EXPLORESPACE TECH

TECHNOLOGY DRIVES EXPLORATION

Envisioned Future Priorities for: “LIVE: Power and Energy Storage”

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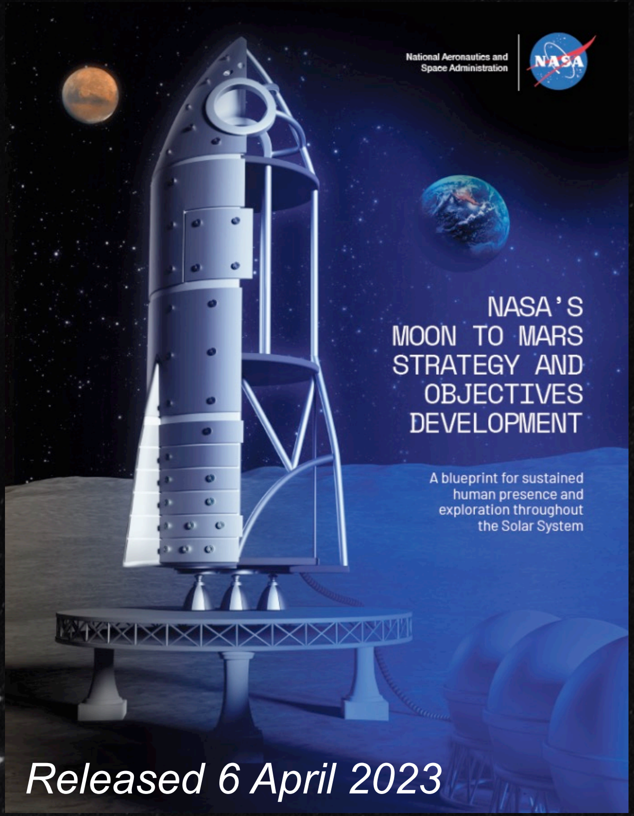
NASA Moon2Mars Strategy and Objectives



Lunar Infrastructure (LI)

LI-1: 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)

MI-1: Develop Mars surface power sufficient for and initial human Mars exploration campaign

Activities depicted are not all funded or approved. This is a "notional future" developed to guide technology vision.

Space Technology Mission Directorate (STMD) Strategic Taxonomy

Go
Rapid, Safe, & Efficient Space Transportation

- Develop nuclear technologies enabling fast in-space transits.
- Develop cryogenic storage, transport, and fluid management technologies for surface and in-space applications.
- Develop advanced propulsion technologies that enable future science/exploration missions.

Land
Expanded Access to Diverse Surface Destinations

- Enable Lunar/Mars global access with ~20t payloads to support human missions.
- Enable science missions entering/transiting planetary atmospheres and landing on planetary bodies.
- Develop technologies to land payloads within 50 meters accuracy and avoid landing hazards.

Live
Sustainable Living and Working Farther from Earth

- Develop exploration technologies and enable a vibrant space economy with supporting utilities and commodities
  - Sustainable power sources and other surface utilities to enable continuous lunar and Mars surface operations.
  - Scalable ISRU production/utilization capabilities including sustainable commodities on the lunar & Mars surface.
  - Technologies that enable surviving the extreme lunar and Mars environments.
  - Autonomous excavation, construction & outfitting capabilities targeting landing pads/structures/habitable buildings utilizing in situ resources.
- Enable long duration human exploration missions with Advanced Life Support & Human Performance technologies.

Power Principal Technologist
TX 3.0 Power and Energy Storage

Explore
Transformative Missions and Discoveries

- Develop next generation high performance computing, communications, and navigation.
- Develop advanced robotics and spacecraft autonomy technologies to enable and augment science/exploration missions.
- Develop technologies supporting emerging space industries including: Satellite Servicing & Assembly, In Space/Surface Manufacturing, and Small Spacecraft technologies.
- Develop vehicle platform technologies supporting new discoveries.

Power – The Key ***Commodity*** Needed to Explore the Lunar Surface

Illumination

The primary and scarce ***resource*** needed to produce power

Equatorial Illumination Limits

- Cyclical periods of 14 days illuminated, 14 days dark
- Consistent

Polar Illumination Limits

- Intermittent with up to 100 hours darkness
- Highly dependent on location/elevation

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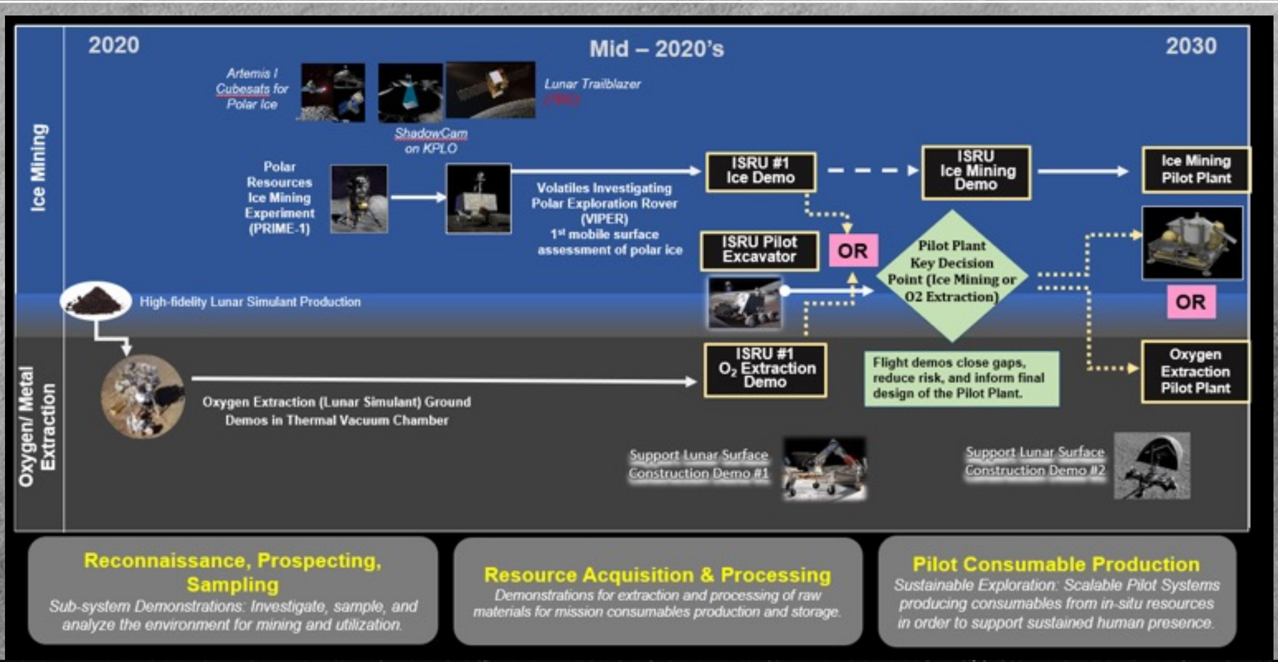
In-Situ Resource Utilization (ISRU) is the "Killer App" for Surface Power

Production of propellant from in in-situ resources is the demand driver for power at the Lunar South Pole

- *Prospecting and tradeoff results will determine whether ISRU propellant will be oxygen from regolith or hydrogen and oxygen from ice mined from permanently shadowed regions. Decision drives power technology development priorities.*
  - *ISRU pilot plants for propellant production will be powered from Artemis Base Camp resources*
  - *Polar power demand may reach ~2 MW_e at full industrial scale (Phase α)after handoff from Artemis to commercial investment.*
  - *ISRU/Construction projections may further drive power demand to GW_e levels as infrastructure expands beyond the Polar region toward the Equator (Phase Ω).*



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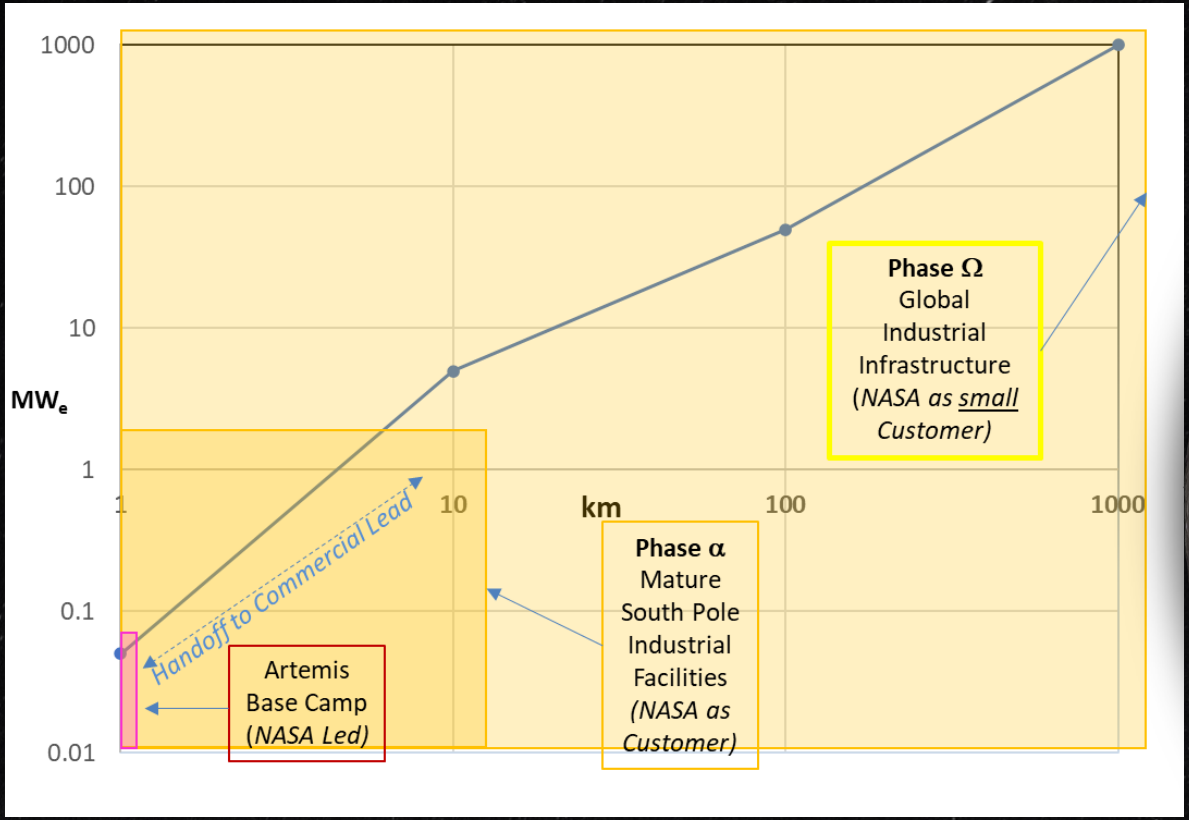
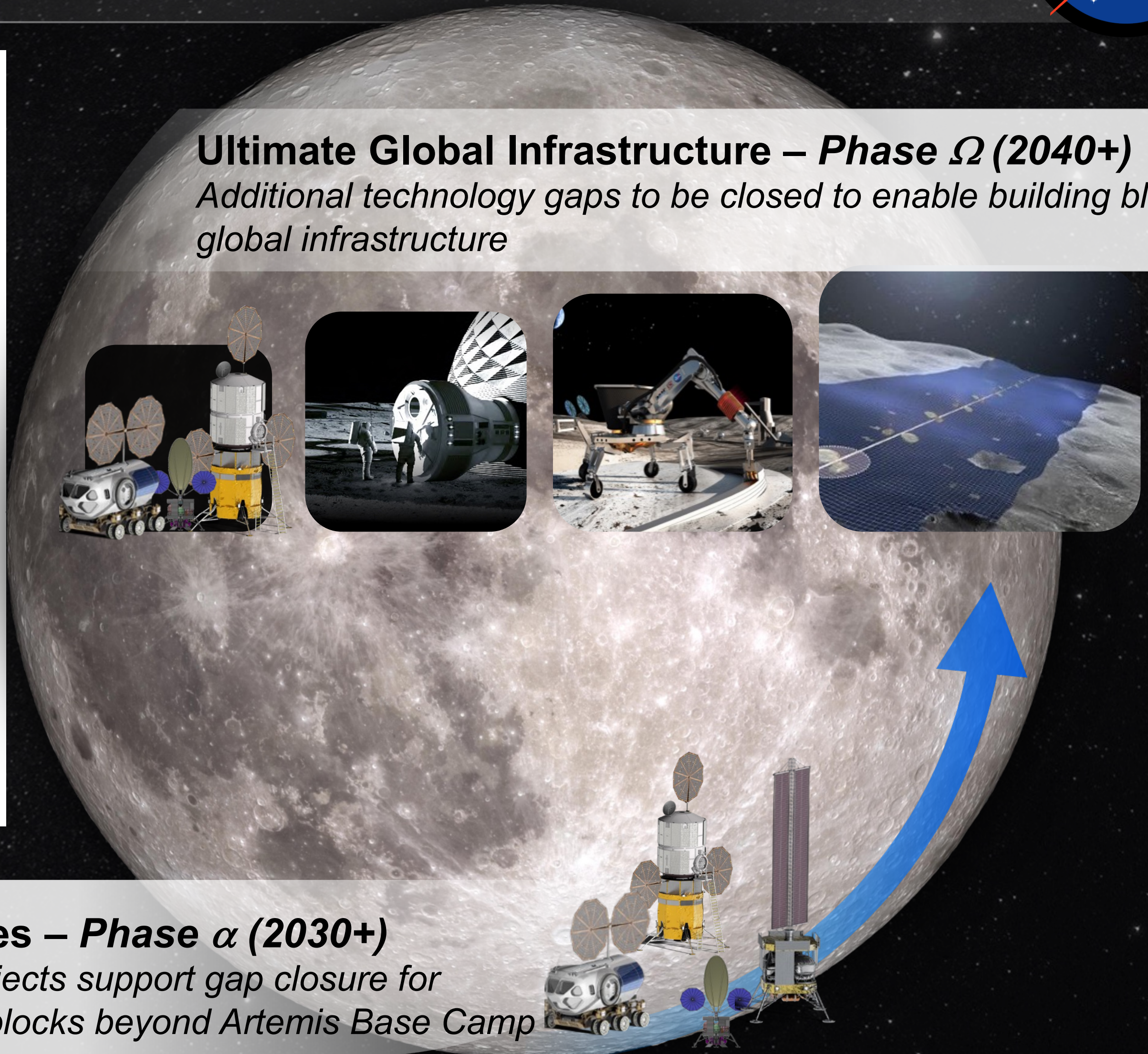
Envisioned Growth of Lunar Presence



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

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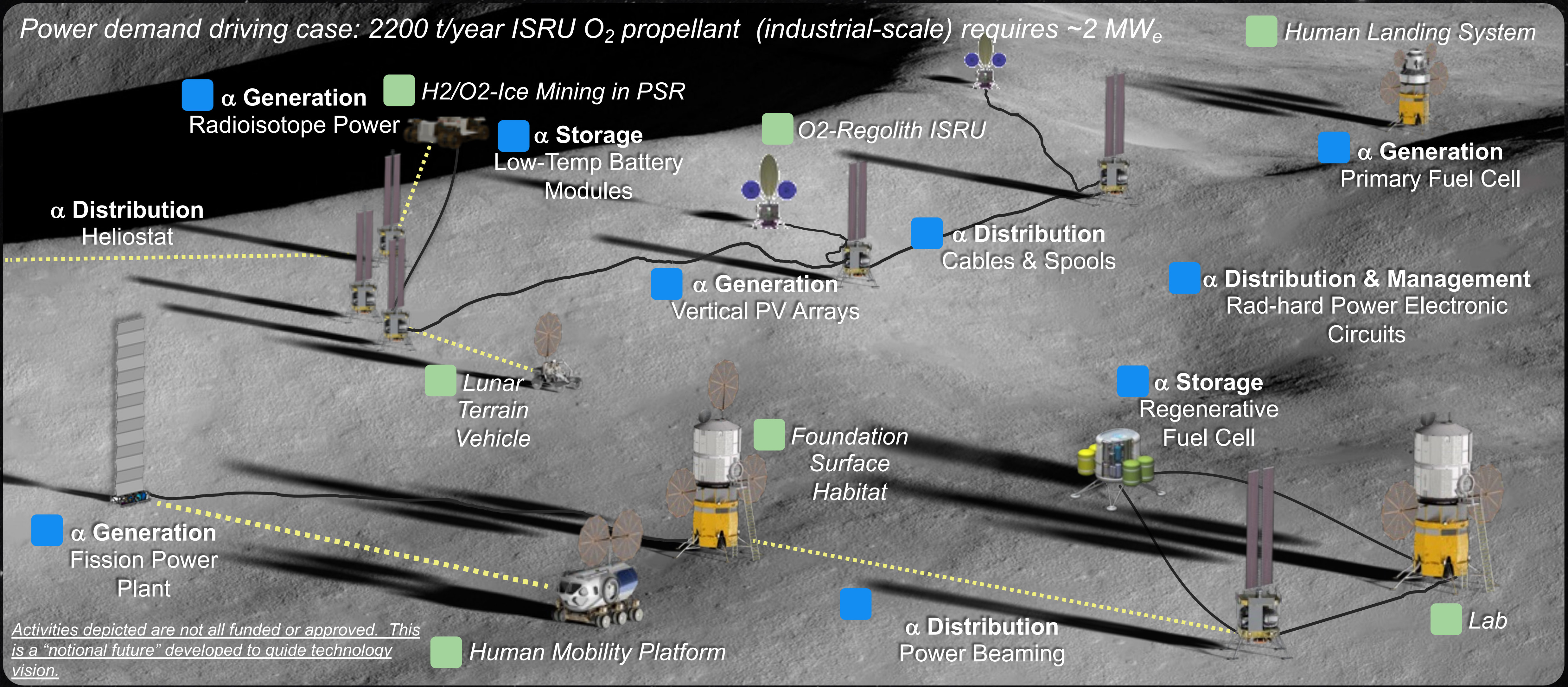
Power Architecture Building Blocks

Phase α South Pole Facilities: Handoff from Artemis Base Camp to Industry (~2030+)

Power system

Load



Power Architecture Building Blocks

Phase Ω: Additional Technology Building Blocks Required to Expand Industrial Activities to Lower Lattitudes (2040+)

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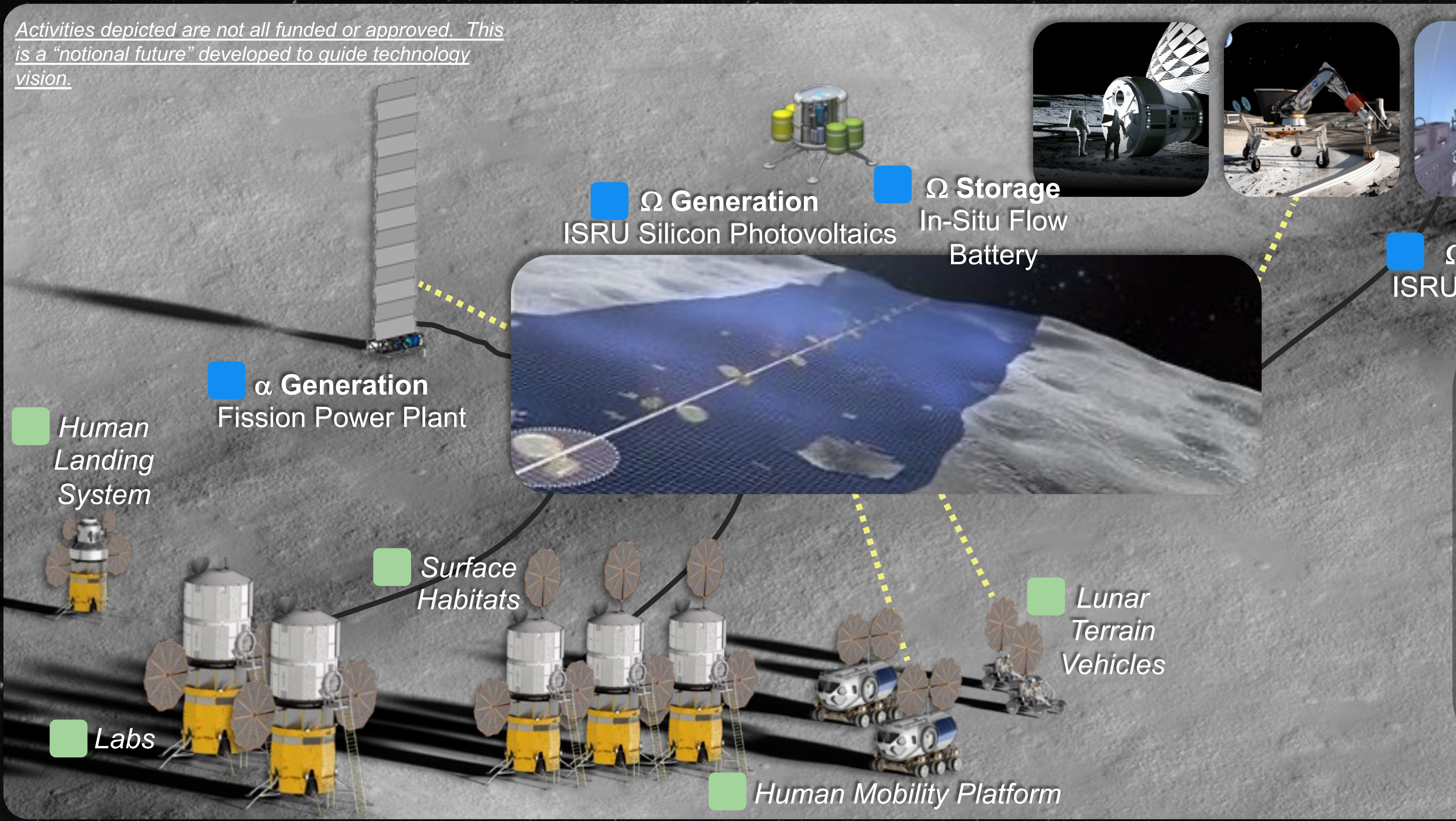

- Landing pads and protective structures
- 100's to 1000's metric tons of regolith-based feedstock for construction projects
- 10's to 100's metric tons of metals, plastics, and binders

STMD Baselined "Envisioned Future Priorities (EFP)"

Guide Investments in Closing Technology Gaps

1

- Highest priority power EFP gap closures support Phase α industrial-scale Lunar ISRU production in the early 2030's at the South Pole
- Other gap closures support subsequent expansion toward Phase Ω construction and ISRU production at lower latitudes in 2040+

A Mobile Fission Surface Power

B Reliable, Rad-Hard Power Conversion and Cable Transmission System

C Solar Power

Long Life, Grid-Scale Secondary Energy Storage

D *PSR Operations*

Wireless Power Transmission

Low Temperature Secondary Battery Modules

Radioisotope Energy Sources

Heliostats and Solar Reflectors

Superconducting Cable Transmission

E *Mars Forward*

CH_4/O_2 Primary Fuel Cell Power

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Gap A: Fission Surface Power

Thrust: LIVE
Outcomes: Sustainable power sources and other surface utilities to enable continuous Lunar and Mars surface operations
Taxonomy Elements: 3.1.2.1, 3.1.4.1

Definition: No multi-kW_e-scale power sources have been developed to be capable of providing sun-independent, mobile power on the Lunar or Martian surface. Such power is needed not only to supplement solar power for sustainable operations on the Lunar pole but also to bootstrap the printing of power system components from Lunar regolith as infrastructure expands toward lower latitudes.

SOA: Though fission reactors have been operated on Earth land and sea for many decades, no reactors have been operated in space since the Soviet Topaz I (~5 kW_e) flight in 1988. The Soviet TOPAZ II development unit (~6 kW_e) was briefly ground tested in the US in 1994. A space fission reactor development unit (~ 1 kW_e) was tested in the US in 2018.

CURRENT INVESTMENTS

NASA:

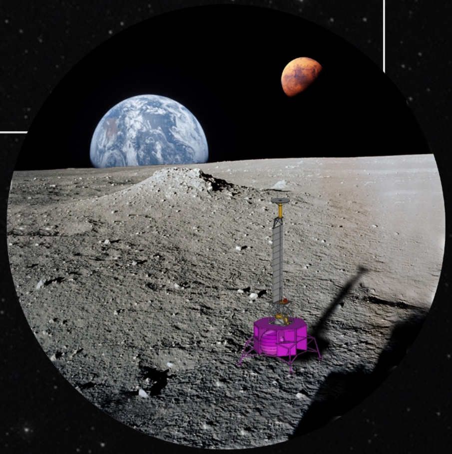
- Energy Conversion
  - *SBIR/STTRs (Stirling, Brayton, ATEG, Heat Ex, Radiators)*
- Radiation Shielding
  - *SBIR (materials)*
- Systems
  - *TDM (FSP)*
-

OGA

- Nuclear fuels
  - DoE SMR
  - DoD Project Pele

Gap A (α) Closure:
Bring to TRL 6 a relocatable 40 kW_e-class mobile fission power system suited for the Lunar polar environment in time to support a TDM on the Moon in 2028. Lower power (e.g., 10 kW_e) units may be developed for Mars.

Closure Roadmap (α):
- Complete NASA TDM FSP Project



Gap B: Reliable and Efficient Long Distance Power Transmission Systems (Cables and Conversion)

Thrust: LIVE
Outcomes: Sustainable power sources and other surface utilities to enable continuous Lunar and Mars surface operations
Taxonomy Elements: 3.3.1, 3.3.2, 3.3.3, 3.3.4

Definitions:
BA: SOA Earth-sourced power converters, transformers, cables and load connection and deployment systems do not provide capability at specific power, voltage, and radiation-, thermal- and dust-tolerance levels sufficient to support reliable power distribution among Lunar pole surface elements. Flight-qualified technologies for all these components are not adapted the Lunar polar environment.
BB: The technology required to print long distance conductors (100's of km) on the Lunar surface from locally-sourced aluminum has seen little conceptual development.
Mission architects must know what capability will be available to them once full-scale ISRU production operations are to start in the early 2030s and once large-scale Lunar surface operations expand toward the lower latitudes in the late 2030s.

SOA: Power converters of sufficient reliability for current missions are at TRL 9 for near- Earth, geosynchronous, and deep space missions at <200 V. Cables, dust-tolerant load connection systems, and cable deployment systems for the Lunar surface have been developed only to the "bench-top" level. Terrestrial microgrid topologies of similar capacity are well understood.

CURRENT INVESTMENTS

NASA:
- Materials:
  - *SBIRs (SiC, Ga_2O_3, Diamond, shielding)*
  - *LuSTR grant (SiC)*
- Circuitry and Devices
  - *SBIR (switches)*
  - *STTR (controller)*
  - *LuSTR grant (router)*
  - *GCD TP (Apogee RPCD)*
  - *GCD (TYMPO)*
  - *GCD (MIPS)*
- Cable & Spooling Systems
  - PCC (WOTM)
  - GCD (TYMPO)
- Dust compatibility/Connectors
  - *GCD (LO-DuSST)*
  - *GCD TP (UFPC)*

OGA (DoD & DoE):
- DARPA BAA: Space Power Conversion Electronics

Gap B (α) Closure
Bring to TRL 6 by 2030 power conversion and cable transmission systems which can (a) invert/boost (b) transmit (c) buck/rectify power between low voltage sources and loads (120 -200 VDC) at a 10 kW_e-scale up to 10 km, transmitting at:
- ~1000-1500 VDC or at:
- ~3000+ VAC, 1 kHz

The systems must lose no more than 3% per km in transmission, must maximize specific power, and must be able to operate at >0.95 power factor and 0.99 reliability for 10 years in the relevant Lunar radiation, dust, and thermal environments and in the Lunar hard vacuum and Mars atmosphere environments.

Closure Roadmap (α) :
- LuSTR or ECF project for integrated subsystem (material, device, circuit) reliability modeling/prediction/verification.
- Further SBIR/ESI efforts for dust tolerant load connection, radiation-hard electronics, and cable/spooling systems
- Continue both MIPS and TYMPO GCD efforts to bring 0.99 reliability converter/transformer/rectifier systems to TRL 6
- TDM projects to demonstrate components (cable/spool, connectors, proximity charging) on CLPS and at Artemis Base Camp

Gap B (Ω) Closure:
Bring to TRL 6 by 2035 MW_e-, 100 km-scale power transmission systems with conductors printed on the Lunar surface from Lunar-sourced aluminum and with minimal material brought from Earth.

Closure Roadmap (Ω):
- *STRG and SBIR efforts for Lunar aluminum mining and conductor printing*
- *GCD efforts to bring integrated, printed power conductor systems to TRL 6 by 2035*
- *TDM project to fly and operate power conductor production equipment on the Lunar surface by 2037*

Gap C1: Solar Power

Thrust: LIVE
Outcomes: Sustainable power sources and other surface utilities to enable continuous Lunar and Mars surface operations
Taxonomy Elements: 3.1.1

Definition:
C1 (α): SOA Earth-sourced solar array blankets do not provide sufficient durability or scale to support full scale ISRU production in the Lunar Pole thermal, dust , and radiation environment. Technology for reflectors/mirrors is likewise not optimized for the Lunar surface environment nor for gathering sunlight low on the horizon as at the Lunar poles.
C1 (Ω): The technology required to print photovoltaic arrays on the Lunar surface from Lunar silicon has seen little conceptual development.
Mission architects must know what capability will be available to them once full-scale ISRU production operations are to start in the early 2030s and once large-scale Lunar surface operations expand toward the lower latitudes in the late 2030s.

SOA: Photovoltaic arrays (<200 V) and deployment mechanisms suitable for LEO operations are at TRL 9. Vertical array deployment mechanisms for Lunar gravity are at a benchtop level of development. Large scale, surface-level photovoltaic arrays, at a GW_e scale and printed from Lunar-sourced silicon, are at a very early stage of conceptual development.

CURRENT INVESTMENTS

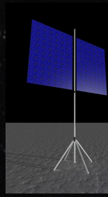
NASA:

- Earth-sourced PV Blankets:
  - *SBIR (composite Blanket)*
  - *GCD ACO (FSAP)*
  - *CLPS (PILS)*
- Earth-sourced Deployment Structures
  - *SBIR*
  - *STRG (BYU)*
  - *GCD (VSAT)*
- Earth-sourced Reflectors
  - *none*
- Dust compatibility
  - *GCD (LO-DuSST)*
  - *GCD ACO (DMFlex)*
- Lunar-sourced PV blankets
  - *None*

OGA (DoD & DoE):

- Earth-sourced PV Blankets

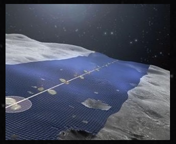
Gap C1 (α) Closure:
Bring to TRL 6 by 2030: 50 kW_e-scale photovoltaic arrays, deployed with concentrators, providing power at >200 V and at 200 W_e/kg BOL. Arrays should exhibit no more than 10% degradation over ten years in the Lunar polar environment (including shadowed periods). Deployment solutions must maximize effective low-horizon insolation within limits of specific power.



Closure Roadmap (α)

- SBIR efforts for rad-hard photovoltaic cell, blanket, and concentrator designs
- GCD efforts to bring optimized blankets (with concentrators, dust tolerance, and rad-hardened PV) to TRL 6
- Continue GCD VSAT Project
- TDM project to fly 10 KW_e-scale VSAT to support PSR prospecting in ~2025
- TDM project to fly ~50 kW_e photovoltaic arrays to support pilot plant ops in 2030

Gap C1 (Ω) CLOSURE:
Bring to TRL 6 by 2035 GW_e-scale photovoltaic blankets, printed horizontally on the Lunar surface from Lunar-sourced silicon and with minimal material brought from Earth.



Closure Roadmap (Ω):

- *STRG and SBIR efforts for Lunar silicon mining and PV array printing*
- *GCD efforts to bring integrated, printed PV generation systems to TRL 6 by 2035*
- *TDM project to fly and operate PV production equipment on the Lunar surface by 2037*

Gap C2: Long Life Grid-Scale Secondary Energy Storage

Thrust: LIVE
Outcomes: Sustainable power sources and other surface utilities to enable continuous Lunar and Mars surface operations
Taxonomy Elements: 3.2.2

Definition:
C2 (α): **Eclipse-period support of industrial scale ISRU production facilities and a crewed outpost at the Lunar pole will require Earth-sourced, large-scale, long life, maintenance-free electrical energy storage** at a MWh_e scale.
C2 (Ω): Expansion of Lunar infrastructure toward the Equator will require large scale electrical and thermal energy storage sourced from Lunar regolith..
Mission architects must know what capability will be available to them once full-scale ISRU production operations are to start in the early 2030s and once large-scale Lunar surface operations expand toward the lower latitudes in the late 2030s.

SOA: For Earth-sourced, electrical energy storage, H_2/O_2 Primary fuel cells are nearing TRL 6/7 at a 1 kW_e-scale with ~5000-hour operating life. High pressure electrolyzers of similar life and scale will be at TRL 5 at completion of NASA STMD's RFC project. Prototype flywheel energy storage systems of ~5 MWh_e capacity have been built for terrestrial grid storage applications. Electrical and thermal energy storage sourced from Lunar regolith, such as metal-oxygen flow batteries and thermal "wadis", remains at only a conceptual level of development.

CURRENT INVESTMENTS

NASA:

- PEM Primary and Regen FC
    - *GCD ACO (AARC)*
    - *GCD ACO (AMPES)*
    - *GCD ACO (LFC-Blue Origin)*
    - *GCD (RFC)*

DoD NUWC:

- PEM Primary FC
    - *Various (SNC, Teledyne)*

Gap C2 (α) CLOSURE:

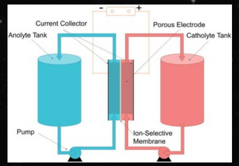
Bring to TRL 6 by 2030 an electrochemical or mechanical energy storage system in up to MWh_e and 10 kW_e increments with maximum specific energy and maintenance-free life in the Lunar polar environment of 50,000 hours and 500 charge/discharge cycles.

Closure Roadmap (α)
- LuSTR or STRG effort for reliability/life modeling
- SBIR efforts for highly durable electrochemical membranes, fluid components, and flywheel rotors and bearings.
- Continue and augment GCD and/or Tipping Point/ACO projects for ultra-long-life RFC and flywheel systems

Gap C2 (Ω) CLOSURE:

Bring to TRL 6 by 2035 GWh_e-scale secondary flow batteries formed from Lunar-sourced chemicals and large-scale thermal wadis printed from sintered regolith.

Closure Roadmap (Ω)
- *NIAC/STRG/SBIR efforts for mining Lunar minerals suitable for secondary electrochemical batteries and for sintering of regolith for thermal energy storage*
- *GCD efforts to bring integrated electrical and thermal energy storage systems to TRL 6 by 2035*
- *TDM project to fly and operate energy storage equipment on the Lunar surface by 2037*



Gap D1: Wireless Power Transmission up to 10 kW_e Increment

Thrust: LIVE
Outcomes: Sustainable power sources and other surface utilities to enable continuous Lunar and Mars surface operations
Taxonomy Elements: 3.3.2

Definition: ISRU ice mining operations in PSR (from prospecting to full-scale industry) will require power transmitted from insolated regions to mobile assets in the PSR interior.

SOA: Subscale wireless power transmission systems have been developed to the bench-top level. Relevant pointing mechanisms have been developed for terrestrial applications.

CURRENT INVESTMENTS

NASA:

- Power Beaming
  - *SBIR*
  - *PCC (WOTM)*
  - *LuSTR grant (UCSB)*

DoD:

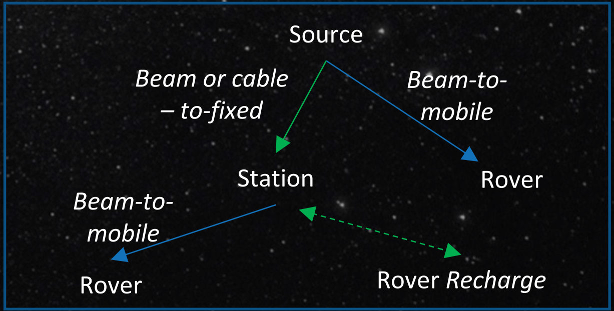
- Power Beaming
  - *Various*
- Pointing Mechanisms
  - *Various*

Gap D1 (α) Closure:

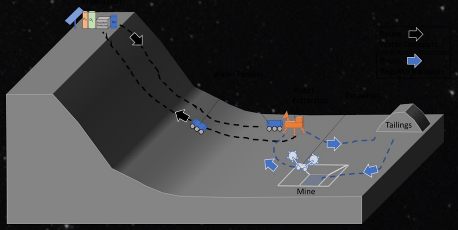
Bring to TRL 6 by 2030 a wireless transmission system delivering power at up to ~10 kW_e scale from a source in either an isolated region or a PSR to a mobile load in a PSR, losing no more than 50% source-to-load over 5 km and at maximized delivered power per unit of system mass.

Closure Roadmap (α) :

- Further SBIR efforts for beaming and pointing mechanisms
- ~100 W_e subscale demos may support CLPS applications.
- GCD project to bring full-scale system to TRL 6
- TDM projects to demonstrate 1 kW_e for 2028 PSR ice mining demo, 10 kW_e for 2030 PSR Ice Mining pilot plant



PSR Distribution/Storage Trade



Gap D2: Low Temperature Secondary Battery Modules up to 50 kWh_e Increment

Thrust: LIVE
Outcomes: Sustainable power sources and other surface utilities to enable continuous Lunar and Mars surface operations
Taxonomy Elements: 3.2.1

Definition: The principal challenge from Artemis for battery technology is mobility energy storage for ISRU operations in PSRs. SOA (Li-ion) batteries lose 75% of their room temperature (295 K) capacity when operating at 235 K. Battery modules that can deliver SOA 295 K performance in a 70 K environment can thus increase specific energy for batteries in PSRs by well over a factor of three. Such performance might be achieved with a combination of cells developed to perform better at lower temperatures, improved insulation/thermal management hardware, and supplemental radioisotope heat sources.

SOA: Li-ion battery modules at 50 kWh-scale can deliver ~500 cycles at 150 Wh_e/kg at 290 K. Insulation and active thermal management hardware are required to maintain the cells in this temperature range when operating in colder environments.

CURRENT INVESTMENTS NASA:

- Cells
  - *ECF (various)*

Gap D2 (α) Closure:
Bring to TRL 6 by 2030 a 50 kWh-class battery module with capability to provide greater than net* 150 Wh_e/kg specific energy at 1 kW_e discharge for 500 cycles in a 70 K environment and to survive with full operational capability after long-duration cold soak at 70 K.
**net of module insulation, extra heat sources, or extra cells to feed heaters.*

Closure Roadmap (α):
- Further SBIR efforts for cell development, thermal management systems, and supplemental (e.g., radioisotope) heat sources.
- GCD project to bring full-scale system to TRL 6
- TDM projects to demonstrate 1 kW_e for 2028 ice mining demonstration

Gap D3: Radioisotope Power Sources in ~100's W_e Increment

Thrust: EXPLORE
Outcomes: Develop vehicle platform technologies supporting new discoveries
Taxonomy Elements: 3.1.2, 3.1.4

Definition: A key strategic mission for NASA's Science Mission Directorate (SMD) and for STMD is an understanding of the distribution of resources in the permanently shadowed regions of the Lunar South Pole. A multi-100 W_e, sun-independent power source is required for mobility assets to conduct through prospecting in the 2026 timeframe. Smaller power sources (~100 W_e) required for CLPS-class science exploration missions in PSR

SOA: The current MMRTG can deliver ~125 W_e BOL from ^{238}Pu General Purpose Heat Sources (GPHS). Its availability for the Lunar PSR prospecting mission is constrained in favor of its value for long duration, deep space missions.

CURRENT INVESTMENTS NASA/DoE:

- SMD RPS program
  - *DRPS Project*

Gap D3 Closure (α)
Bring to TRL 6 by 2024 a 100's W_e-class power source based on radioisotopes other than ^{238}Pu and delivering specific power of at least 2 W_e/kg for at least 1 year.

*"heat-source" = heat source material, analogous to PuO_2

Closure Roadmap (α):

- Augment and accelerate SMD's Dynamic Radioisotope Power System (DRPS) project to integrate with heat sources other than ^{238}Pu.
- GCD Projects on alternative radioisotopes and conversion techniques.

Gap D4: Solar Heliostats/Reflectors up to 30 kW_{solar} Increment

Thrust: LIVE
Outcomes: Sustainable power sources and other surface utilities to enable continuous Lunar and Mars surface operations
Taxonomy Elements: 3.3.2

Definition: ISRU ice mining operations in PSR (from prospecting to full-scale industry) will require power transmitted from insolated regions to mobile assets in the PSR interior.

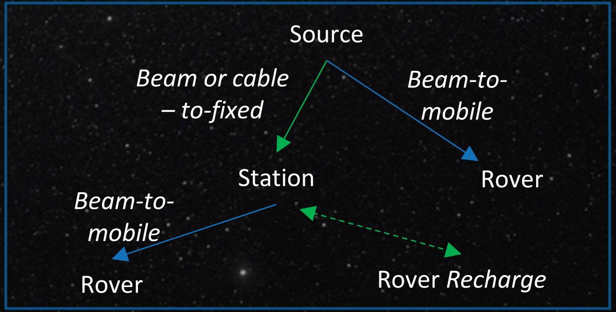
SOA: Heliostats have been developed for terrestrial applications at large (MW_t) scales. However, no examples have gone beyond TRL 3 for space applications

CURRENT INVESTMENTS

- Heliostat
  - *NAIC/LaRC (LightBender)*

Closure (α):
Bring to TRL 6 by 2030 a heliostat optics system directing the Lunar solar flux at a 30 kW_{solar} scale across wavelengths from 330 to 1800 nm from an insolated region to a mobile or static receiver in a PSR with losses of no more than 5% over a distance of 3 km and at maximum delivered solar flux per unit of heliostat mass.

Closure Roadmap (α):
- SBIR/ESI efforts for lens and reflector development
- GCD project to bring full-scale system to TRL 6



PSR Distribution/Storage Trade

Gap D5: Superconducting Cable Transmission

Thrust: LIVE
Outcomes: Sustainable power sources and other surface utilities to enable continuous Lunar and Mars surface operations
Taxonomy Elements: 3.3.2

Definition: ISRU ice mining operations in PSR (from prospecting to full-scale industry) will require power transmitted from insolated regions to mobile assets in the PSR interior.

SOA: High Temperature Superconducting (HTS) wires have been developed which show transition to the superconducting state at ~ 100 K. These have been successfully used terrestrially in magnetic coil applications However, no examples have gone beyond TRL 3 for space applications.

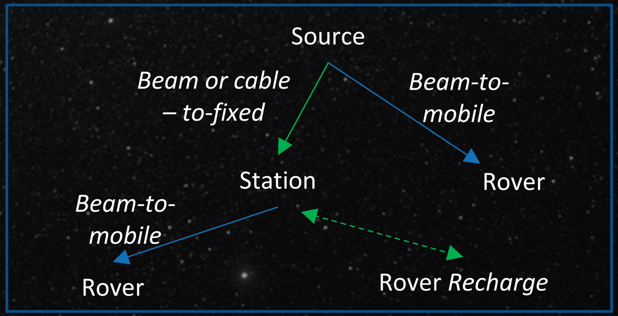
CURRENT INVESTMENTS

- None

Closure (α):
Bring to TRL 6 by 2030 an HTS cable system capable being spool-deployed across up to 5 km across the Lunar regolith in the PSR thermal environment and of operating at specific power greater than that of copper- or aluminum-based cables for 10 years in the Lunar PSR radiation, dust, hard vacuum, and thermal environments.

Closure Roadmap (α):

- SBIR/ESI efforts for materials development
- GCD project to bring full-scale system to TRL 6



PSR Distribution/Storage Trade

Gap E: CH_4/O_2 Primary Fuel Cell Power up to 10 kW_e Increment

Thrust: LIVE
Outcomes: Sustainable power sources and other surface utilities to enable continuous Lunar and Mars surface operations
Taxonomy Elements: 3.2.

Definition: Primary power from LO_2/LCH_4 reactant storage may be the mass-optimal solution for certain Lunar/Mars mobility assets and Landers

SOA: Air/Natural Gas Solid Oxide Fuel Cells are in common terrestrial use up to ~50 kW_e scale. Multi-kW_e-scale Jet Fuel/O_2 power plants tested by USN NUWC in operational configurations. NASA and vendors have tested LO_2/LCH_4 SOFC 1 kW_e-scale in breadboard configurations.

CLOSURE:
Bring to TRL 6 by 2032 LO_2/LCH_4 primary fuel cell power generation systems in up to 10 kW_e increments with maximum specific energy and maintenance free life in the Lunar polar or Martian environments of 10,000 operating hours

CLOSURE PLAN:
- Further SBIR efforts for cell development and thermal management systems
- GCD project to bring full-scale system to TRL 6

CURRENT INVESTMENTS

NASA:
- SOFC
    - *SBIR Ph 3 (Precision Combustion)*