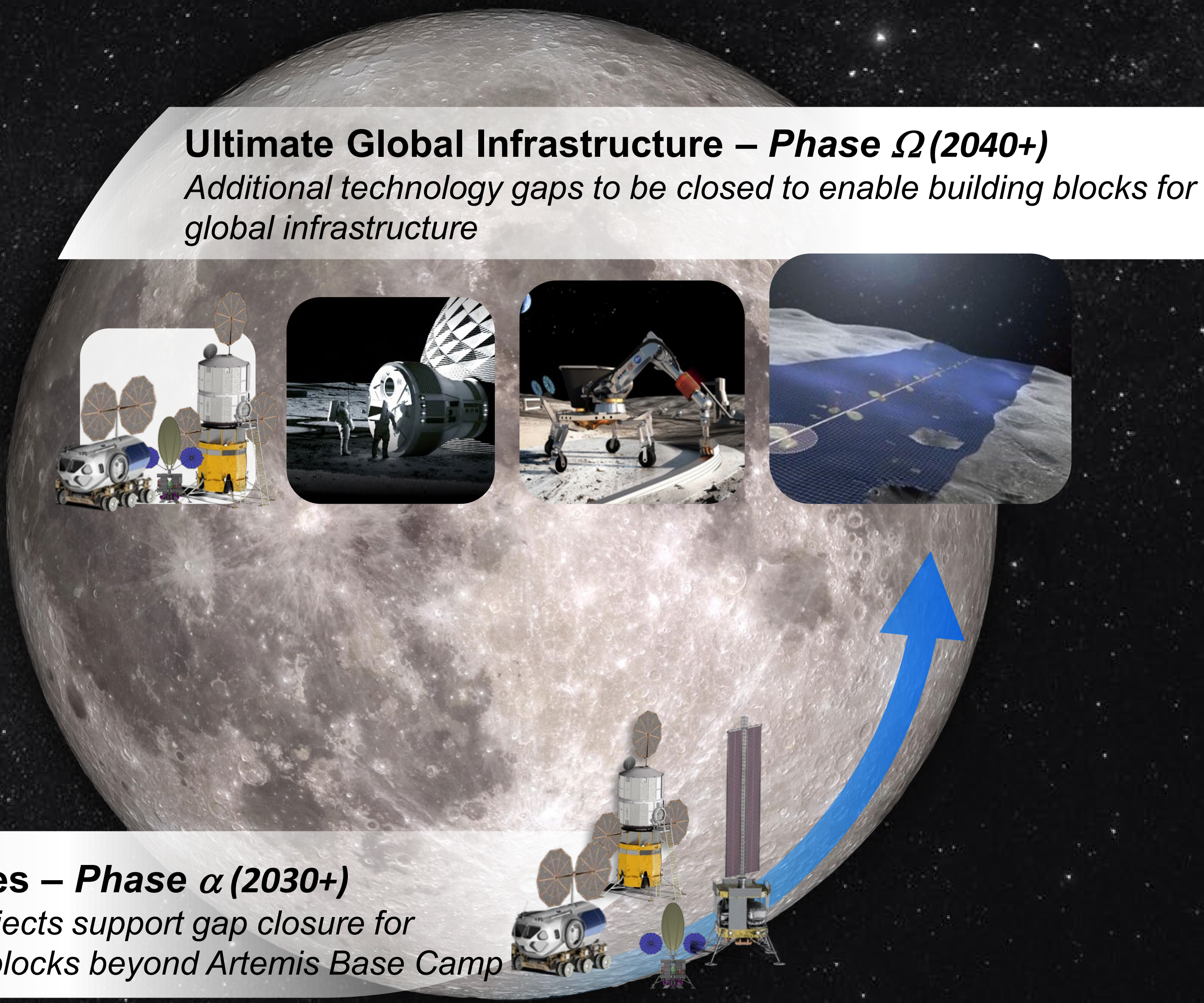
- **LI-1L:** Develop an incremental lunar power generation and distribution system that is evolvable to support continuous robotic/human operation and is capable of scaling to global power utilization and industrial power levels.

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.

Envisioned Growth of Lunar Presence





Ultimate Global Infrastructure – *Phase Ω (2040+)*

Additional technology gaps to be closed to enable building blocks for global infrastructure

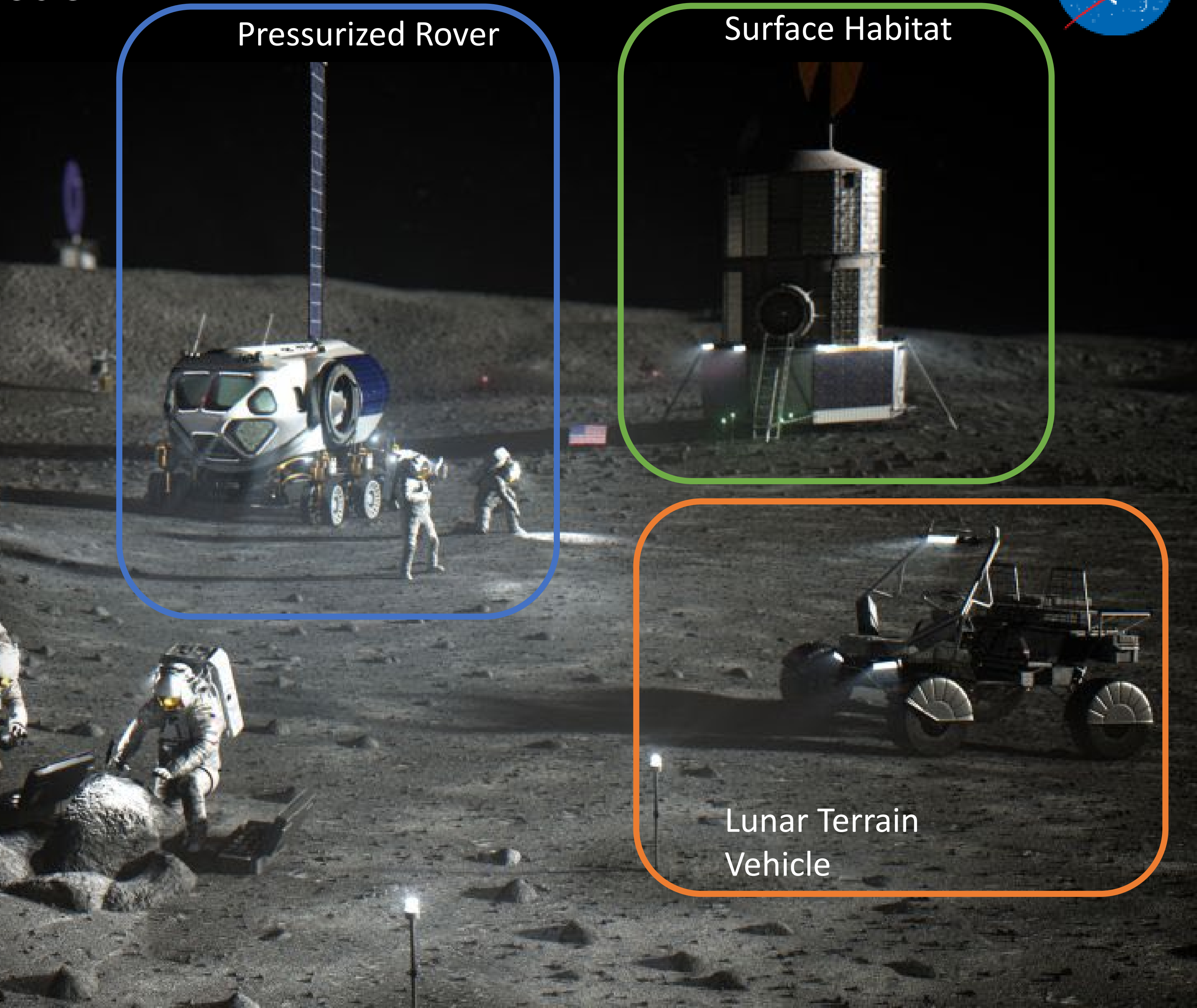
Mature South Pole Industrial Facilities – *Phase α (2030+)*

Current and high priority new technology projects support gap closure for industrial-scale Polar infrastructure building blocks beyond Artemis Base Camp

Chart provided JSC/John Scott
STMD Principal Technologist for Power And Energy Conversion

NASA M2M 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)
  - Control and operational challenges associated with integration of multi-source hardware
- **Prioritizes cost to flight vs long-term and on-board mass vs total mass (on-board + sparing)**



NASA M2M Space Power Approach

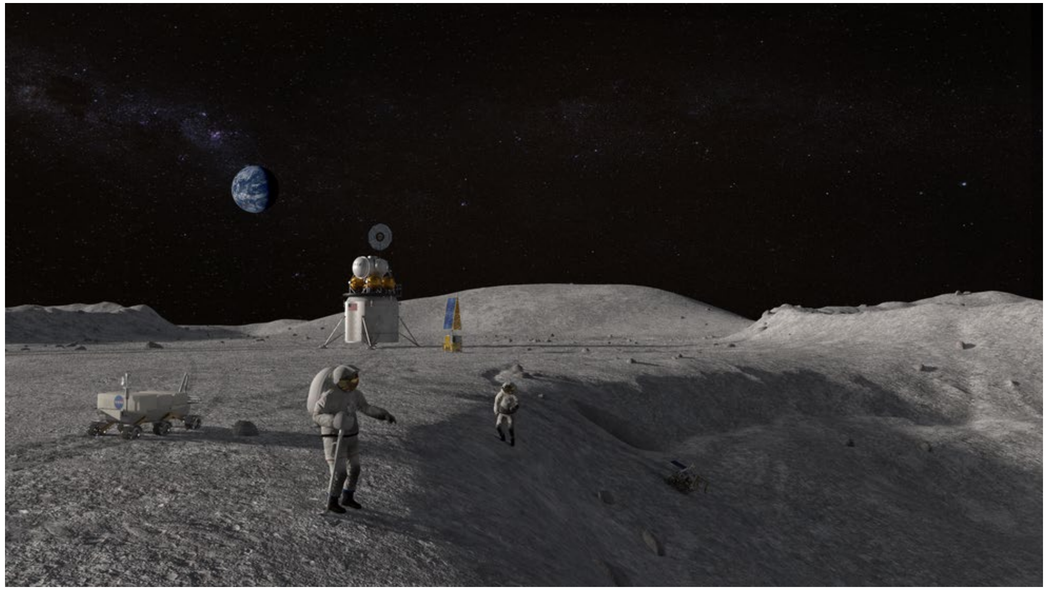
- **Lunar/Martian surface operations will grow and expand**
  - Power demands will exceed elements capability
  - Systems have to be integrated together (share power or share access to centralized system)
  - May require reconfiguring the overall power system

- **Lunar and Martian surface operations will require autonomous operation**
  - Allow system to be operational before Astronauts arrive
  - Continue operations when uncrewed
  - Must be able to react to unplanned disturbances and faults

M2M (Lunar and Martian) Surface Power Needs

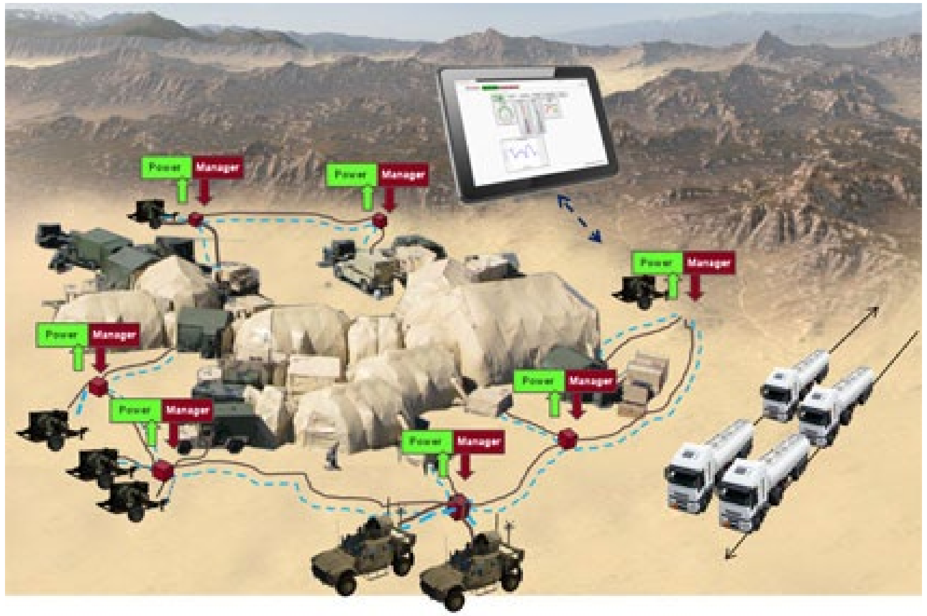
- **Flexible mission-driven power architectures**
  - Adaptable / scalable to meet mission needs
  - Autonomous
    - Bring to operation without human intervention
  - Modular {Common} components
  - Provide highly reliable power
    - Flexible power strategy / integrate "any source"
      - Convenience and availability
  - Mixed power types
    - DC space sources and loads
    - AC to distribute power longer distances

- **Government developed open standard**
  - Interoperability across vendors / elements
    - With or without commonality

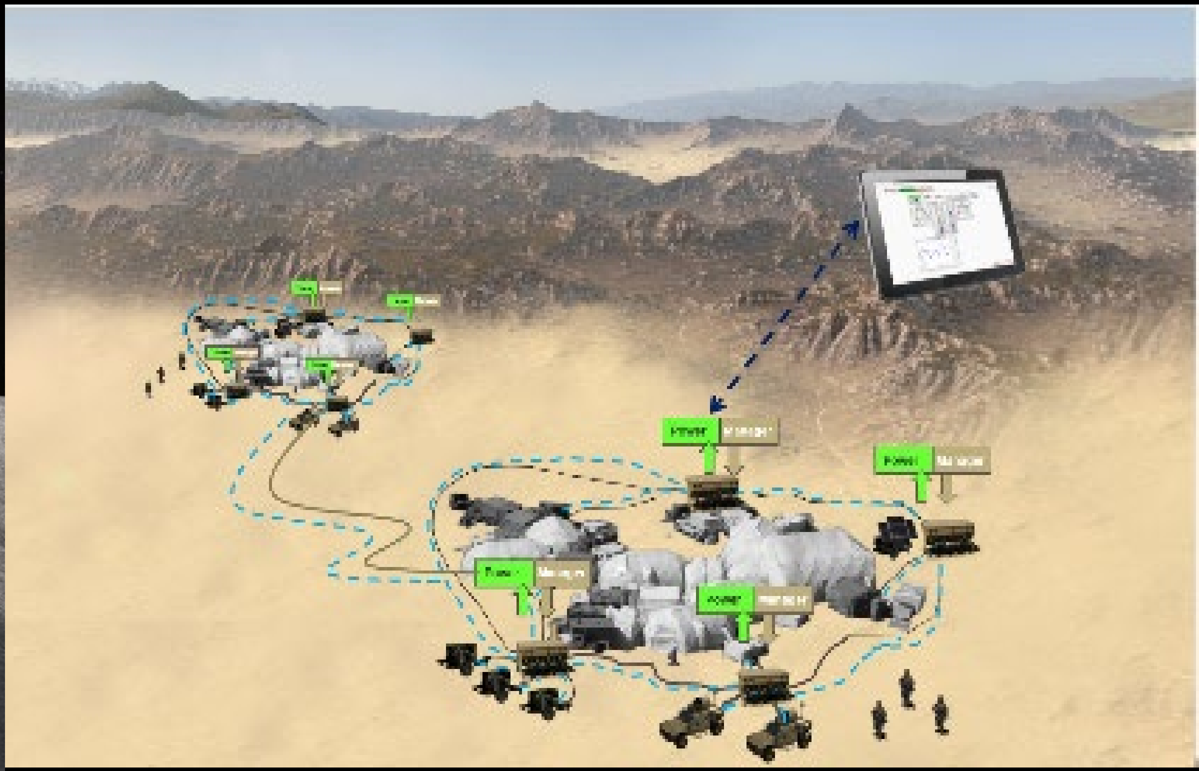


Universal Power for Space Power Systems

- **Ability to seamlessly integrate dissimilar power sources (generation & storage) into electrical power system and utilize as needed to maximize availability**
  - Use available sources for power generation, such as solar, fission surface power, etc.
    - Enhance reliability and availability of electrical power
  - Systematical integration of new sources and loads as activities evolve
    - Ideally with no or limited human intervention
  - Common grid interface for sources/loads to facilitate growth and interchangeability



Collaboration Opportunity: Universal Power



"In the future fight, soldiers engaged in battle will likely be cut off from outside resources and support. They might as well be on the moon."

-Tom Bozada on the similarities of Army and NASA interest in future power needs

NASA / US Army Collaboration

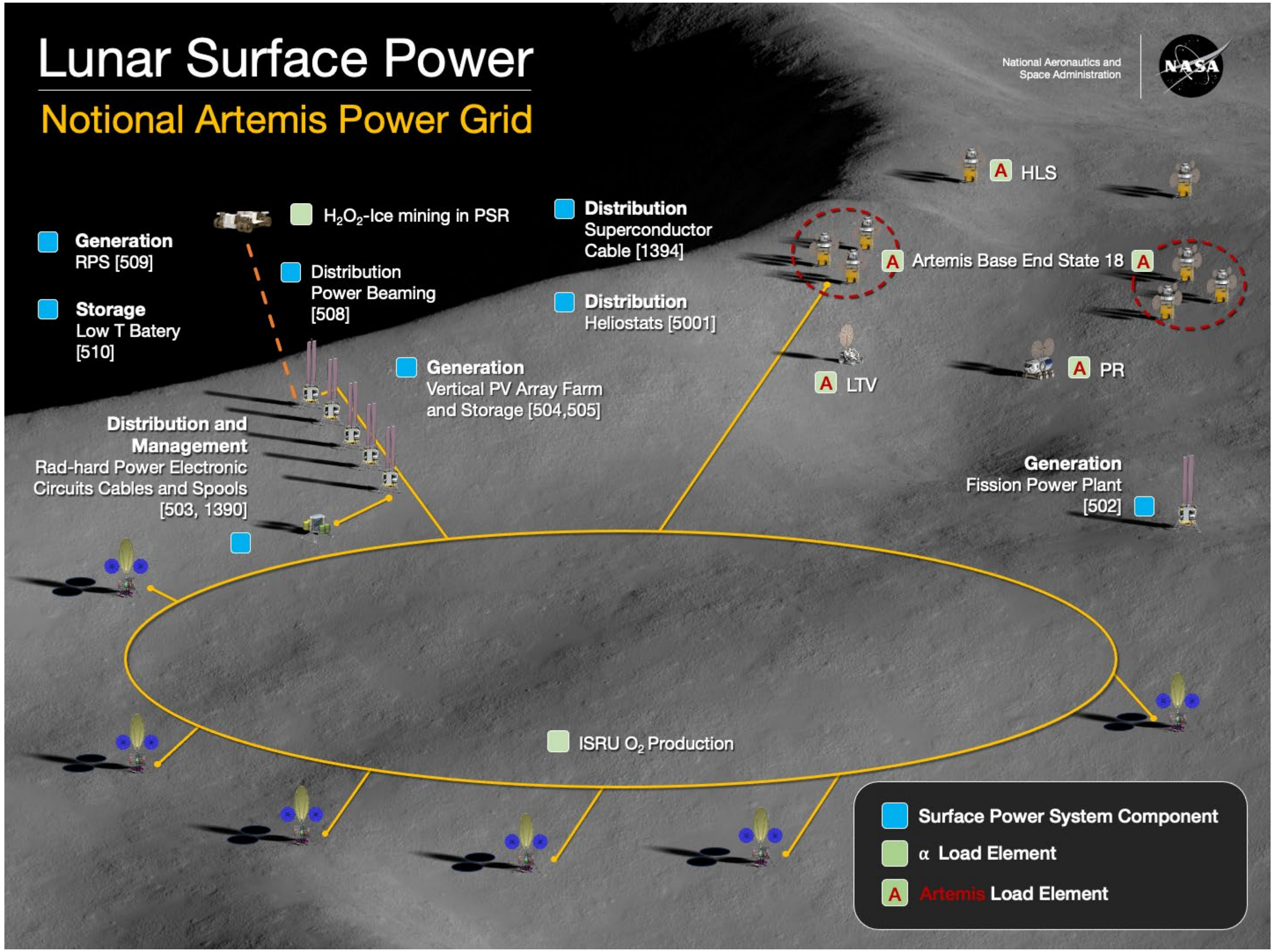
- **Integrate the Tactical Microgrid Standard (TMS) within AMPS – FY23**
  - Update modular electronic units to comply with the TMS standard
  - Update the autonomous power controller to comply with the TMS standard
  - Provide feedback on TMS and identify missing capabilities needed for TMS to applied to space based power systems (Feed into TMS Space Addendum)

- **Demonstrate an autonomous Plug and Play (PnP) Capability – FY24/25**
  - Allow for power system configuration to be updated as new components/elements are connected to the EPS
  - Update energy management (power forecast) and fault management algorithms to automatically update to the current configuration
  - Advance power system security (interoperability) for PnP systems

Back Up

Lunar Power Grid

- **Benefits of a lunar microgrid**
  - Optimal dispatch of power sources / energy storage to service loads
    - Dissimilar source and storage methodologies to enhance reliability and availability
  - Systematic integration of new sources and loads as lunar surface activities evolve
  - Adoption of 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



Modular Power Approach for Commonality

- **Promotes power system commonality across vehicles, elements, and/or modules**
  - Allows 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**
  - 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)
- **Improves sparing and logistics up-mass impacts by making components interchangeable**
  - Individual spare power modules can be shared between docked systems
  - Reduces storage volume needed for on-orbit power module spares
- **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)

Universal Battlefield Power (UBP)

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28 September 2023

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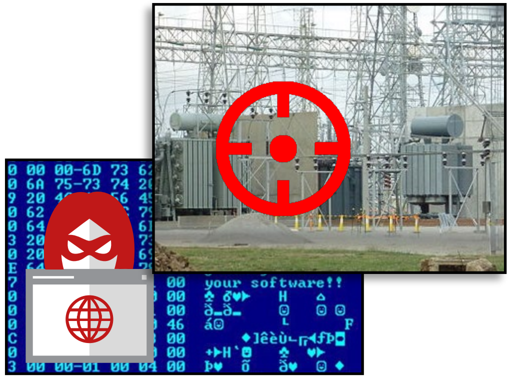
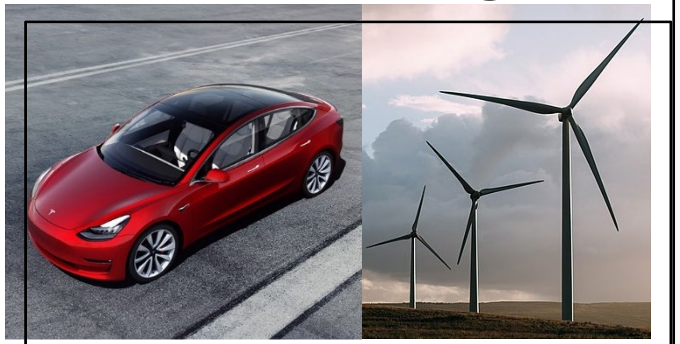
The Need for New Power System Architectures

Disasters

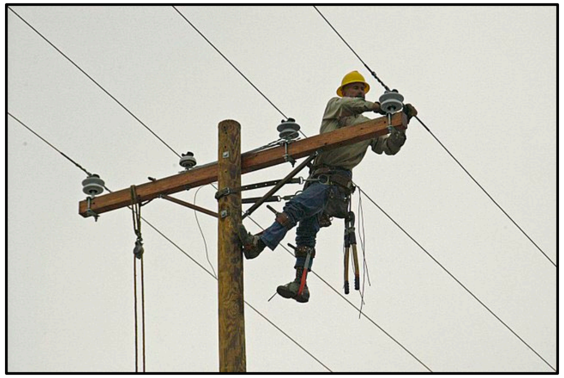
Attacks



New Technologies



Better Integration



Simple

Efficient

Resilient

Modular

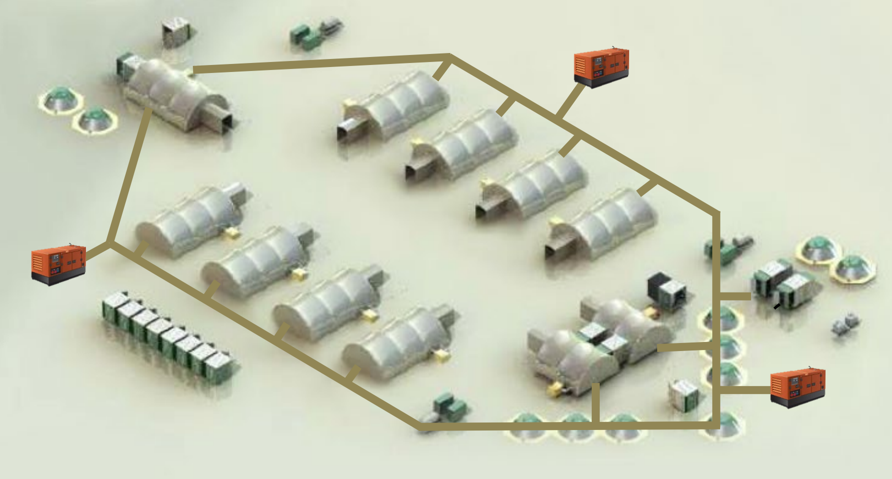
Scalable

Extensible

Open Architecture

DoD Tactical Power Context

Example Forward Operating Base



- Source
- Distribution
- Load

- Self-sufficient power
- Warfighter owned and operated
- Thousands of sites
- Each site unique

Supporting Missions


Communications


Sensors

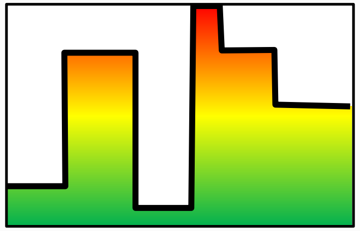

Weapons


Climate Control

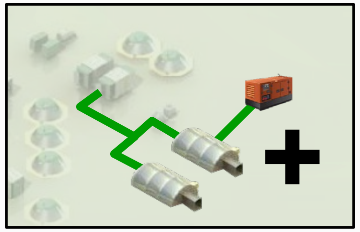
Operational Challenges


Rapid Deployment


Operator Training


Dynamic Loads


Equipment Failures


Organic Growth


Insert New Tech

Universal Battlefield Power: Breaking Traditional Stovepipes

Operational Energy

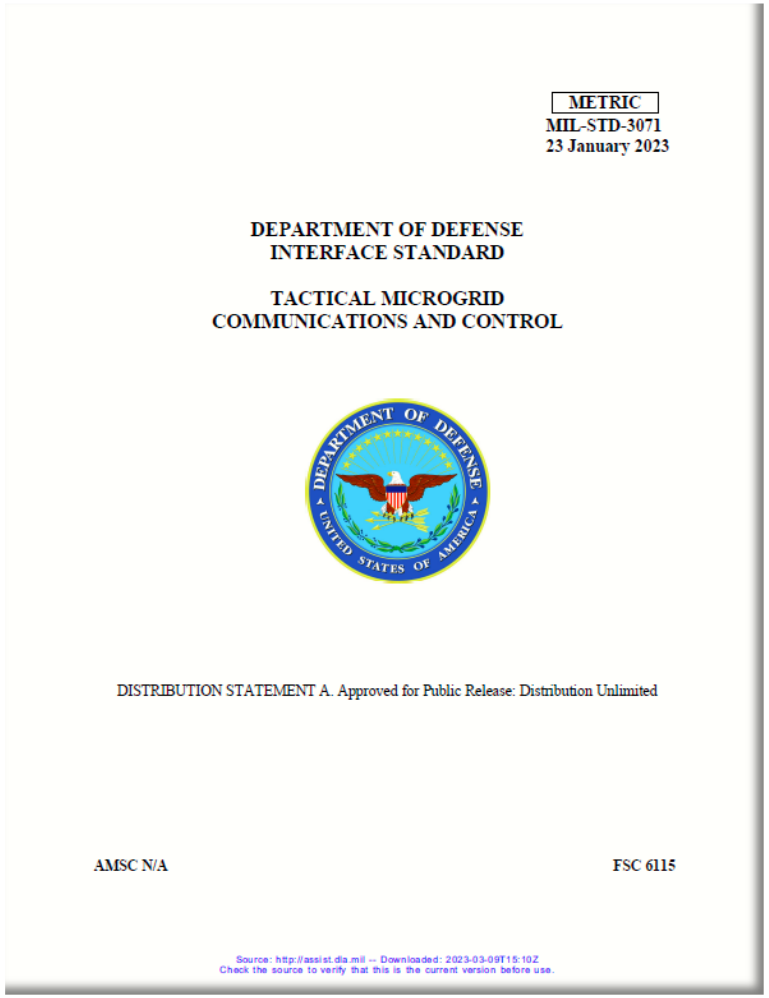
Installation Energy

UNCLASSIFIED

Universal Battlefield Power Endstate

Seamless power from the installation to the forward edge

Game Changing Advancement in Power Device Interoperability


METRIC
MIL-STD-3071
23 January 2023

DEPARTMENT OF DEFENSE
INTERFACE STANDARD

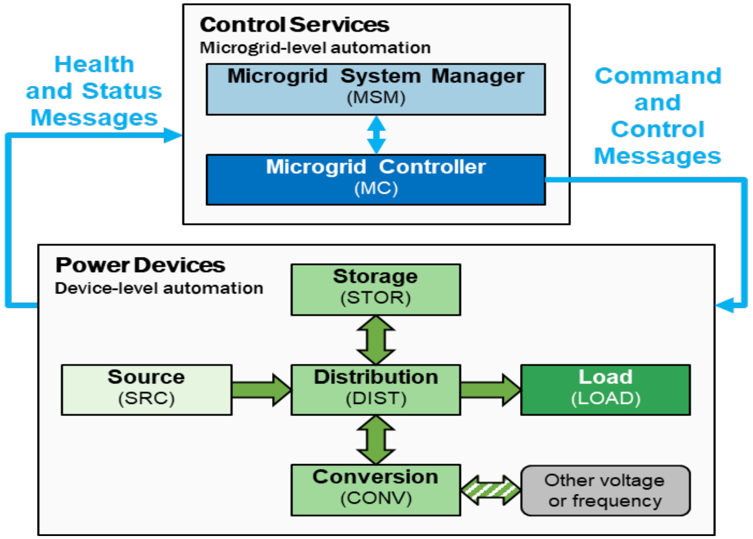
TACTICAL MICROGRID
COMMUNICATIONS AND CONTROL

DISTRIBUTION STATEMENT A. Approved for Public Release: Distribution Unlimited

AMSC N/A FSC 6115

- Draft "Tactical Microgrid Standard (TMS)" developed by CERL led, OECIF funded Tactical Microgrid Standards Consortium
- Transitioned to the Lead Standardization Agency, PM E2S2 (supported by C5ISR)
- Formally approved the document 23 January 2023 as MIL-STD 3071, DoD Interface Standard; Tactical Microgrid Communications and Control
- Approved document is 411 pages

Tactical Microgrid Standard



- New MIL-STD 3071, DoD Interface Standard, Tactical Microgrid Communications and Control approved on 23 January 2023
- Government developed and owned open standard
- Modular open systems approach (MOSA) to microgrid development
- Publish – Subscribe Architecture
- Supports AC & DC applications
- Developing support for electric vehicles

- Allows for formation of ad hoc microgrid using configured to mission requirements
- Provides scalable, modular, and highly resilient power
- Medium and user voltage applications
- Enables interoperability across vendors
- Most power components such as generators can be made TMS capable

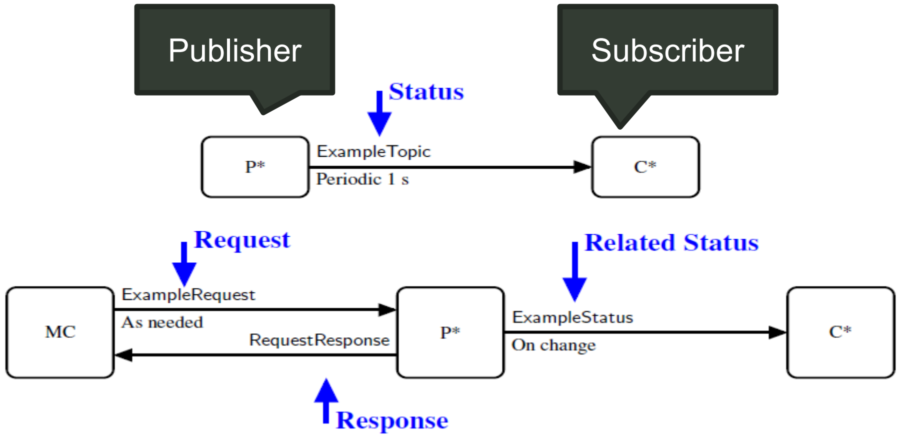
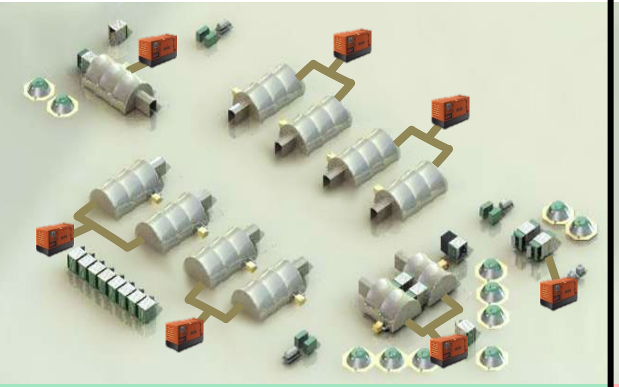
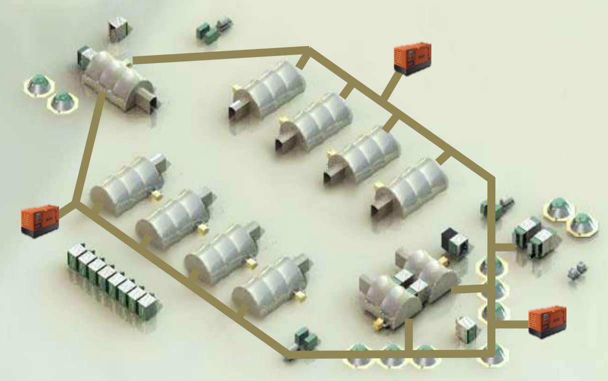


Figure 2.9: Common Data Flow Patterns

Tactical Microgrid Architecture Options

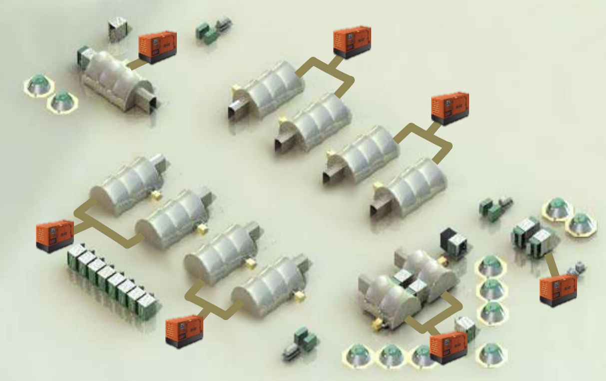
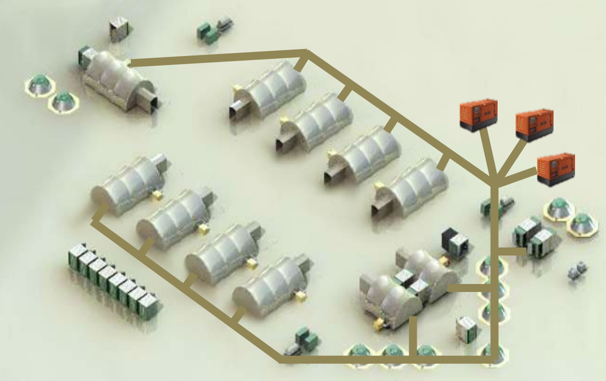
Before TMS

Spot Generation	Consolidated Generation	Central Microgrid	Distributed Microgrid
			
• Simple setup	• Complex setup	• Simple setup	❑ Very complex setup
• Inefficient	• Efficient	• Efficient	• Efficient
• Fragile generation	• Fragile generation	• Backup generation	❑ Spread out generation
• Minimal distribution	• Fragile distribution	• Fragile distribution	• Resilient distribution
• Extensible, modular	• Extensible, modular	❑ Proprietary vendor lock	❑ Proprietary vendor lock

Typical DoD Approach	Limited Use	Initial Deployment	Prototyping Today

Tactical Microgrid Architecture Options

With TMS

Spot Generation	Consolidated Generation	Central Microgrid	Distributed Microgrid
			
• Simple setup	• Complex setup	• Simple setup	✓ Simple Setup
• Inefficient	• Efficient	• Efficient	• Efficient
• Fragile generation	• Fragile generation	• Backup generation	✓ Resilient generation
• Minimal distribution	• Fragile distribution	• Fragile distribution	• Resilient distribution
• Extensible, modular	• Extensible, modular	✓ Open Architecture	✓ Open Architecture
Typical DoD Approach	Limited Use	Initial Deployment	Prototyping Today

STAMP Operational Challenge

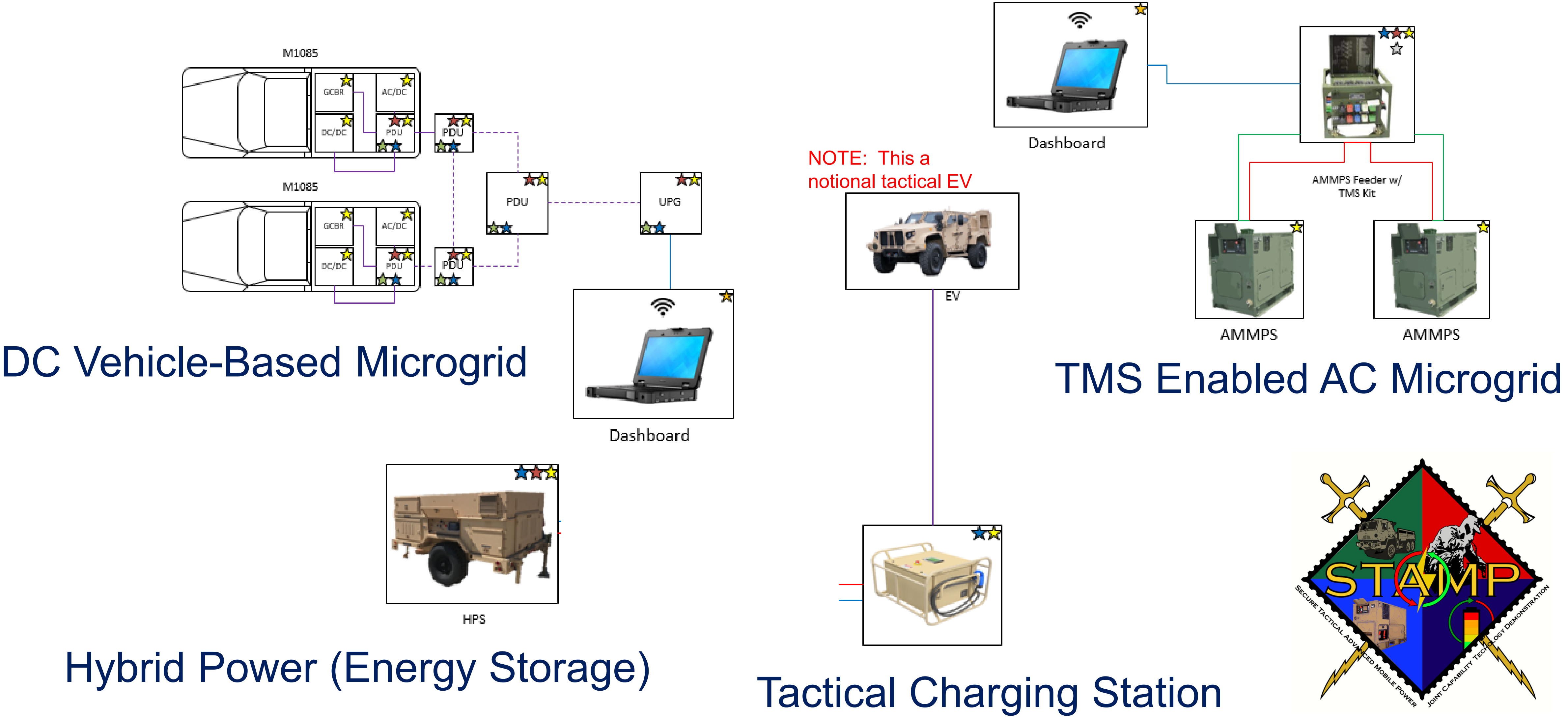
- **The Challenge:** Legacy tactical power systems decrease combat system availability, create a vulnerable static posture, lack energy storage, lack consumption awareness, and impose unsustainable logistical requirements.

- **The Opportunity:** The integration of power generation, distribution, battery storage, metering, control systems, and on-board vehicle power from mobile tactical platforms into an AC/DC microgrid will enhance resiliency, mobility, and flexibility of tactical units to execute distributed cross domain maneuvers in multi-domain operations.

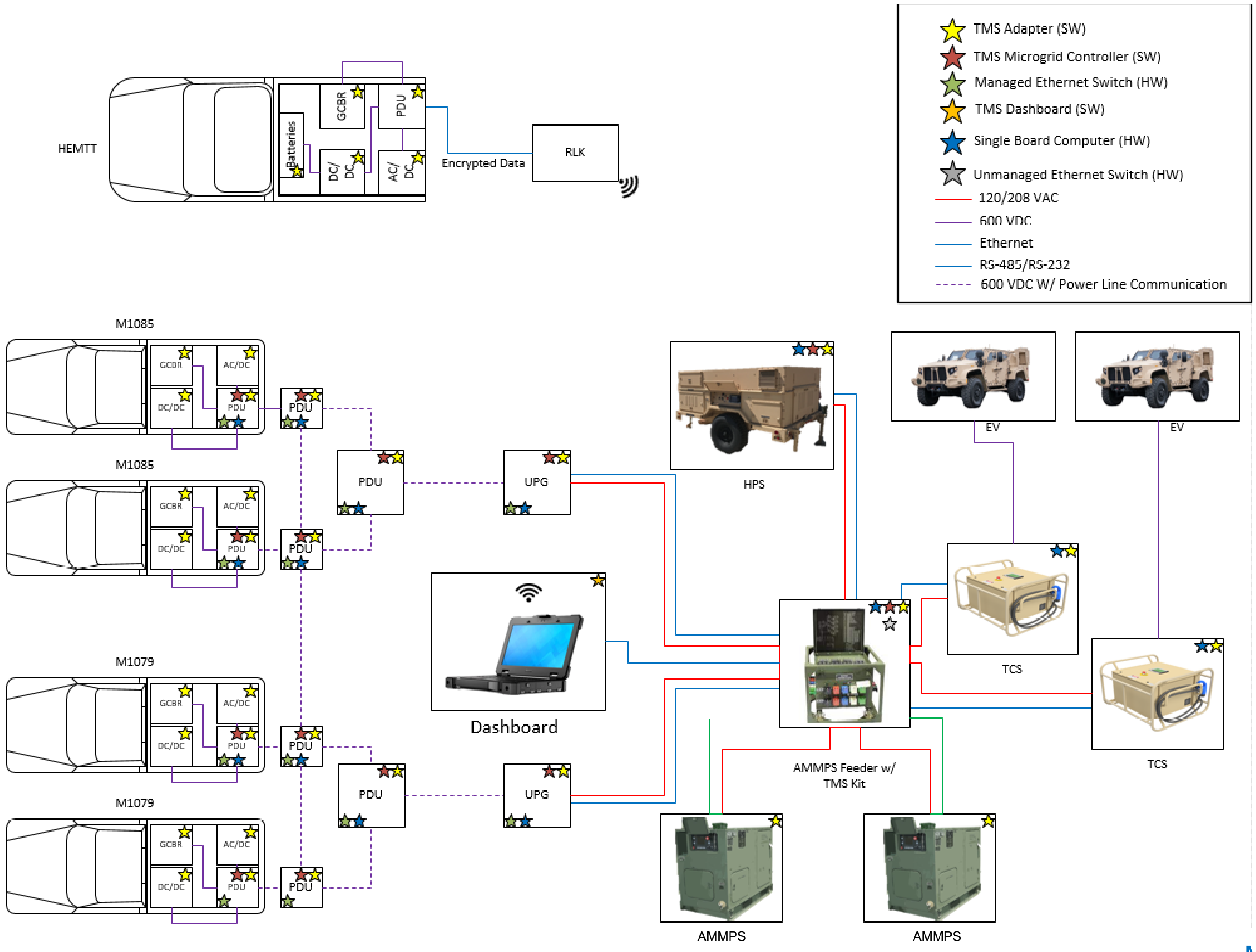
- **Operational Benefit: Create More Combat Lethality While Reducing Logistical Requirements**
  - Less fuel
  - Fewer generators
  - Reduces footprint
  - Reduces maintenance
  - Fewer spares
  - Lowers operating cost
  - Extends Reach
  - Reduces combat support
  - Increases mobility
  - Enables joint force maneuvers
  - Tactical power goes from static to mobile
  - More operational availability
  - Enables silent operations
  - Reduces vulnerability
  - Paves the way for EV and UV charging
  - Provides awareness of fuel usage

Universal Battlefield Power Solution for Next Generation Distributed Operations

STAMP Building Blocks



STAMP Grid Overview



STAMP Grids

- Grid 1: AMMPS Microgrid
- Grid 2: Hybrid AC Microgrid*
- Grid 3: DC Vehicle Microgrid*
- Grid 4: AMMPS AC with TCS
- Grid 5: Hybrid AC with TCS
- Grid 6: Hybrid AC with DC Export
- Grid 7: STAMP AC/DC Microgrid
- Grid 8: Four-Vehicle STAMP AC/DC Microgrid

* Demonstrated at the STAMP Operational Demonstration, McGregor Range, New Mexico, 21 August – 1 September 2023

STAMP Operational Demonstration

28 August – 31 August 2023

McGregor Range, New Mexico   *Soldiers from the 11th Air Defense Artillery Brigade*

Detroit Arsenal – TMOA Microgrid Deployment

Goal: Demonstrate TMOA Microgrid

Currently: Microgrids are proprietary

Idea: An Open Microgrid would not be locked into a single vendor and would allow for interoperability between power upgrade projects and across vendors

Will Benefit: Vendors of microgrid controllers that utilize the MIL-STD-3017 aka the TMS, Army DPW's, taxpayers

Risks:

Mixing old and new equipment is unpredictable

"How to contract" is a moving target

Eye to the Future

All Sources of Power

- Host Nation Power
- Medium voltage tactical power
- Transmission and Distribution
- Renewable and Alternative power (Hydrogen, Hydro, etc)
- Tactical nuclear power

SMART and High Energy Loads

- Improved grid management
- “Extreme Loads”

Autonomous Platforms

- Autonomous mobile power
- Autonomous recharging

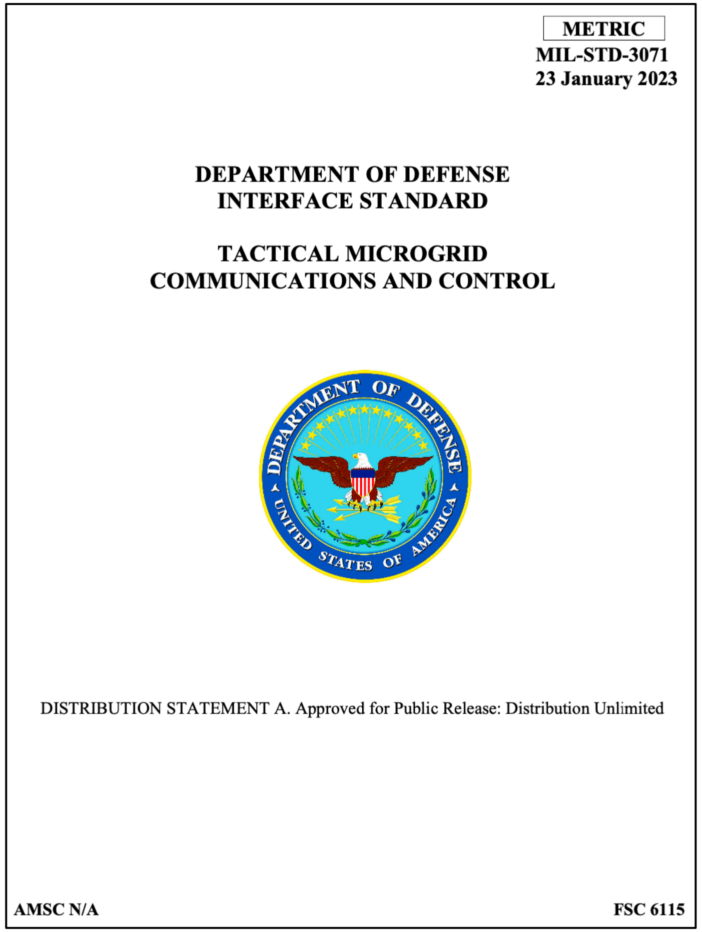
Artificial Intelligence and Machine Learning

- Provides advanced controls and protections
- Increased use of non-standard equipment
- Improved and safer management of tactical grids
- Improved resiliency

MIL-STD-3071

Tactical Microgrid Communications and Controls

Published 2023



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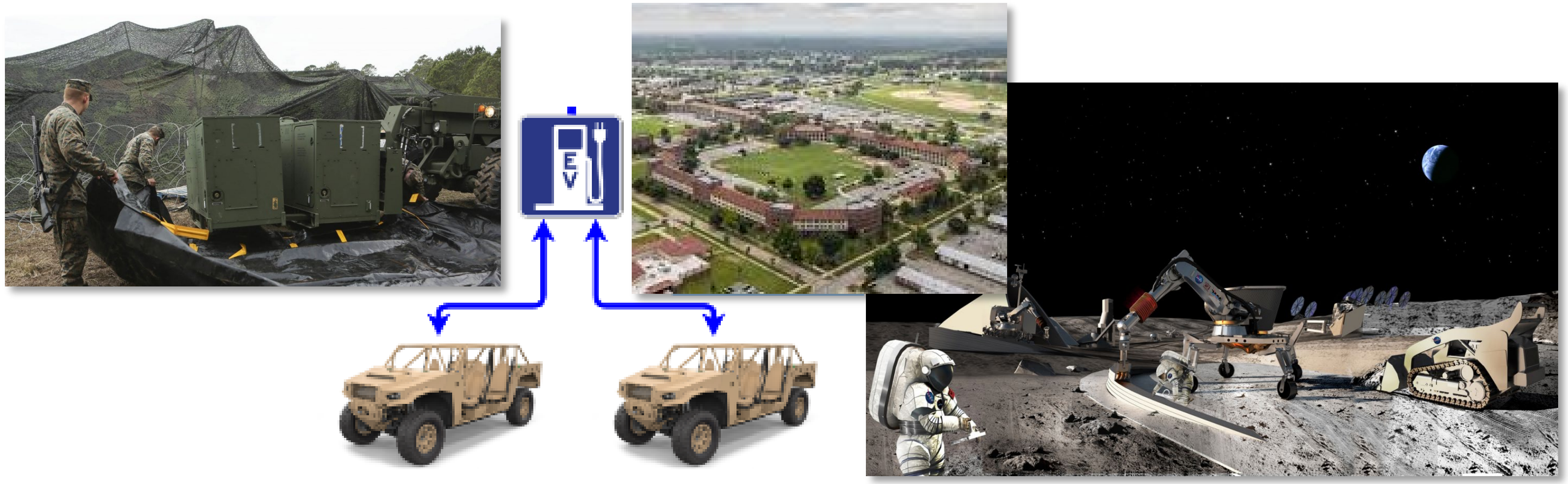
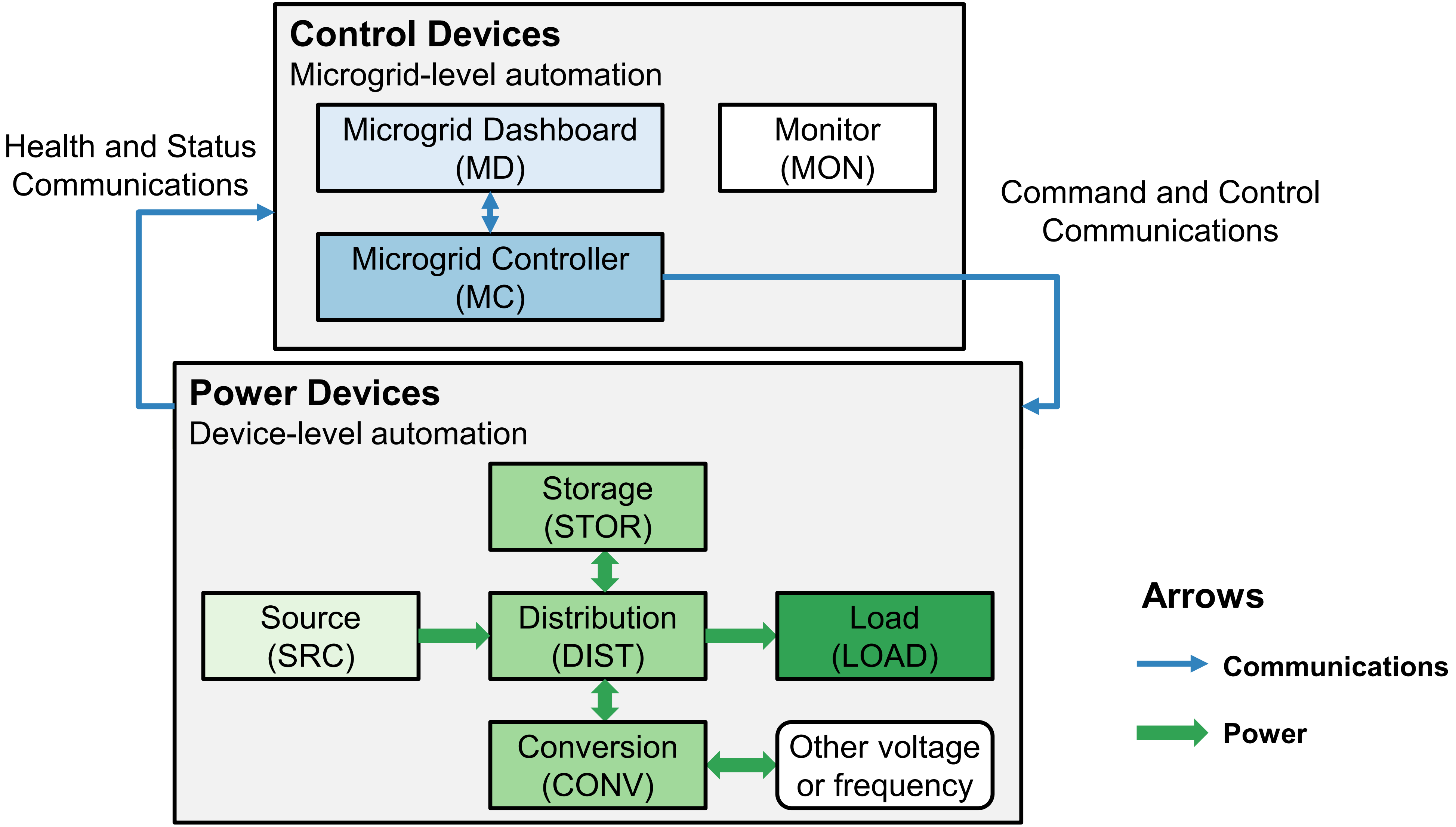
Modular Open Systems Approach (MOSA) for power, with many applications

Form Factor	Domain	Market
Mobile	Land	Defense
Vehicle	Sea	Civilian
Installation	Air	Lunar
	Space	

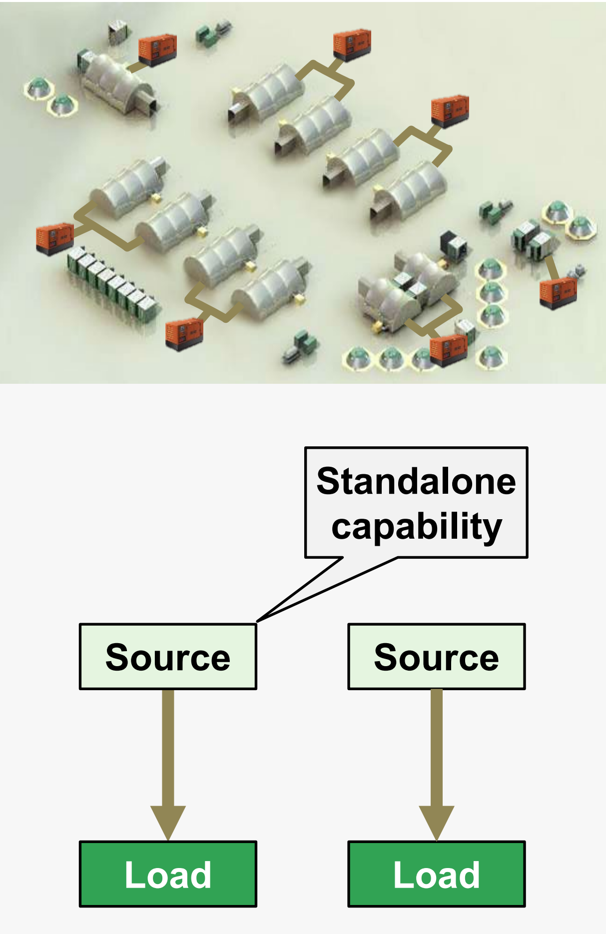


TMS Architecture Overview

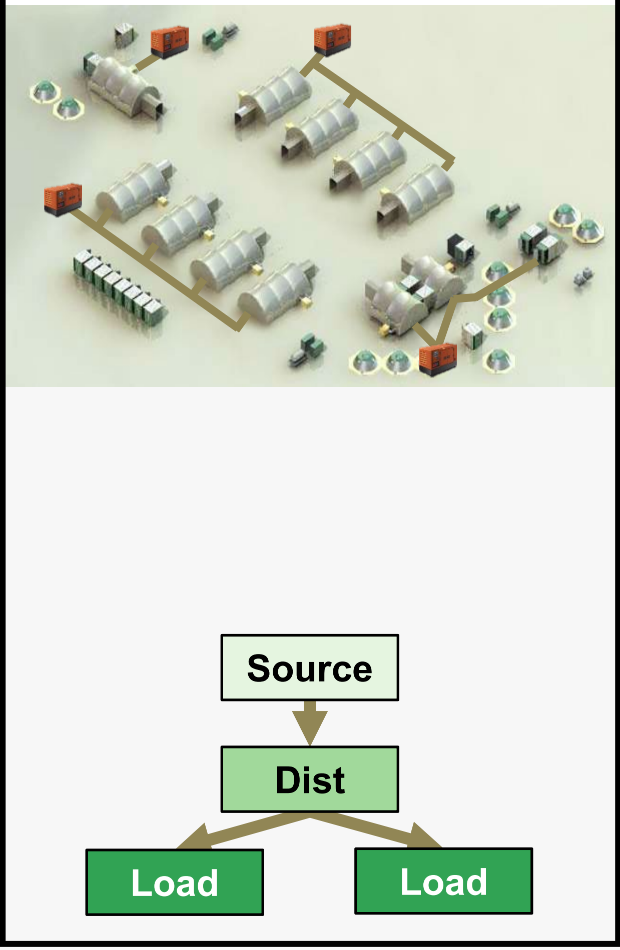


Assemble Devices to Meet Mission Needs

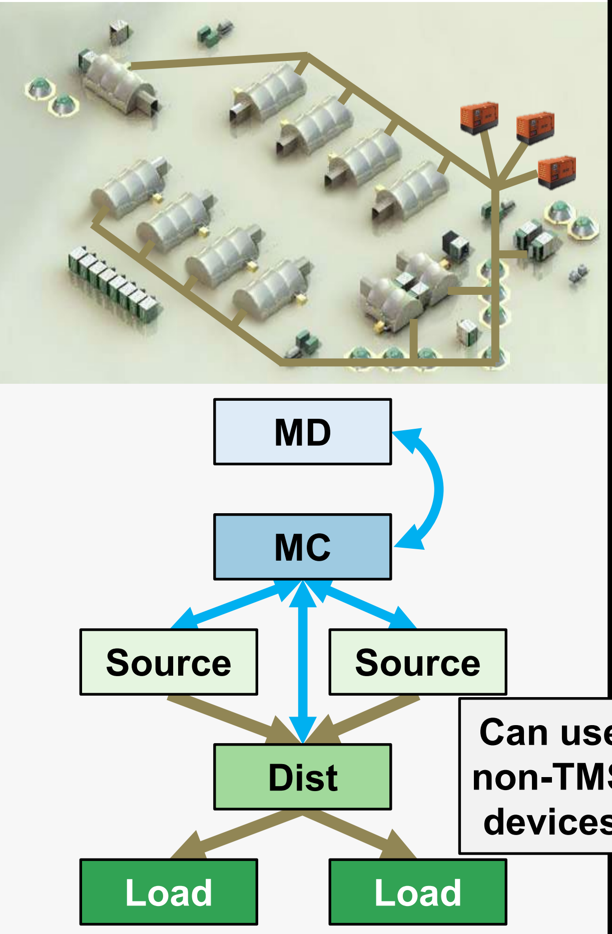
Spot Generation



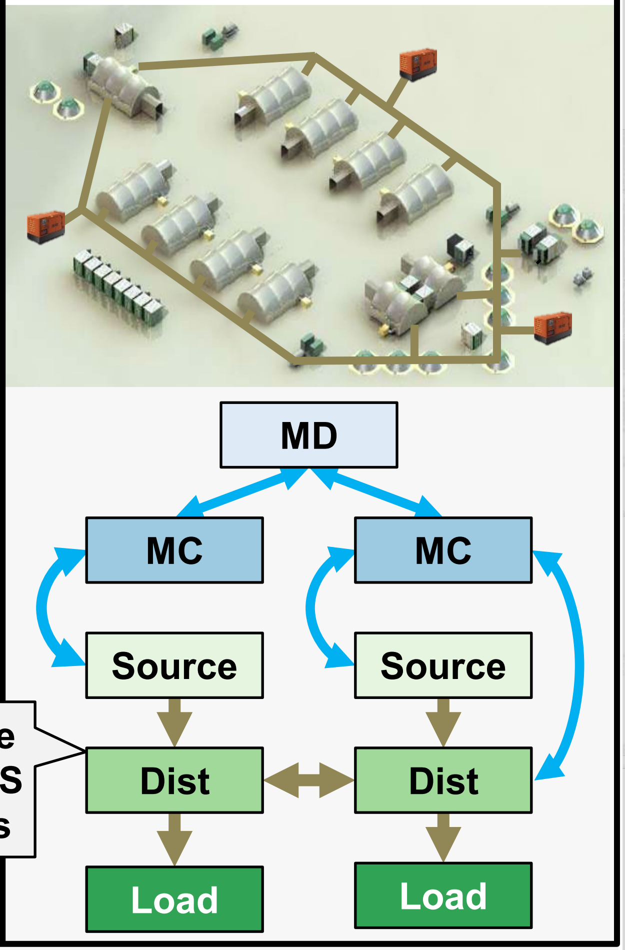
Consolidated Generation



Central Microgrid

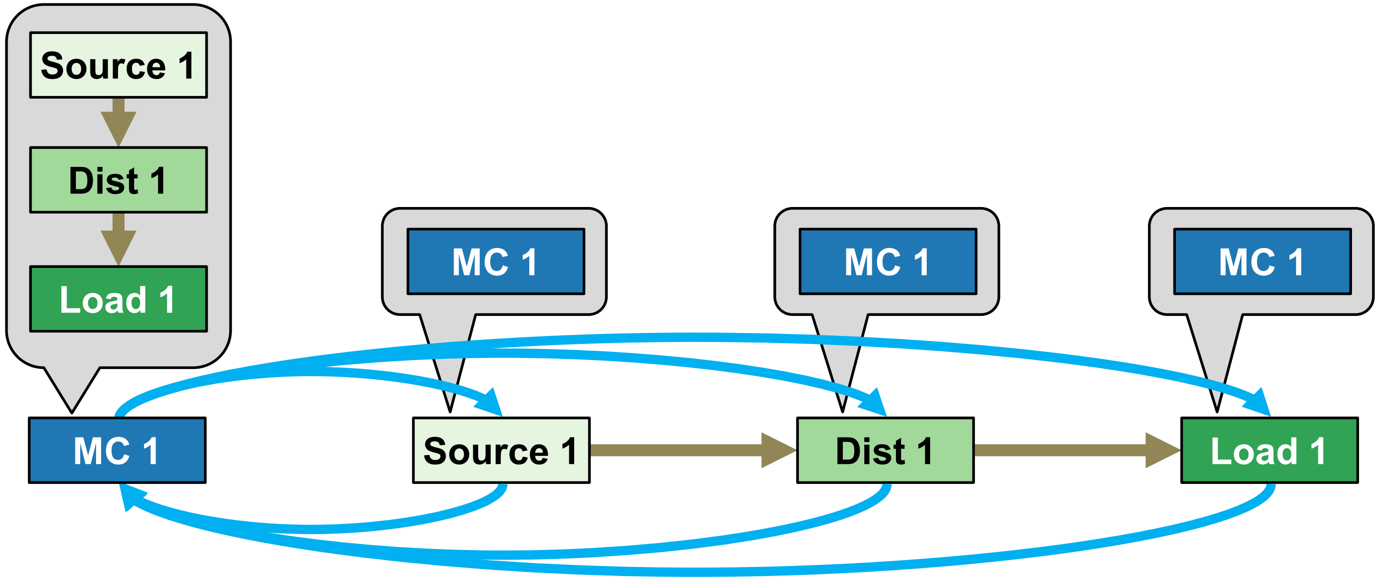


Distributed Microgrid



Discovery

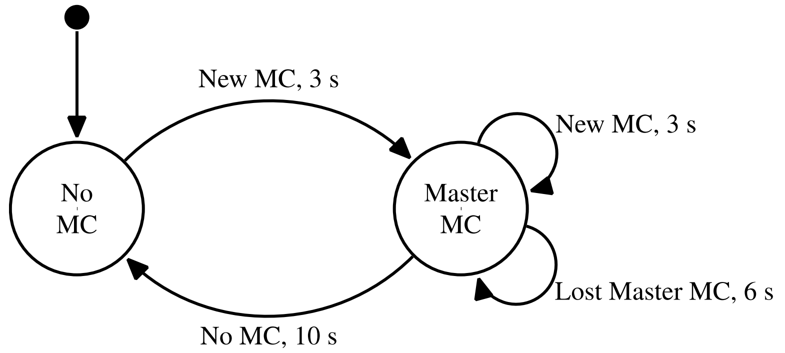
- All devices announces identity, type, and ratings.
- Enables rapid, ad-hoc deployment.
- Can happen in any order.



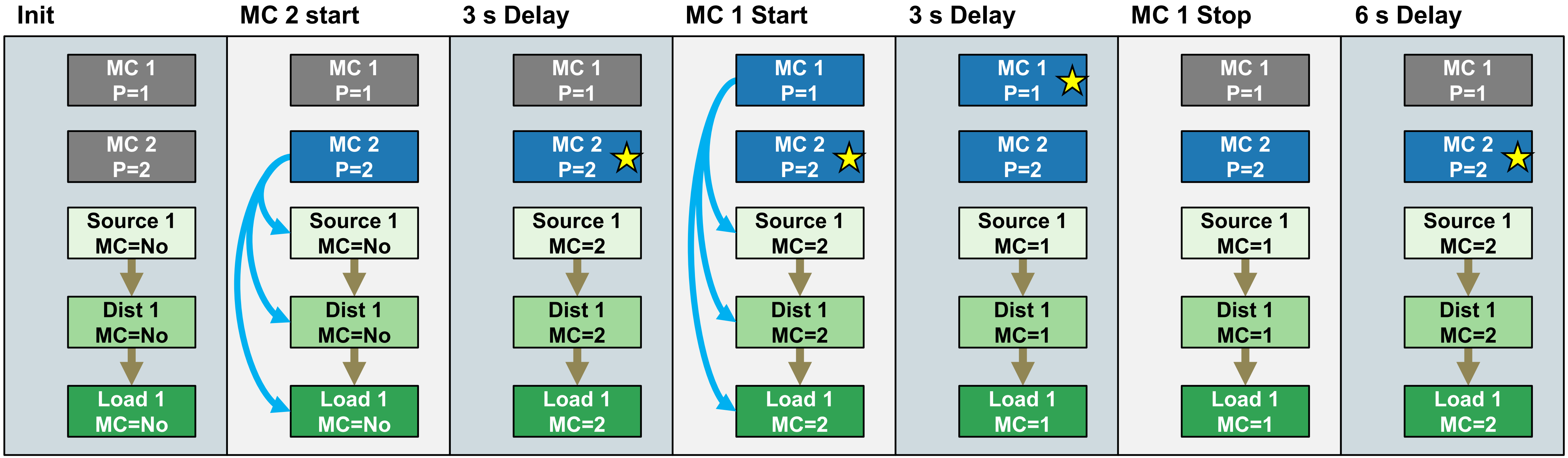
Power connections:
- Smart cables
- Power correlation
- Manual entry

Microgrid Controller Priority

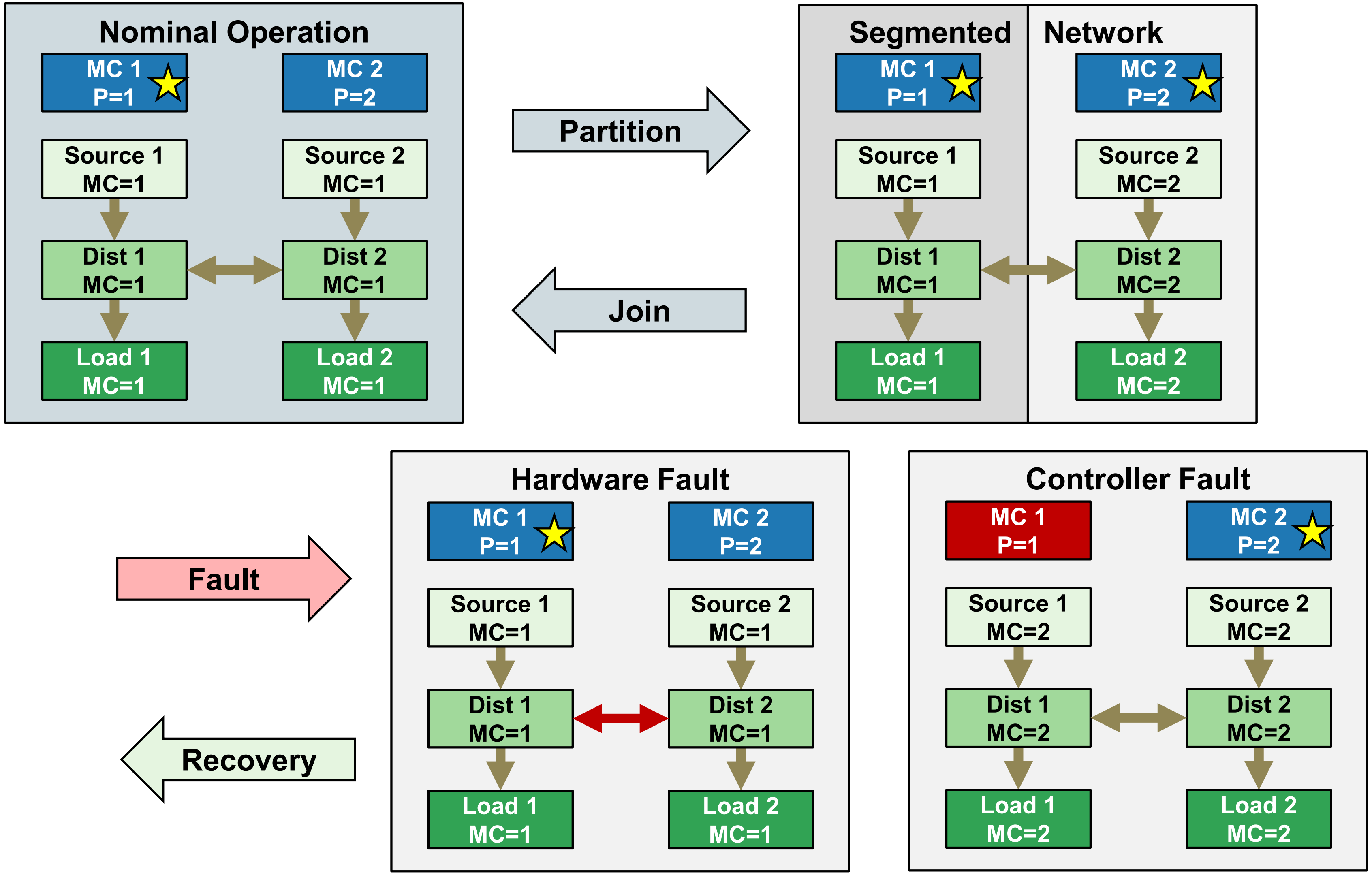
- Highest priority active MC gains control.
- All devices run same MC selection algorithm.



Example Sequence:



Resilient Control



CAP Theorem:

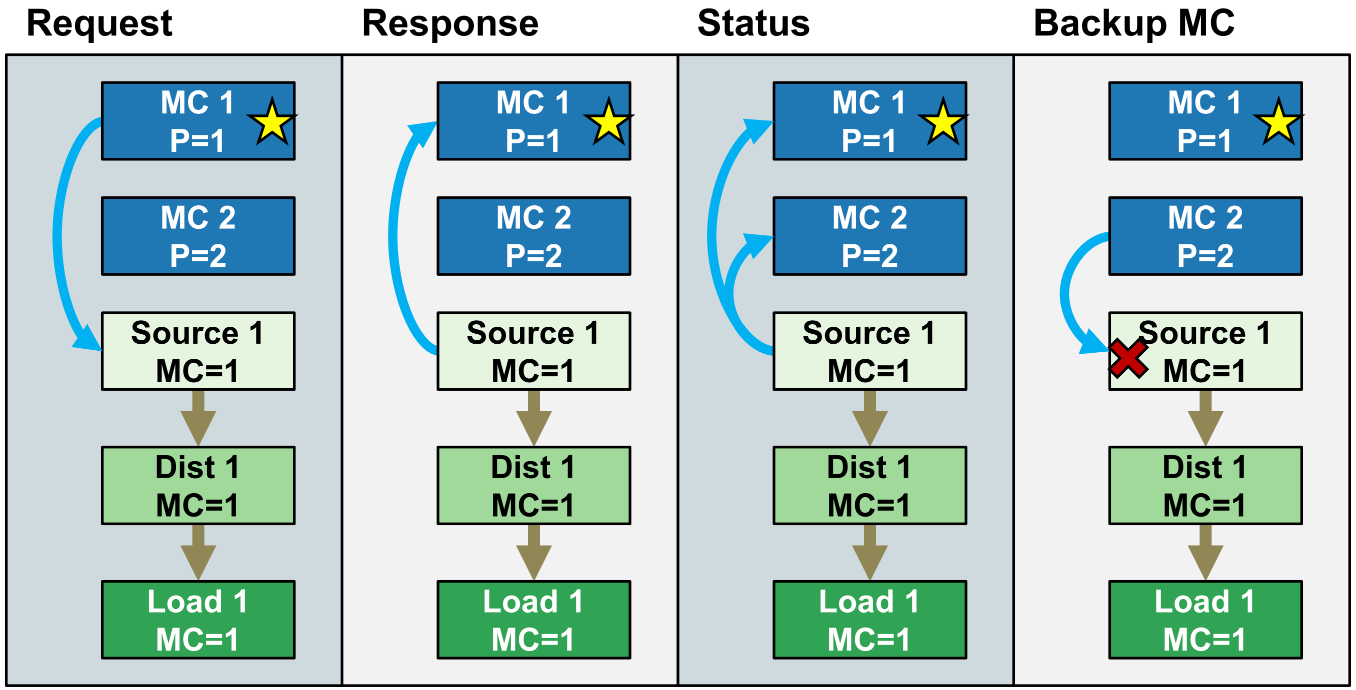
Choose 2 of 3

1. Availability
2. Partition Tolerance
3. Consistency

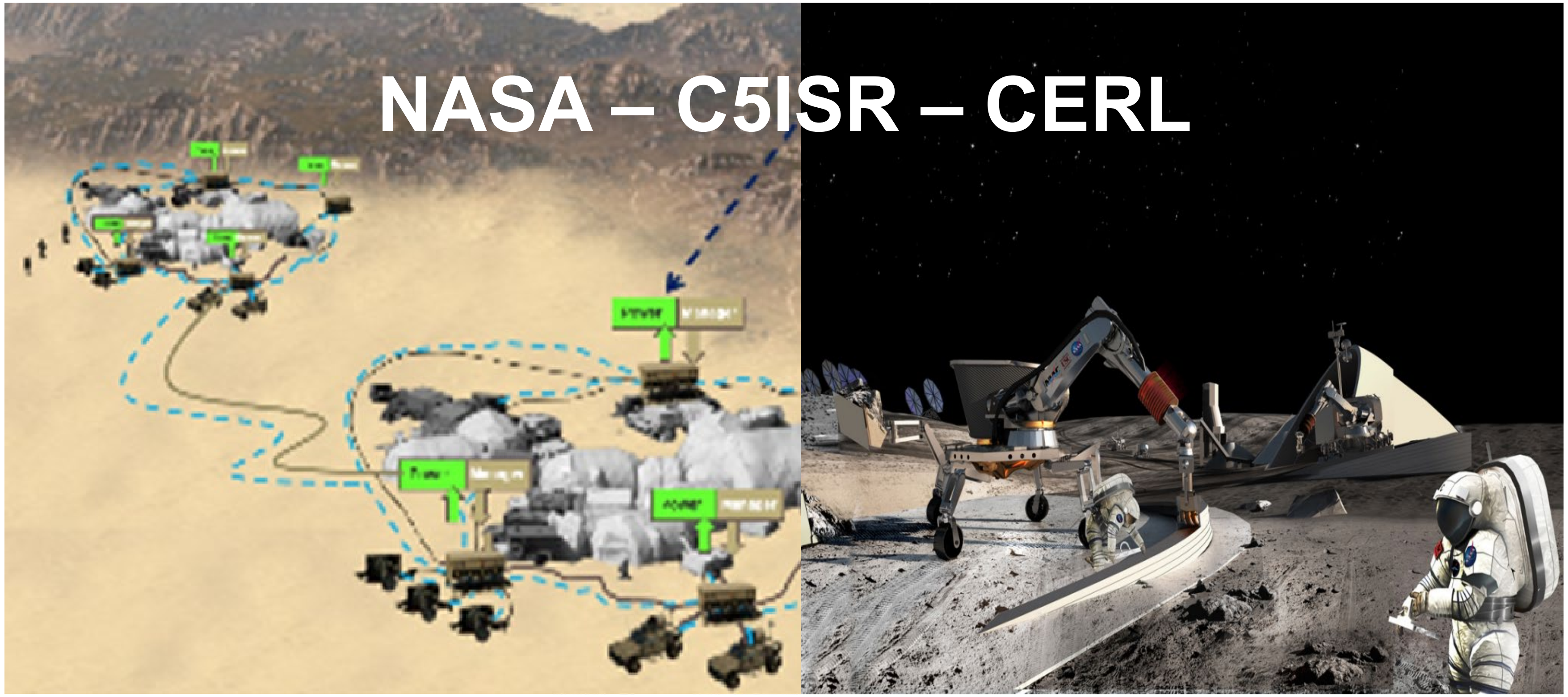
(TMS priorities shown)

Control and Status Messages

- Master MC sends commands.
- Backup MC cannot.
- All MCs monitor status.



TMS Space

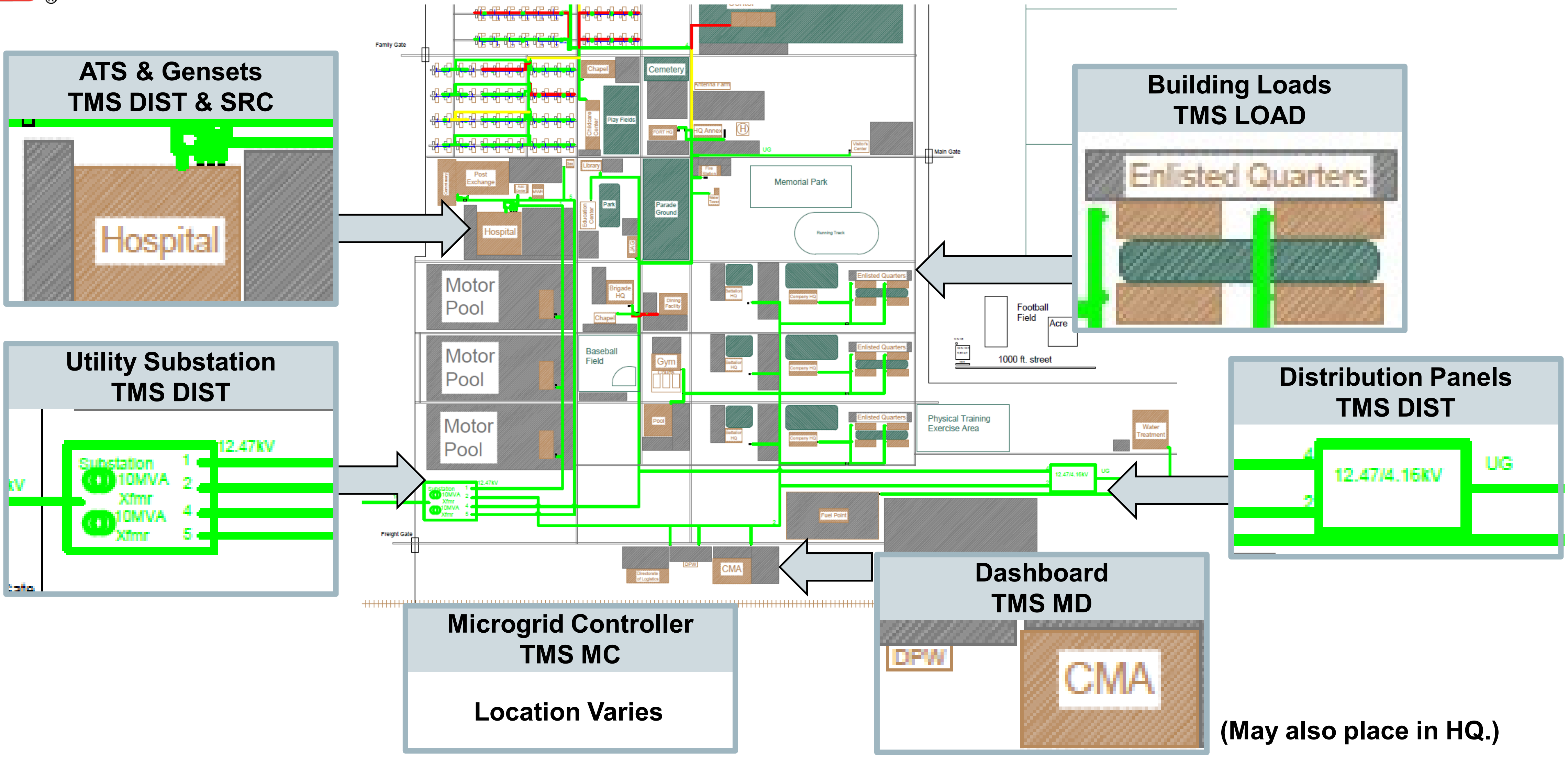


Interoperable autonomous and robotic power systems to enable terrestrial, in-orbit and lunar missions.

Questions and Discussion

Additional Information

TMS in Facility Related Control Systems (FRCS)



(May also place in HQ.)

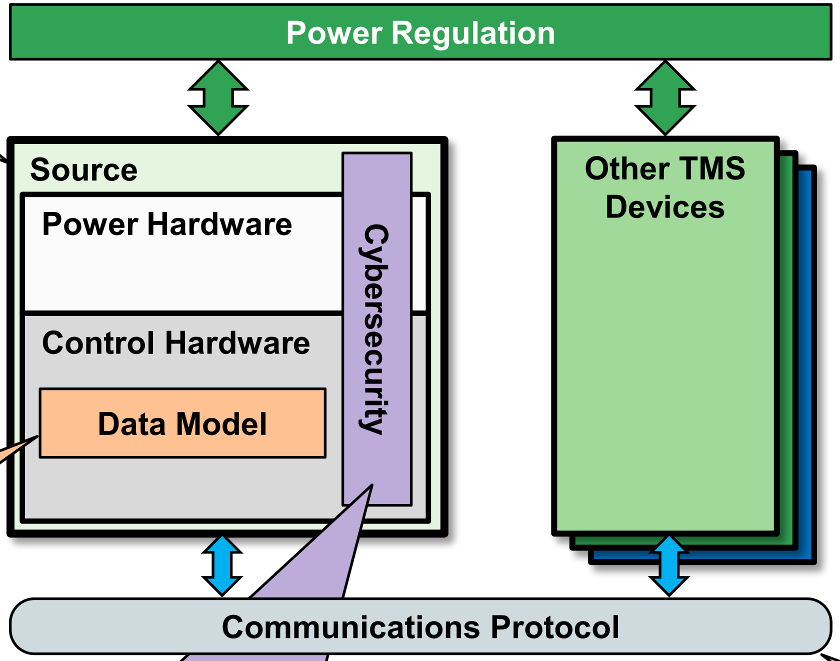
TMS Interface Definitions

User Interface (not shown)
- **Human engineering**
- **Consistent look and feel**

Future work

- **Ratings** (voltage, frequency, current, …)
- **Power quality** (noise, voltage disturbance, …)
- **Load sharing** (isoch / droop, stability, …)

No change. Use existing standards.



- **Content** (data types)
- **Semantics** (definitions, selected behaviors)

Defined in appendices

- **Strong Identities**
- **Assured Access**
- **Trustworthy Logging**
- **Integrity Protection**

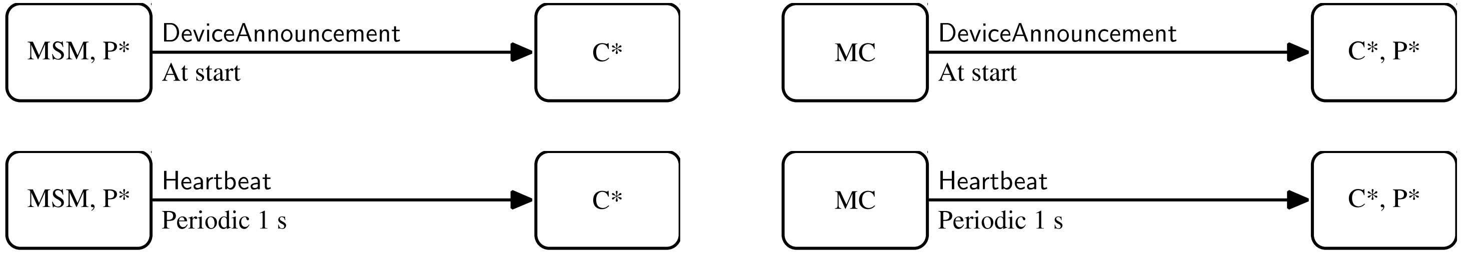
Laying foundation for future editions

- **Format** (digital representation)
- **Flow** (protocol and traffic pattern)

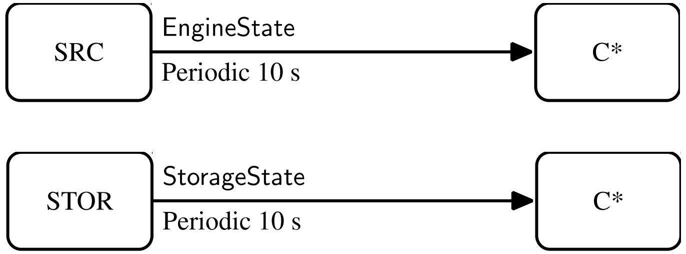
Appendices define use of OMG DDS

Example Data Flows

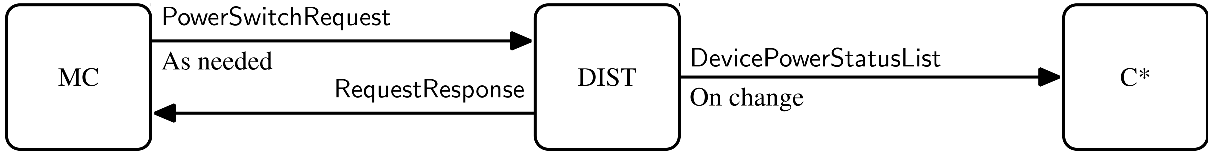
Discovery



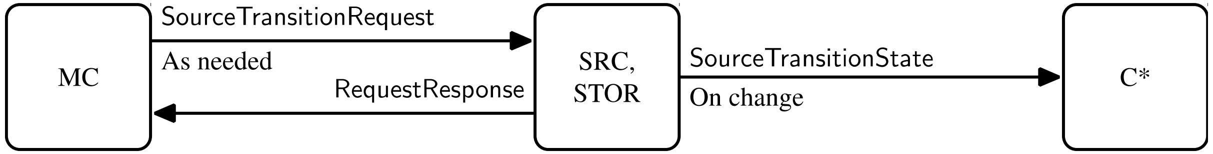
Subsystem Status



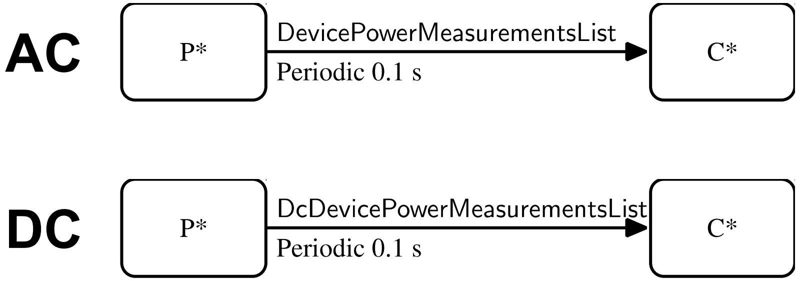
Remote Switching



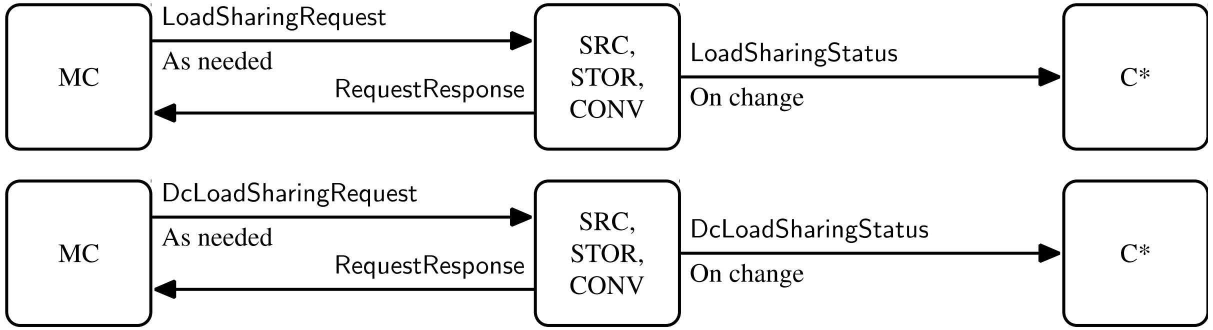
Remote Start/Stop



Power Measurements



Load Sharing



A.8 Data Flows

Functional Topics & Participants

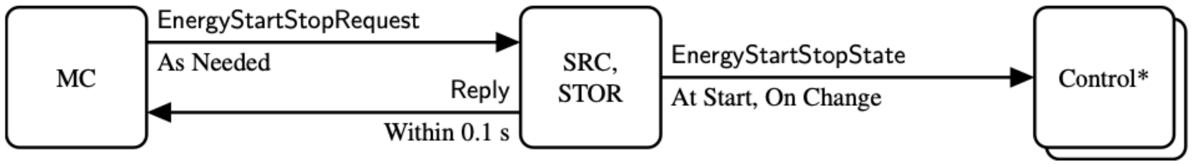
Topic	MD	MC	SRC	STOR	DIST	LOAD	CONV
AcLoadSharingRequest		*P*	*S*	*S*			*S*
AcLoadSharingState	*S*	*S*	*P*	*P*			*P*
AcMeasurementUpdate	*S*	*S*	*P*	*P*	*P*	*P*	*P*
AcSummaryMeasurementUpdate		*S*	*P*	*P*	*P*	*P*	*P*
ActiveDiagnosticState	*S*	*P S*	*P*	*P*	*P*	*P*	*P*
ActiveMicrogridControllerState	*S*	*S*	*P*	*P*	*P*	*P*	*P*
AuthorizationToEnergizeReply	*P S*		*S*	*S*	*S*		
AuthorizationToEnergizeRequest	*S*		*P*	*P*	*P*		*P*
AuthorizationToEnergizeResult	*S*	*S*	*P*	*P*	*P*		*P*
ClockState	*P S*	*P S*	*P*	*P*	*P*	*P*	*P*
ControlHardwareUpdate	*P S*	*P S*	*P*	*P*	*P*	*P*	*P*
ControlParameterRequest		*P*	*S*	*S*	*S*	*S*	*S*
ControlParameterState	*S*	*S*	*P*	*P*	*P*	*P*	*P*
DcLoadSharingRequest		*P*	*S*	*S*			*S*

***P* = publish, *S* = subscribe**

Timing

Topic	Data Trigger	Rate Class	Burst Size	QoS Profile
EnergyStartStopState	At Start, On Change	10 s	10	PublishLast
EnergyStartStopRequest	As Needed	10 s	1	Command
Reply	Within 0.1 s	All	1	Reply

Interaction Patterns

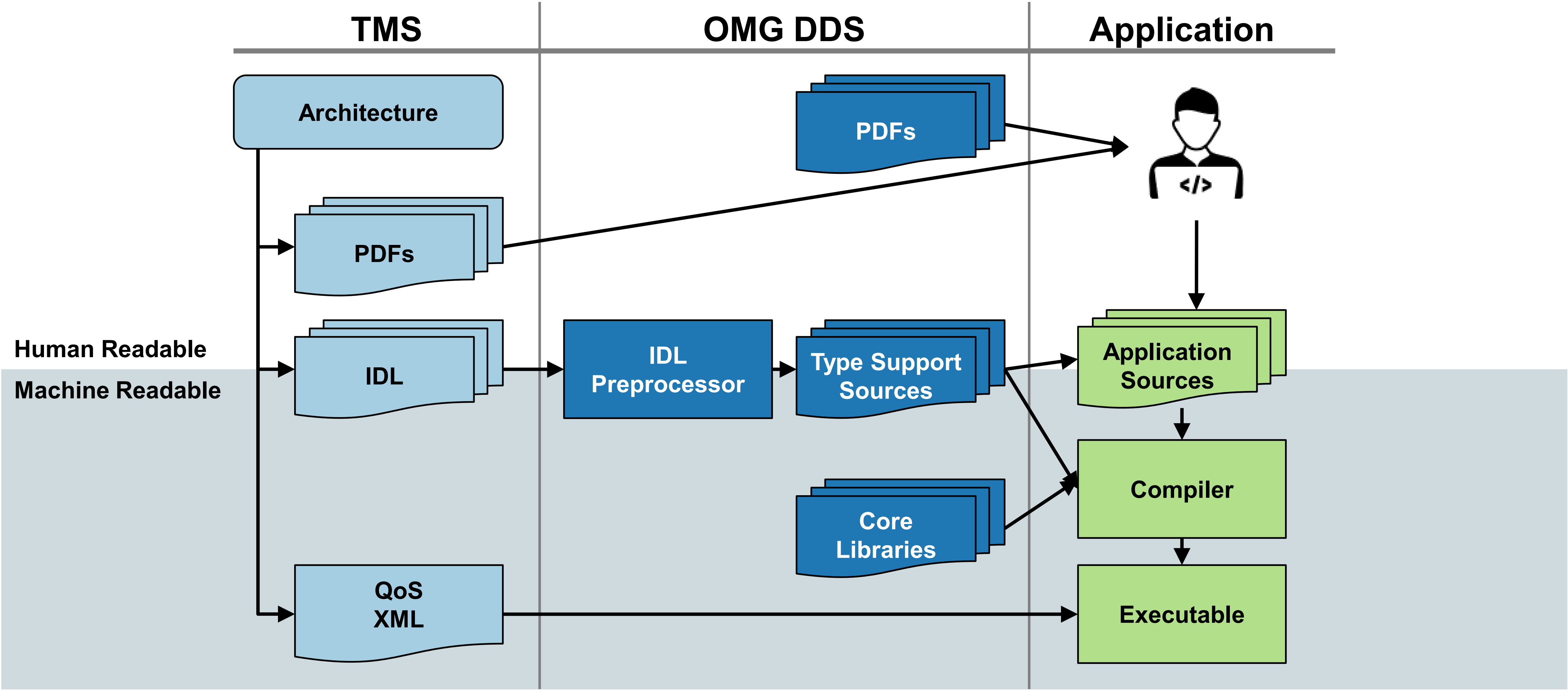


Data Types

ATTRIBUTES:

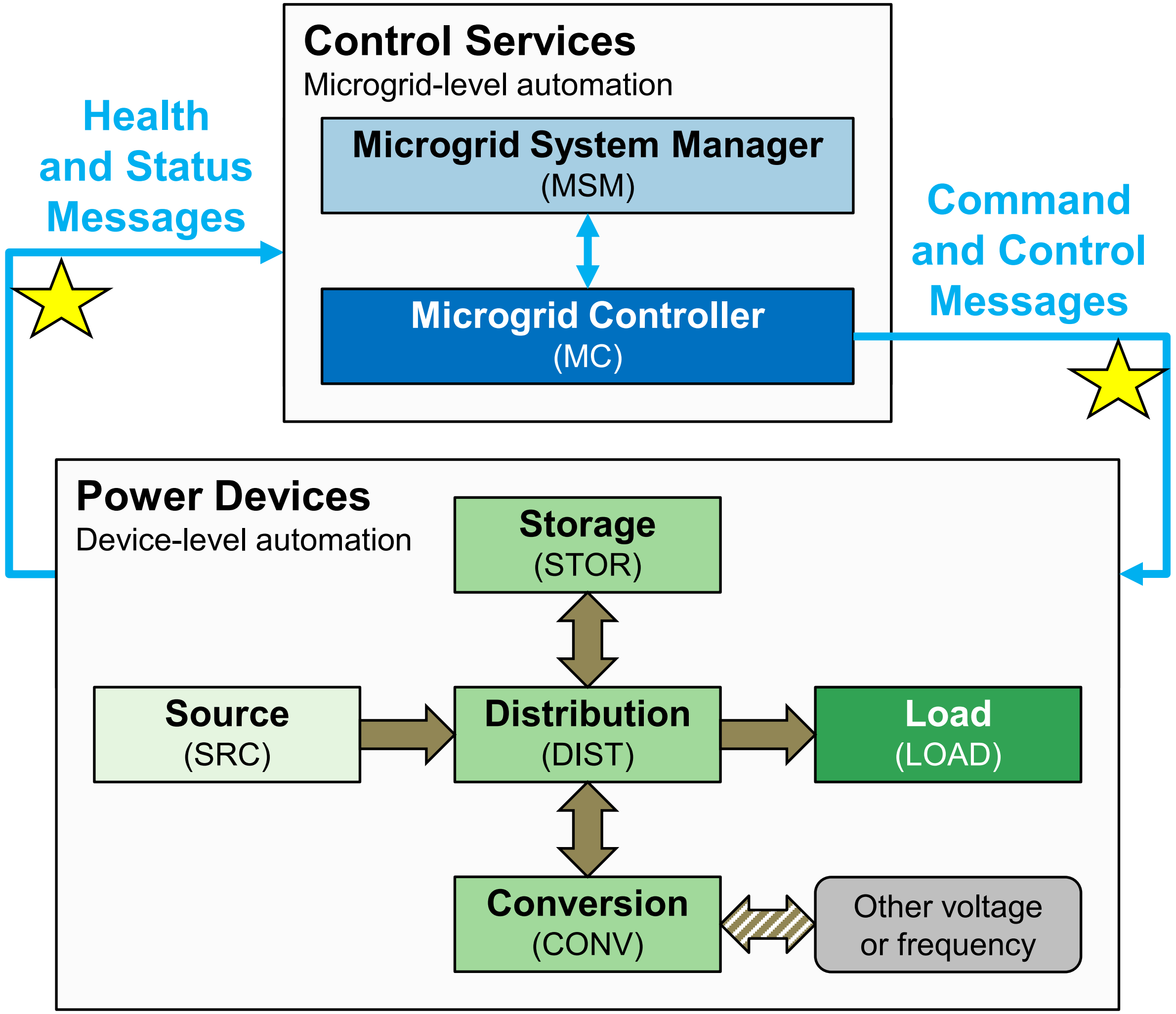
Name	Type and Description
`deviceId`	`Identity` The device described by this structure. Annotations: *keyval*
`presentLevel`	`EnergyStartStopLevel` Present operating level.
`futureLevel`	`EnergyStartStopLevel` Level that the device is transitioning to, or presentLevel if no transition.
`requestLock`	`boolean` This device or power switch is known to be locked and requests will get REPLY_PRECONDITION_FAILED. A device-level lock must be reported on all affected ports. Unknown locks may REPLY_OK and then PSTC_MALFUNCTION.
`elapsedTime`	`float32` Elapsed time the device has been in the present transition. Remains at the total elapsed time when the transition is complete.

TMS Software Integration

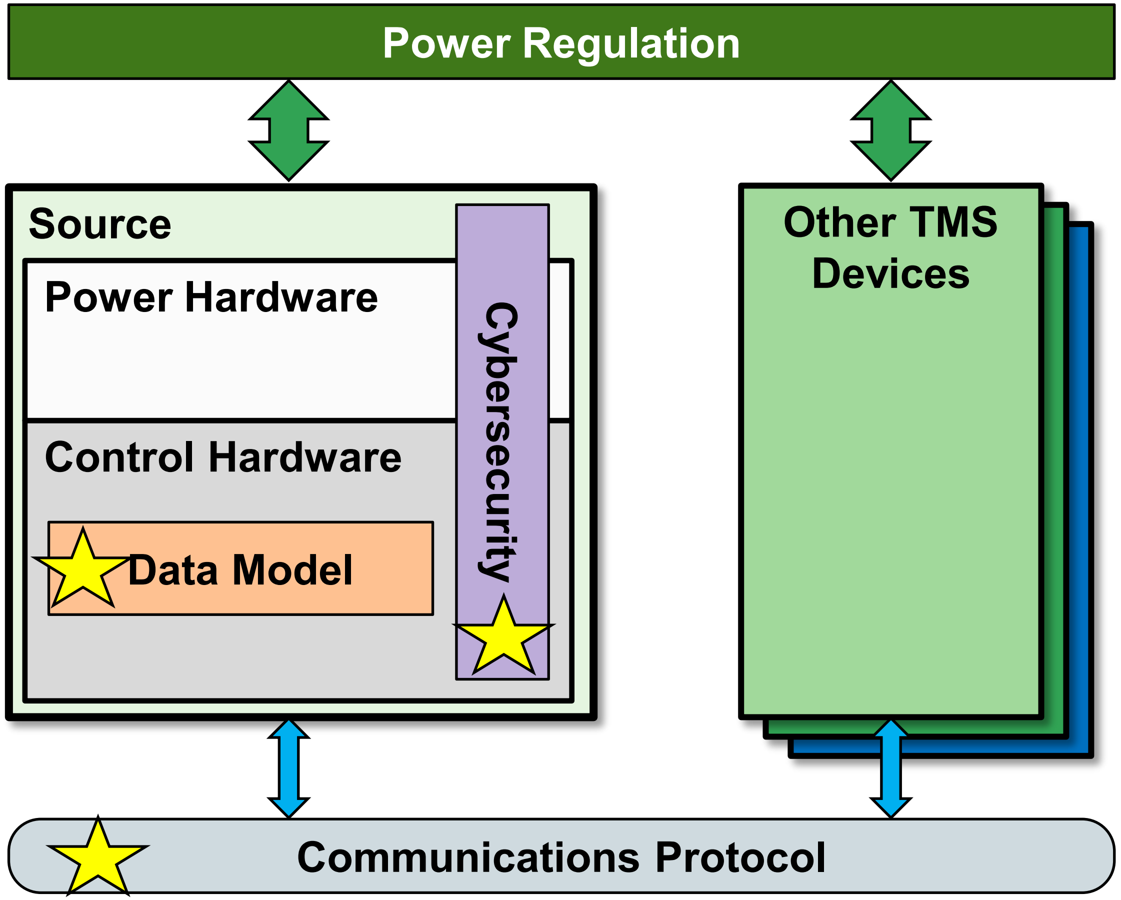


Where OMG DDS is Used in TMS

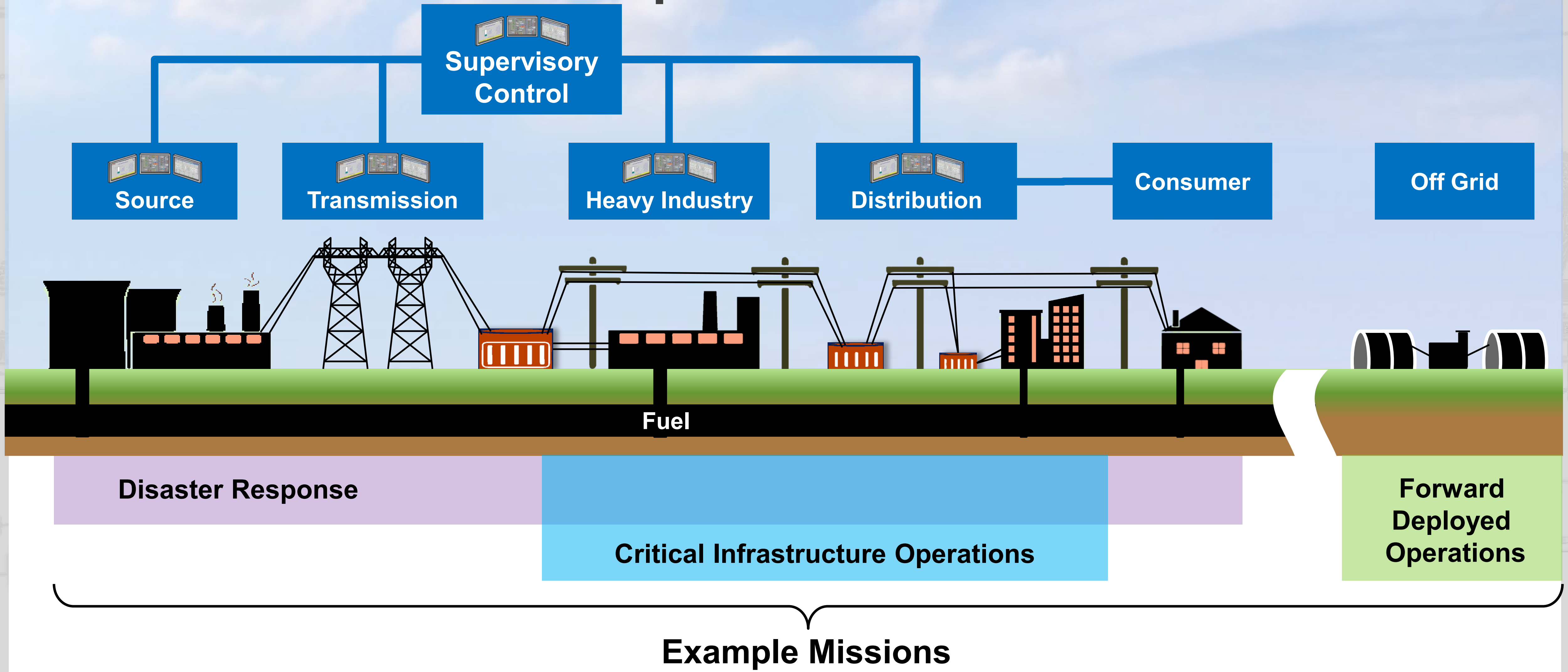
Components



Interfaces



Canonical Power System Architecture and Example Power Missions



Canonical Power System Architecture and Example Power Missions