Space Power Workshop
Celebrating 40 Years of Space Power: Supporting mission success in an increasingly agile space domain
April 25–27, 2023 | Torrance Marriott Redondo Beach | Torrance | CA

EXPLORE SPACE TECH
TECHNOLOGY DRIVES EXPLORATION

Lunar Surface Power Systems

- Moon2Mars Objectives
- Agency Vision for Lunar Surface Power
- Power Building Blocks and Technology Gaps
- System Reliability and Resiliancy

John H Scott | Principal Technologist, Power and Energy Storage, Space Technology Mission Directorate | April 9, 2023

NASA Moon2Mars Strategy and Objectives

Released 6 April 2023

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)

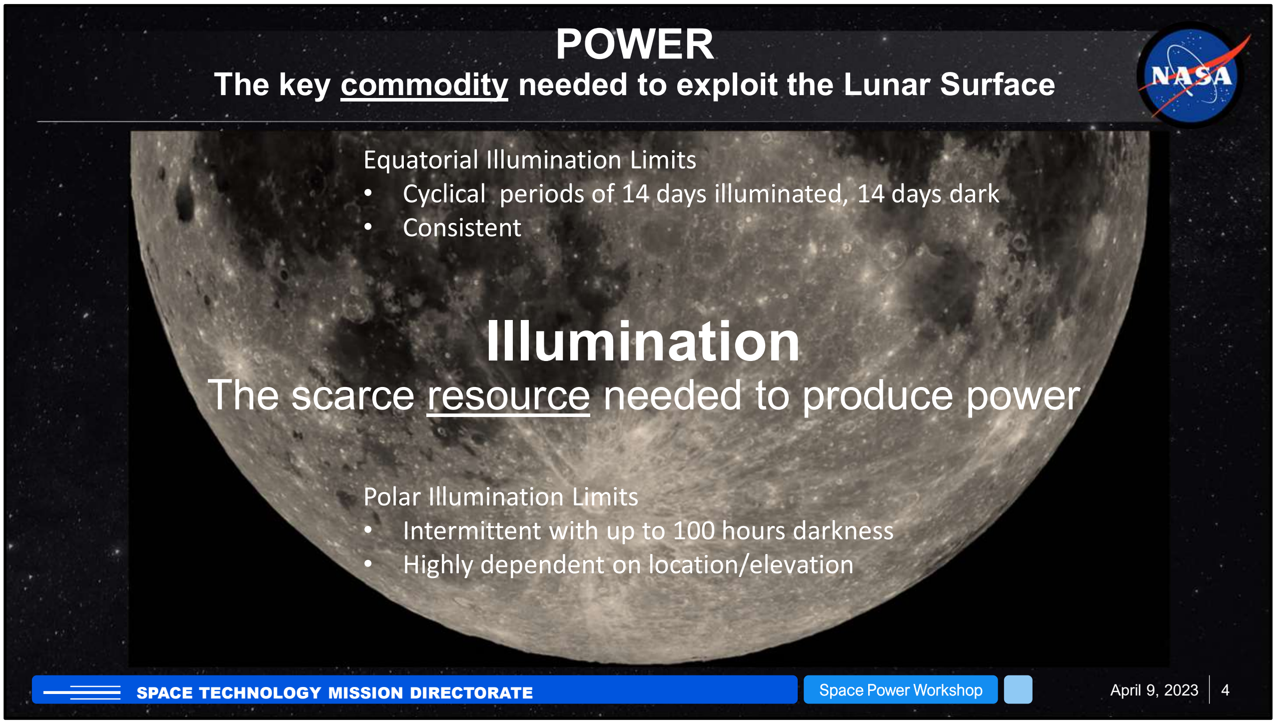
MI-1: Develop Mars surface power sufficient for and initial human Mars exploration campaign

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

NASA Moon2Mars Strategy and Objectives

Omnibus Appropriation Bill – FY2023: NASA STMD

- *Lunar Surface Power.*—In addition to the reporting requirement in the House report, the agreement urges NASA to devote the re- sources required to ensure that lunar surface power systems, such as vertical solar arrays and fission surface power, are fully developed and prepared for deployment when the time for surface missions arrives in the mid-2020s. In lieu of the funding provided in the House report, the agreement provides up to $40,000,000 for payload development and delivery to the lunar surface via the Commercial Lunar Payload Services (CLPS) program to execute a surface power demonstration by 2026. NASA is also encouraged to identify areas of alignment between nuclear propulsion and fission surface power research.
  - *HOUSE LANGUAGE Lunar Surface Power.*—The Committee recognizes the need for steady, reliable, and uninterrupted power for future extended science and exploration missions on the lunar surface, particularly at the poles, and is supportive of past and ongoing investments in a mix of technologies, including both Vertical Solar Array Technology (VSAT) and Fission Surface Power (FSP). The Committee notes the strategic benefits of a portfolio approach to lunar surface power, including affordability, mobility, and readiness. NASA is directed to sponsor the development and deployment of a mix of lunar surface power solutions in support of the Artemis program and to enable the commercialization of lunar power as a service. NASA is directed to report to the Committee not later than 180 days after enactment of this Act on its plan to leverage investments made in surface power with its over-arching plan for a sustainable lunar presence into the 2030s. Further, the Committee directs the Space Technology Mission Directorate to utilize existing technology maturation efforts with commercial partners to execute one surface power demonstration by 2026 and provides $40,000,000 in fiscal year 2023 to begin this initiative. Funds provided for this demonstration shall be used for both payload development and for associated delivery services to the lunar surface via the Commercial Lunar Payload Services program


POWER
The key commodity needed to exploit the Lunar Surface
NASA
Equatorial Illumination Limits
• Cyclical periods of 14 days illuminated, 14 days dark
• Consistent
Illumination
The scarce resource needed to produce power
Polar Illumination Limits
• Intermittent with up to 100 hours darkness
• Highly dependent on location/elevation
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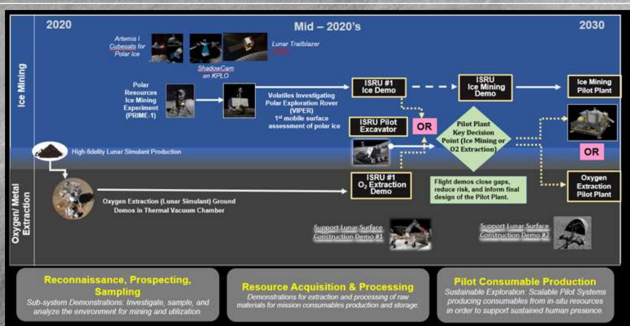
Space Power Workshop
April 9, 2023
4

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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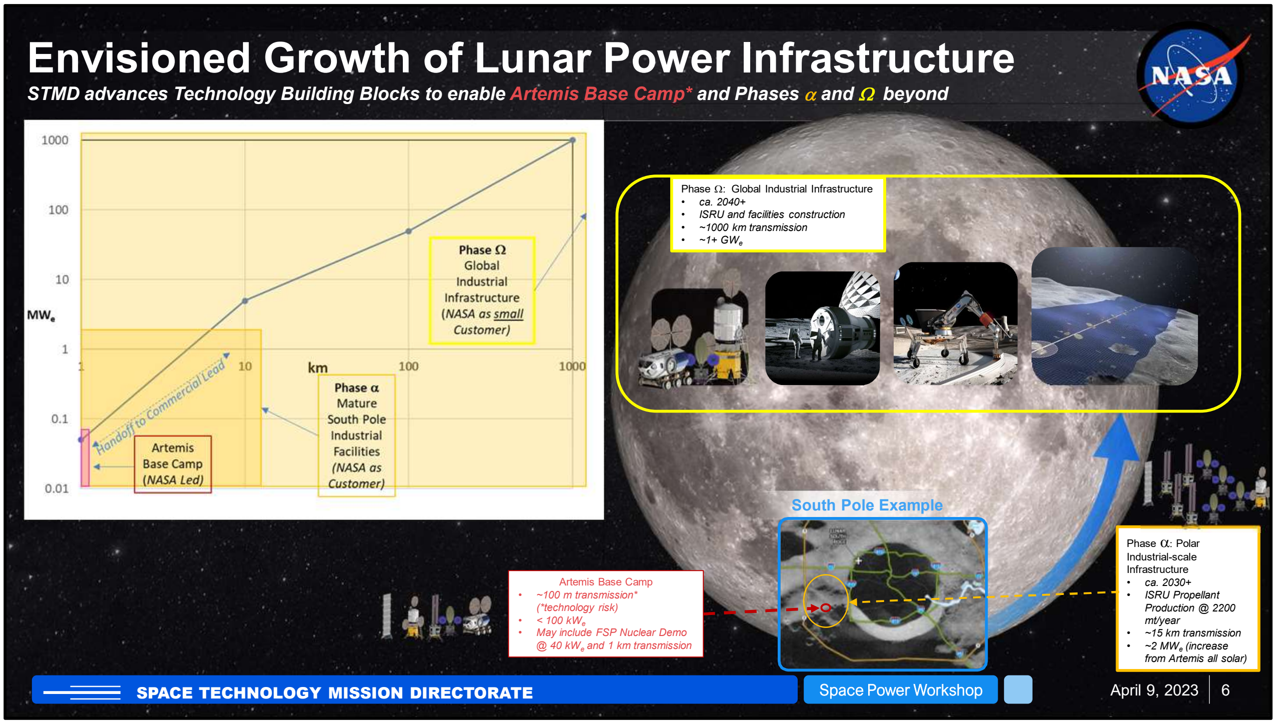
Envisioned Growth of Lunar Power Infrastructure
STMD advances Technology Building Blocks to enable Artemis Base Camp* and Phases α and Ω beyond
NASA
1000
100
10
1
0.1
0.01
MWe
1
10
km
100
1000
Handoff to Commercial Lead
Artemis Base Camp (NASA Led)
Phase α Mature South Pole Industrial Facilities (NASA as Customer)
Phase Ω Global Industrial Infrastructure (NASA as small Customer)
Phase Ω: Global Industrial Infrastructure
• ca. 2040+
• ISRU and facilities construction
• ~1000 km transmission
• ~1+ GWe
South Pole Example
Artemis Base Camp
• ~100 m transmission* (*technology risk)
• < 100 kWe
• May include FSP Nuclear Demo @ 40 kWe and 1 km transmission
Phase α: Polar Industrial-scale Infrastructure
• ca. 2030+
• ISRU Propellant Production @ 2200 mt/year
• ~15 km transmission
• ~2 MWe (increase from Artemis all solar)
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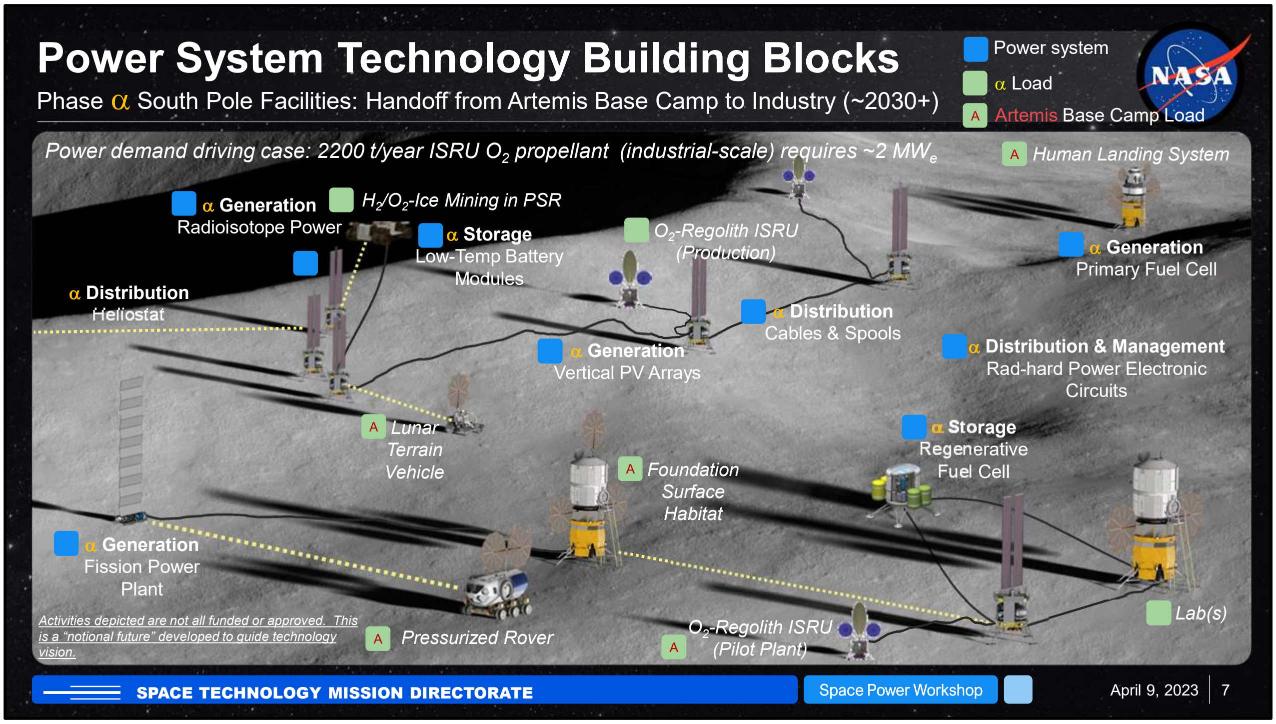
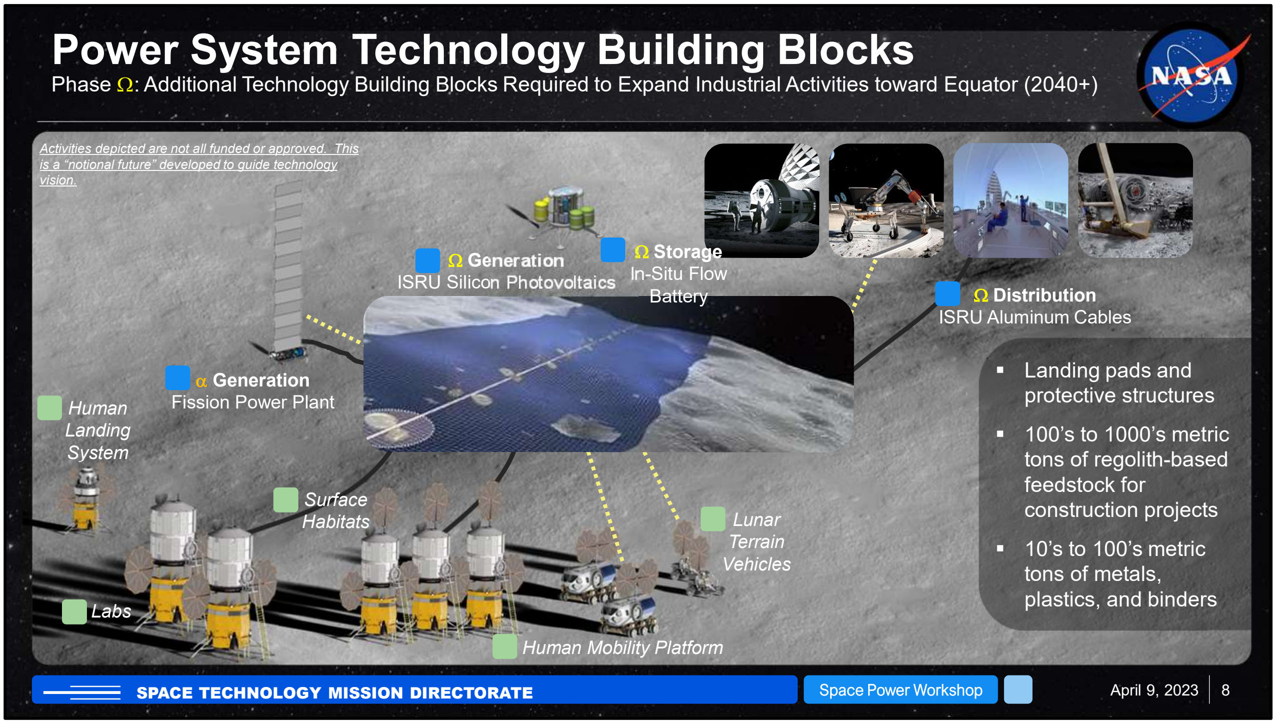
Space Power Workshop
April 9, 2023
6

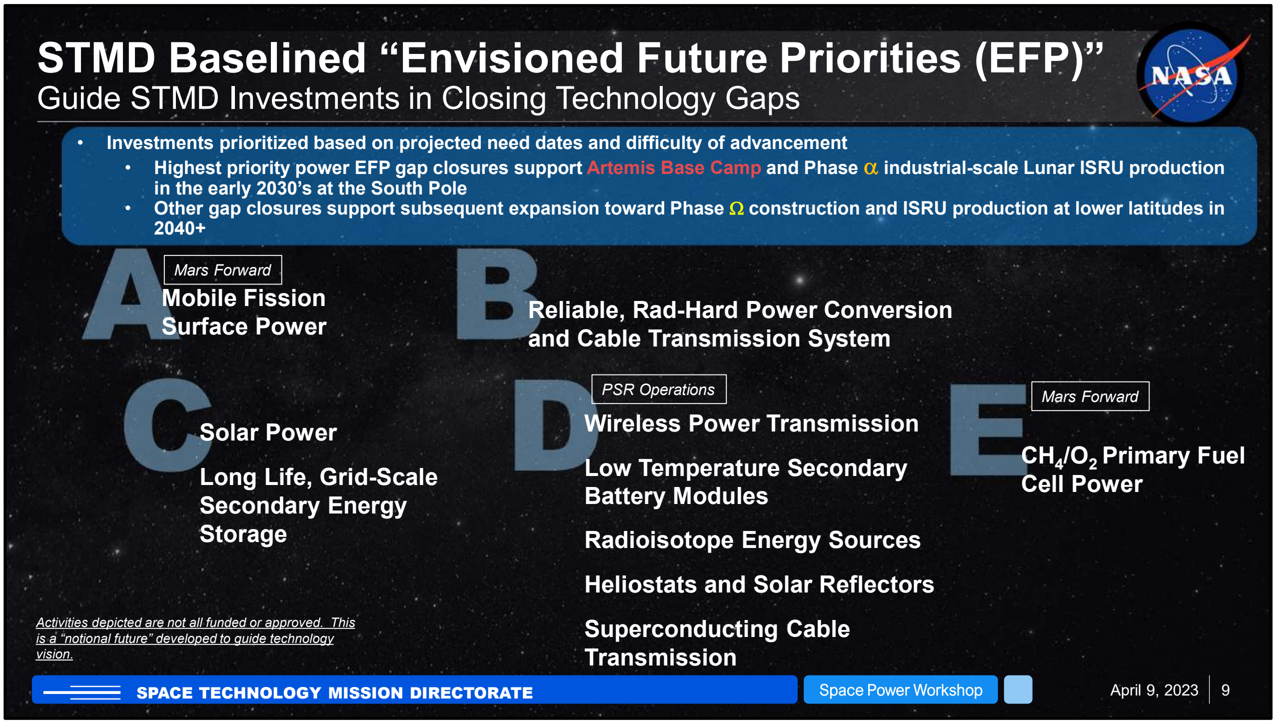


NASA Space Technology Mission Directorate has identified a number of technology building blocks as required to enable this surface power system, whose development is being subsidized by NASA

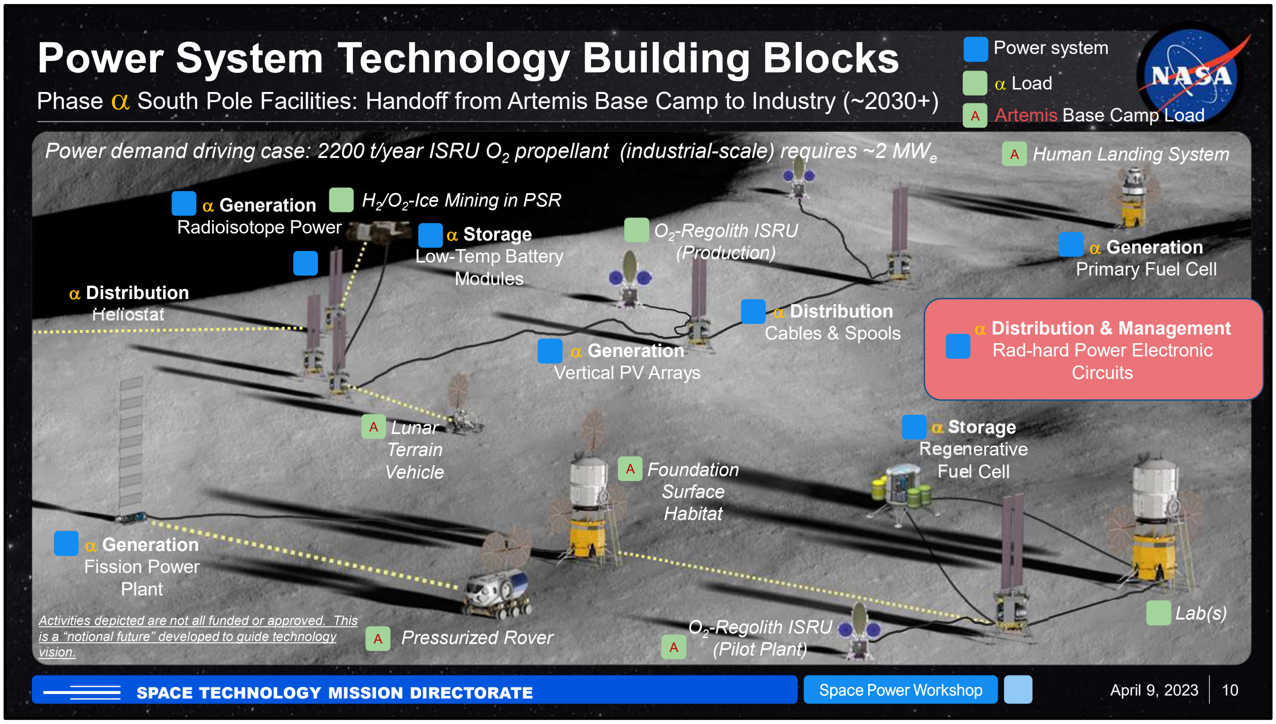
Loads identified with the A are part of the Artemis base camp (each of which has its own independent power source. Other elements are to be delivered by commercial partners to make up the Phase alpha surface system



Further building blocks will be needed to get to the ultimate Phase omega.



NASA STMD has prioritized the efforts ("Gap Closures" to bring about the various building blocks. Note Gap D, which includes several items all related to operations in the PSR. Gaps A-C are generic needs for Lunar surface power. Gap E is Mars forward.



None of these building blocks or growth ambitions will do any good if the whole grid goes dark on the first Solar storm. This is where we're going to get bit.

Power electronics which are reliable in the Lunar surface environment thus make up the most important of the technological building blocks.

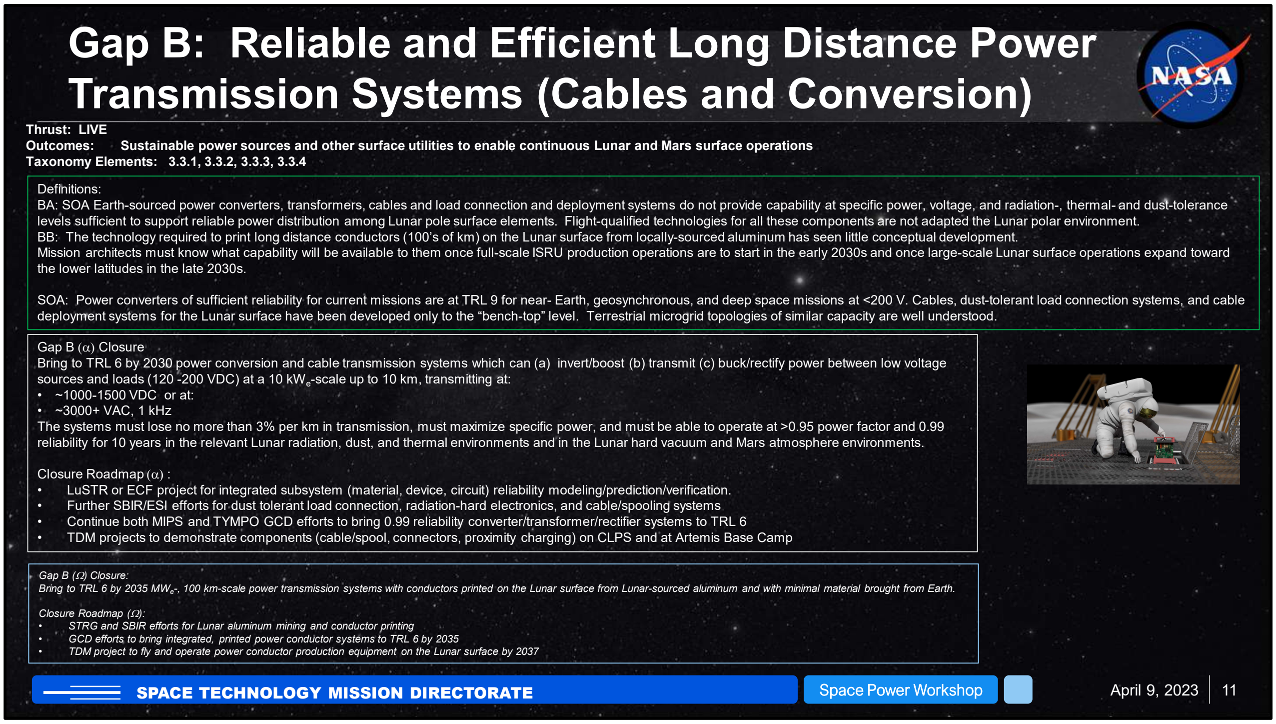
However, the direction for NASA to enable "Power-as-a-service" means that NASA is not going to be the architect of the grid. Private capital will be.

There are many possible grid topologies, and, as Lunar surface activity grows, the grid will be reconfigured many times. Reliability requirements have a lot of subtle effects on the architecture. The commercial grid provider(s) must select the best configuration at each stage, providing the reliability that power customers demand at the minimum cost.

NASA's role as "first out the gate" customer for power is to:

- Subsidize development of technology to maximize component reliability in the Lunar environment

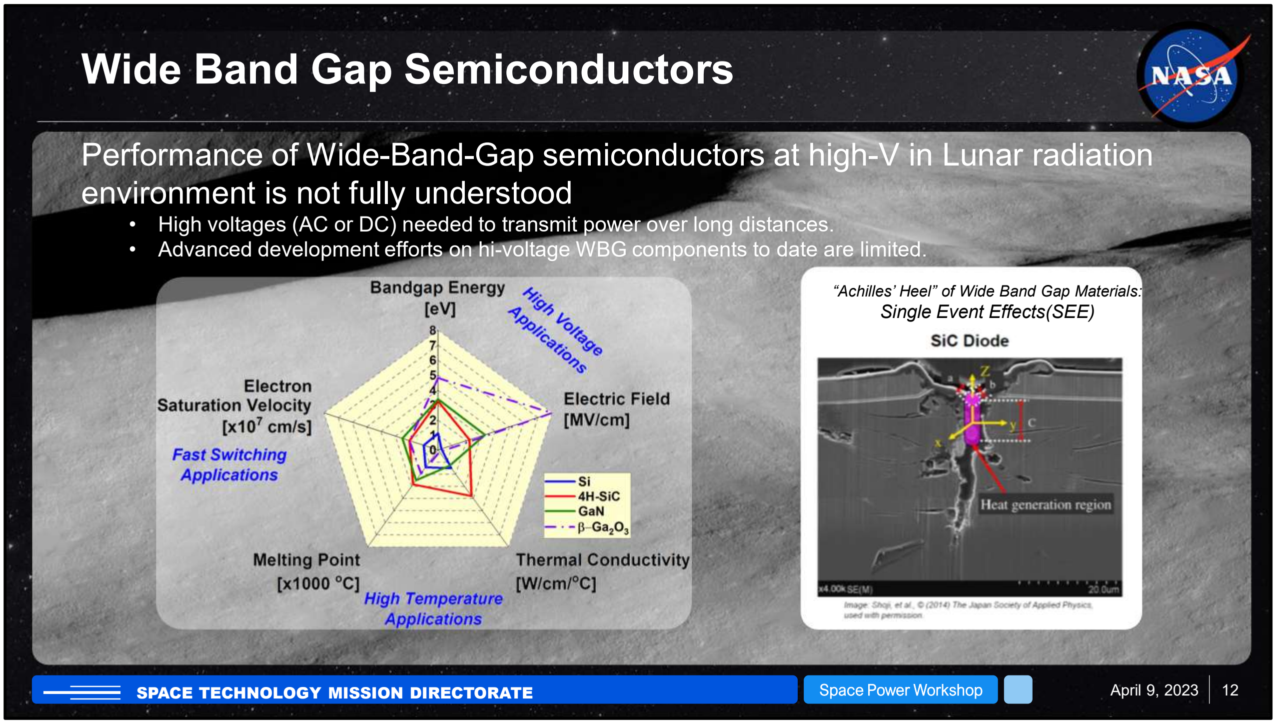
- Set up a consensus-building community to agree upon design standards for components, interface power quality, and reliability analysis and PRA methods to assess system reliability against customer requirements.



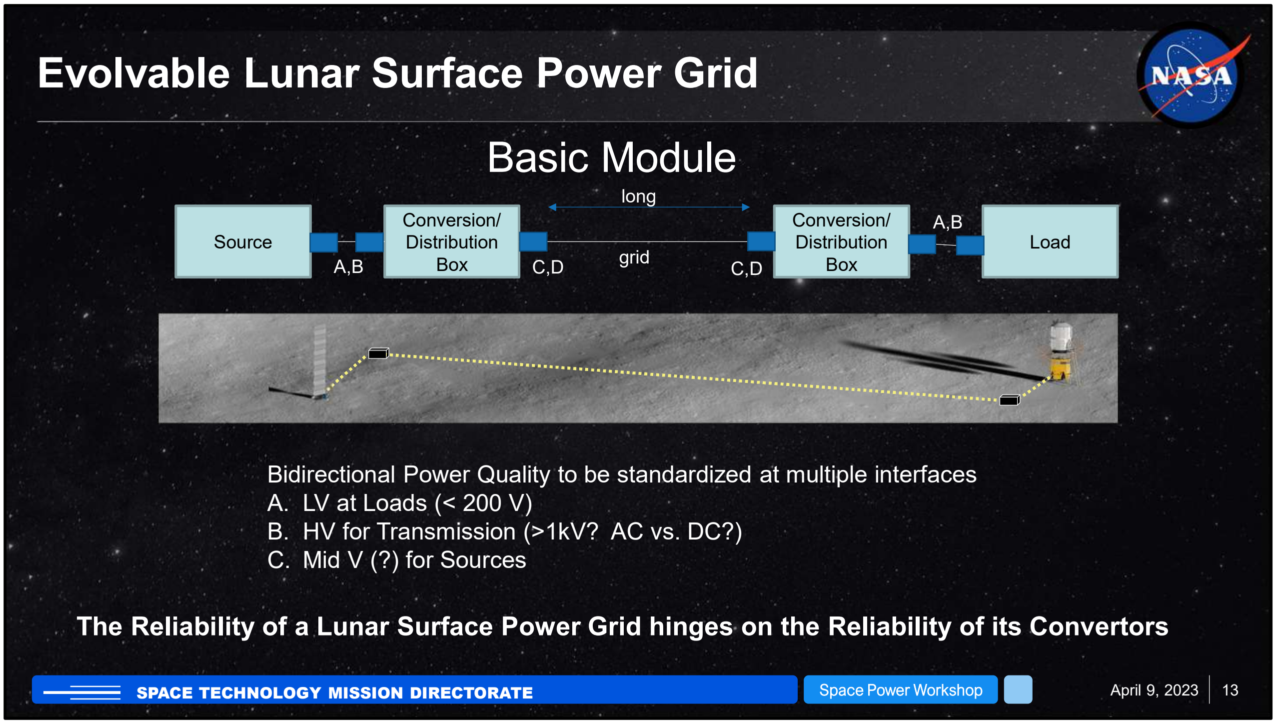
The high priority Gap defined for power transmission is closed by technology efforts in:

- Semiconductors
- Convertor circuit design (AC vs DC)
- Cable design
- Connector design

All tolerant of the Lunar surface environment (radiation, temperature, dust) with maximum prior reliability with a narrow distribution.



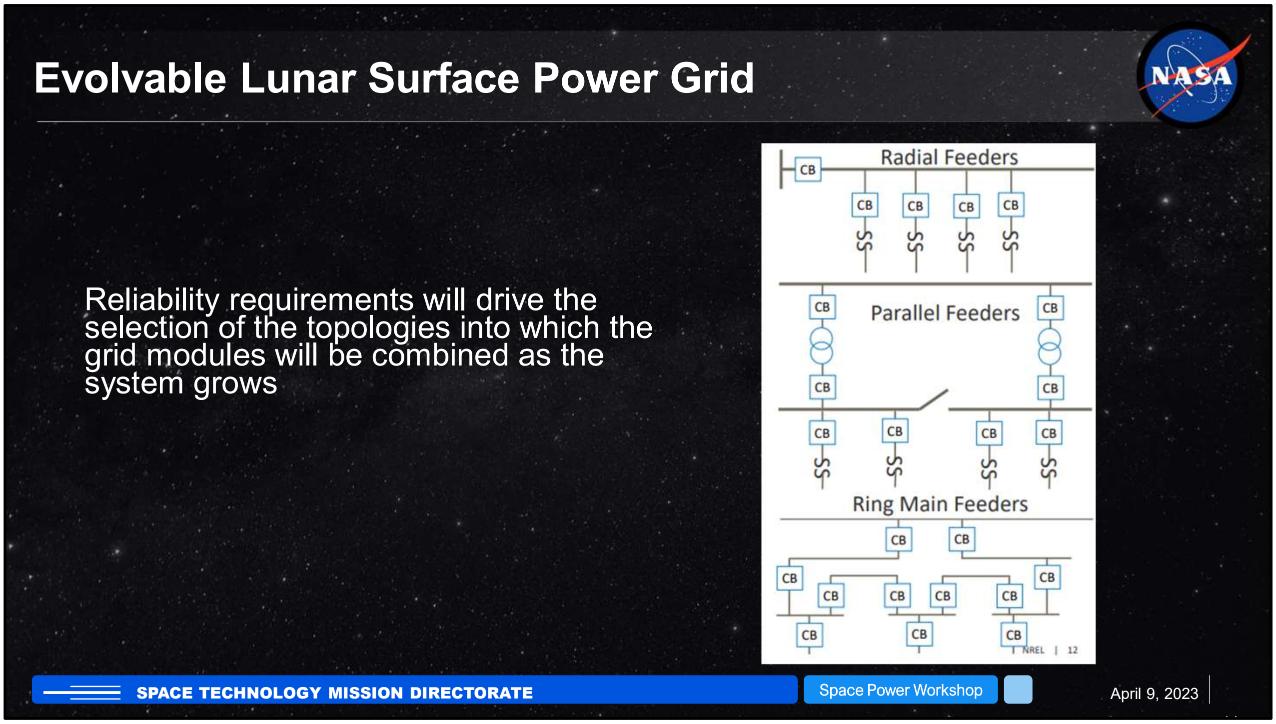
- The "achilles heal" of WBG semiconductor devices is SEE. NASA is funding development efforts in Si-C, GaN, Ga2O3 and diamond to determine which offers the best combination of properties and availability. Note that NASA's demand is so small as to have little influence on the availability.



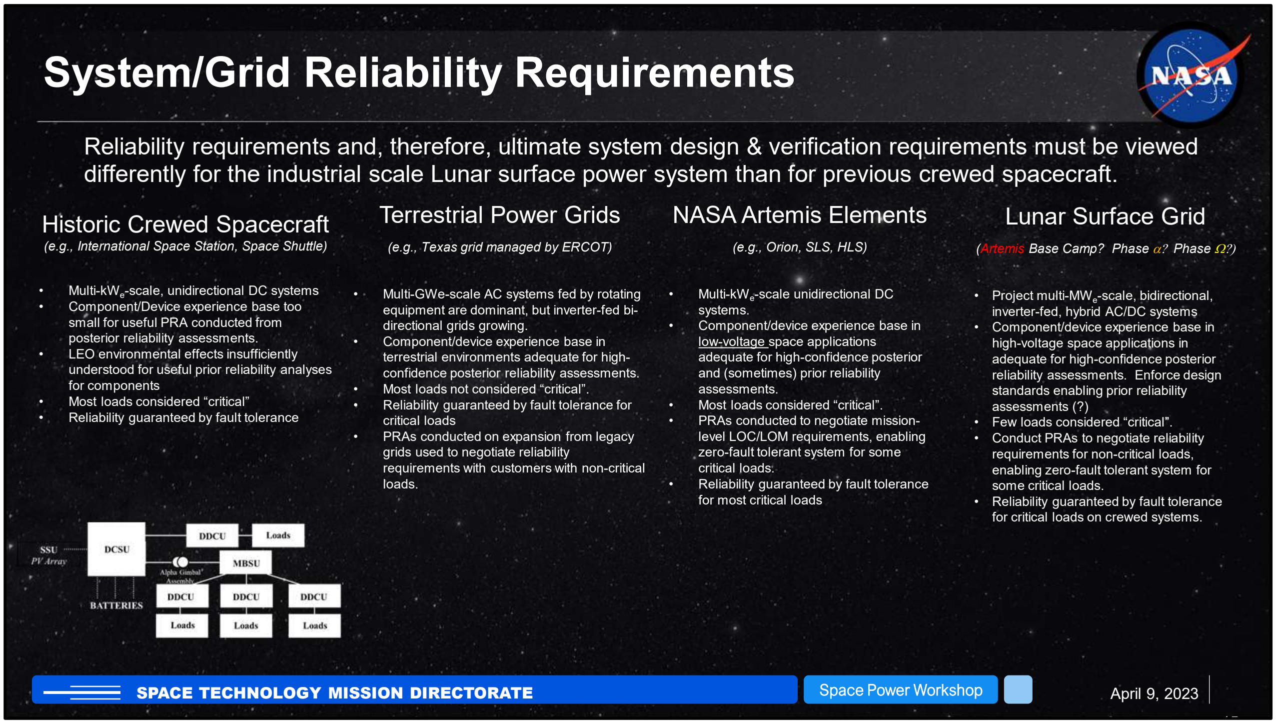
WBG Devices are more radiation tolerant (reliable) at low voltages. This calls for a trade between AC and DC for long distance transmission.

- Convertors operating at low voltage can be combined with AC transformers to make a low frequency (50Hz to ~2 kHz) grid.
- Alternatively, Low voltage converters can also be combined in redundant series arrays to get high DC voltages. This would allow a DC grid.
    - Terrestrial HVDC lines often use a similar redundancy scheme.

This trade needs to be made on reliability as well as on specific power and will inform power quality standards at the various interfaces in the grid.



This will in turn inform the choice of optimal topology as the power grid grows.



Trades on devices, components, modules, and topologies all roll up into a system reliability assessment.

Reliability management for the future Lunar surface power system may be a combination of the Artemis element paradigm and terrestrial grid paradigm.

Reliability requirements will have be negotiated across a diverse community of source providers and load customers.

Much more study to be done.

Oldest surviving human writings refer to the Moon as a light or sign but also as a source of riches.

In 1865, When Jules Verne sat down in Paris to write the book that kicked off the space age, reasonable people still believed there might be life on the Moon.

Maybe by the bicentennial of Verne's book, there will be life on the Moon and riches untold found.