Establishing a Lunar Surface Power Grid

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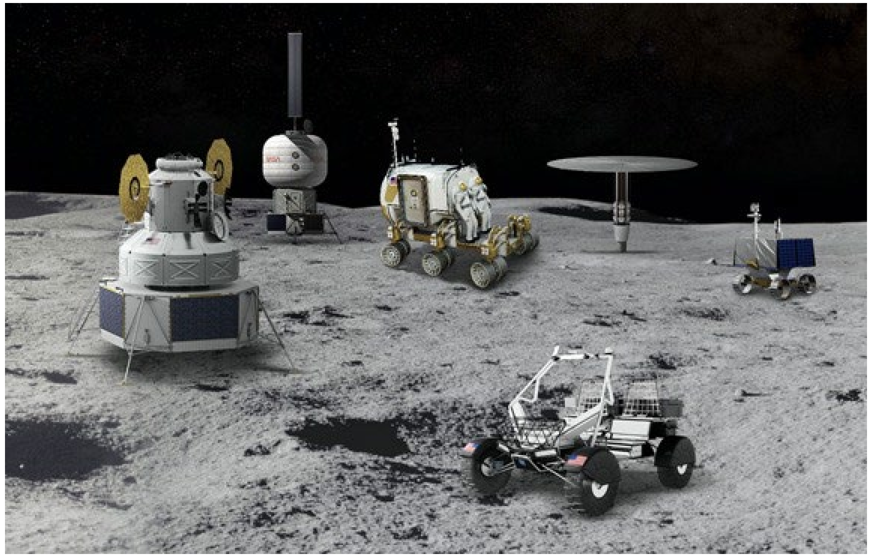
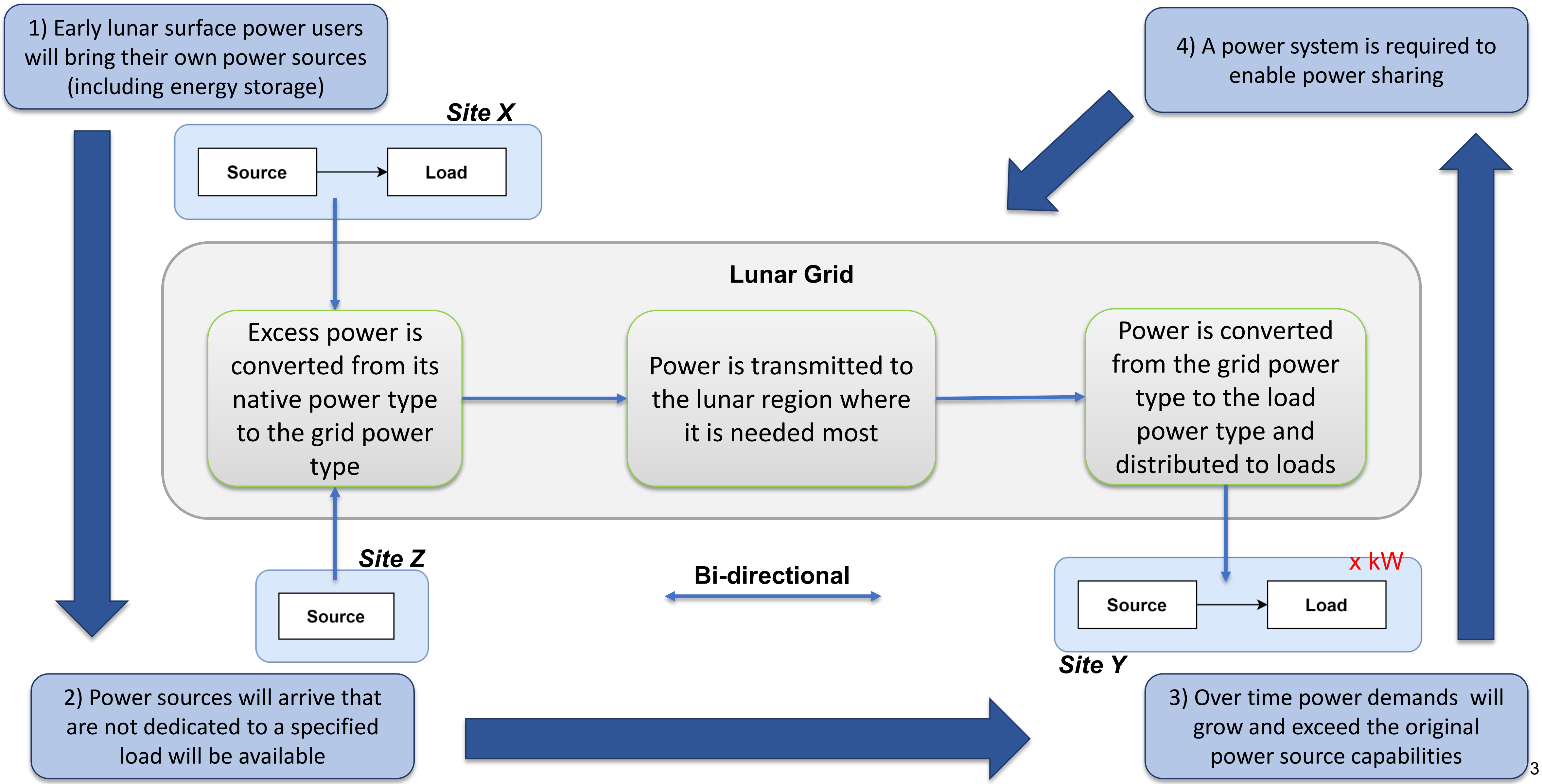
Background

- **NASA's long term vision includes crewed missions to Mars**
- **Current focus is on Artemis program**
  - First 21st century crewed lunar mission
  - Will demonstrate key Mars enabling technologies
    - Permanent habitat
    - In-situ resource utilization (ISRU)
    - Fission surface power (FSP)



- **Anticipating expansion to commercial lunar economy**
- **Artemis and future planetary surface missions require highly available and reliable power**
  - Power needs to be as reliable/universal as terrestrial utility
  - Necessitates planetary surface power grid

Expected Evolution of Lunar Surface Power (Lunar Grid)



Evolution of Lunar Power Systems

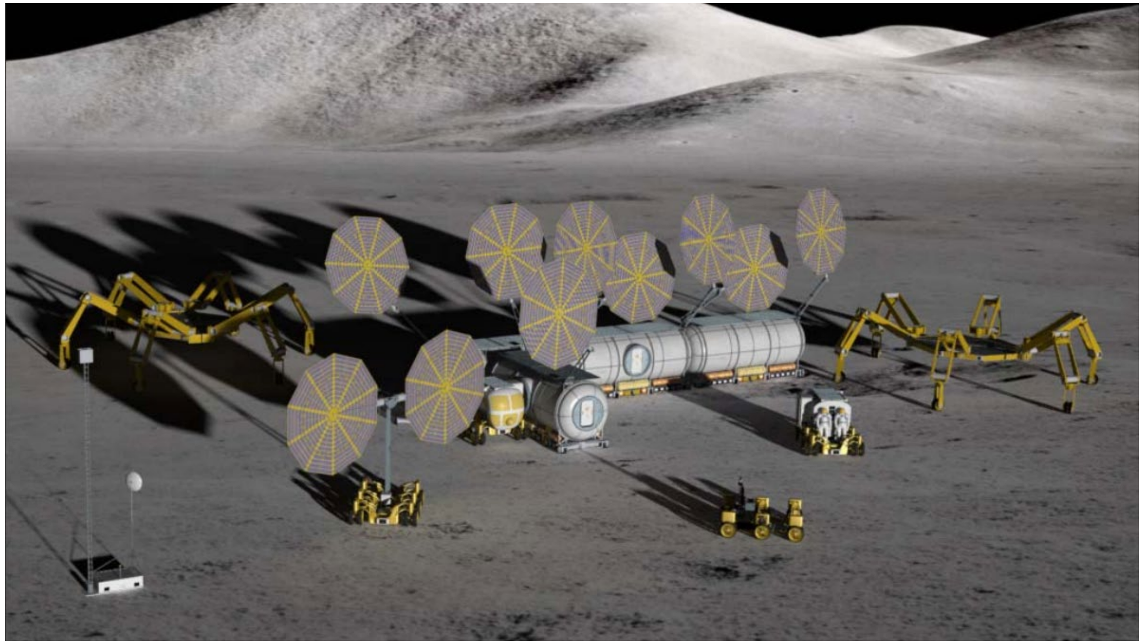
Artemis
Beyond Artemis

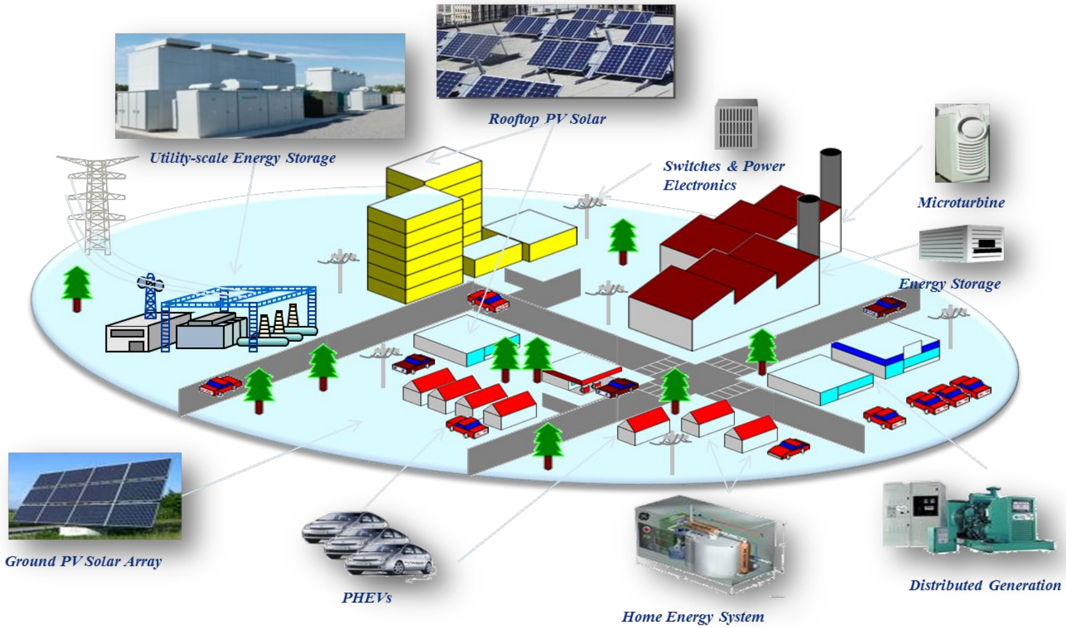
- **Initial Lunar Power Needs (~1 – 5 kW)**
  - Exploration and lunar science (robotics, rovers, etc.)
  - Sources: solar arrays, primary fuel cells, and batteries
- **Initial Demonstrations (~10 – 20 kW)**
  - Lunar habitat, first ISRU systems, exploration, and lunar science
  - Sources: solar arrays, primary fuel cells, and batteries
- **Advanced Demonstrations (~80 – 100 kW)**
  - Lunar habitat, full scale ISRU, exploration, and lunar science
  - Sources: solar arrays, primary fuel cells, fission surface power, regenerative fuel cells and batteries
- **Lunar Expansion / Globalization (~1 MW – 100s MW)**
  - In-space: In-space manufacturing demonstrations
  - Sources: solar arrays, primary fuel cells, fission surface power, regenerative fuel cells and batteries
- **Full Lunar Economy (~100s MW – 1 GW)**
  - In-space manufacturing, commercial operations, etc.
  - Sources: solar arrays, primary fuel cells, fission surface power, regenerative fuel cells and batteries

Lunar surface activities and the need for power will continue to grow and evolve

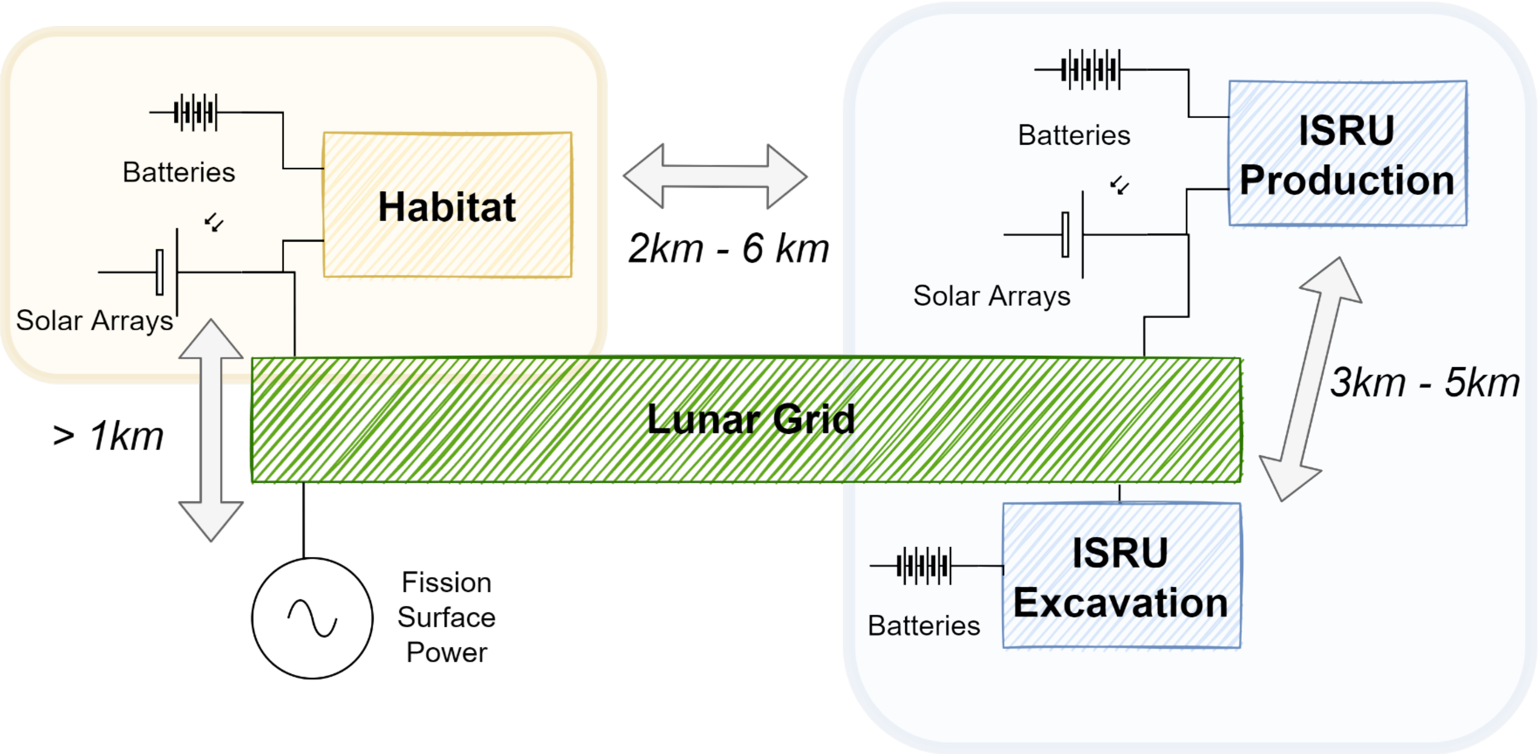
Case for a Lunar Power Grid

- **Lunar power grid to provide electrical power**
  - Flexibility, evolvability, and reconfiguration
  - Optimal dispatch of power sources and energy storage to service loads & enhance reliability
  - Systematic integration of new sources and loads
  - Allow development and use of a common grid interface
  - **Allows for the deployment of future loads that do not need to carry their own power generation**





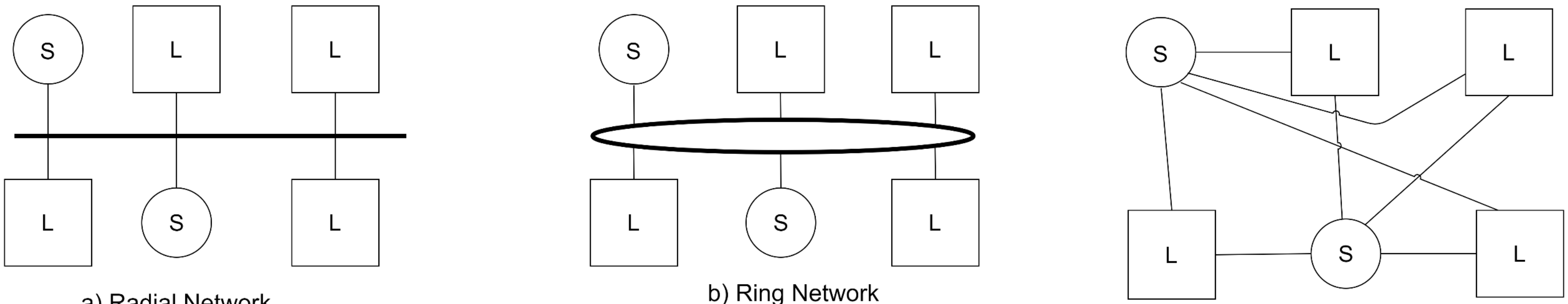
Baseline Artemis with a Lunar Microgrid



- **Create a regional lunar grid with:**
  - Primary distribution system to enable power sharing between local microgrids
  - Additional power source (FSP) that can be utilized by local microgrids
- **NASA has conducted grid trade studies to inform grid and interface converter design**

Artemis Grid Trade Study

- **Electrical Power System—Sizing and Analysis Tool (EPS-SAT) used for studies**
  - MATLAB-based tool for power system concept analysis, available for general govt purpose use
  - https://software.nasa.gov/software/LEW-20017-1
  - Planetary surface cable and converter models developed and used for this work
- **Transmission bus voltage, power type, and frequency allowed to vary**
  - Voltage: 1.2 kV to 6 kV, DC and 3-Ph AC
  - Frequency: 60 Hz to 1 kHz
- **Evaluate radial, ring, and mesh architectures for overall grid design**

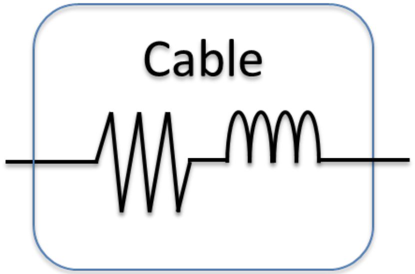


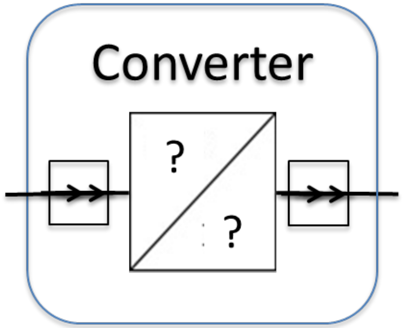
a) Radial Network b) Ring Network c) Mesh Network

Trade Study Assumptions

- **Cables**
  - Copper 10-14 AWG wires with ETFE insulation (~90% design efficiency at 40 kW)
  - If individual wire cannot handle the line power, a bundle of parallel wires will be used
  - Skin/proximity effect, inductance, temperature modeled, others (e.g. regolith) ignored
- **Converters**
  - 95% efficient if DC-DC (bidirectional DC-DC)
  - 96.5% efficient if DC-AC (bidirectional inverter)
  - 98% efficient if AC-AC and no AC frequency changes (a transformer)
- **Loads/Sources**
  - Habitat includes 2x 10 kW, 120 VDC sources, and 20 kW load
  - ISRU includes 8x 10 kW 120 VDC sources, and 68 kW load
  - FSP is a 40 kW AC source

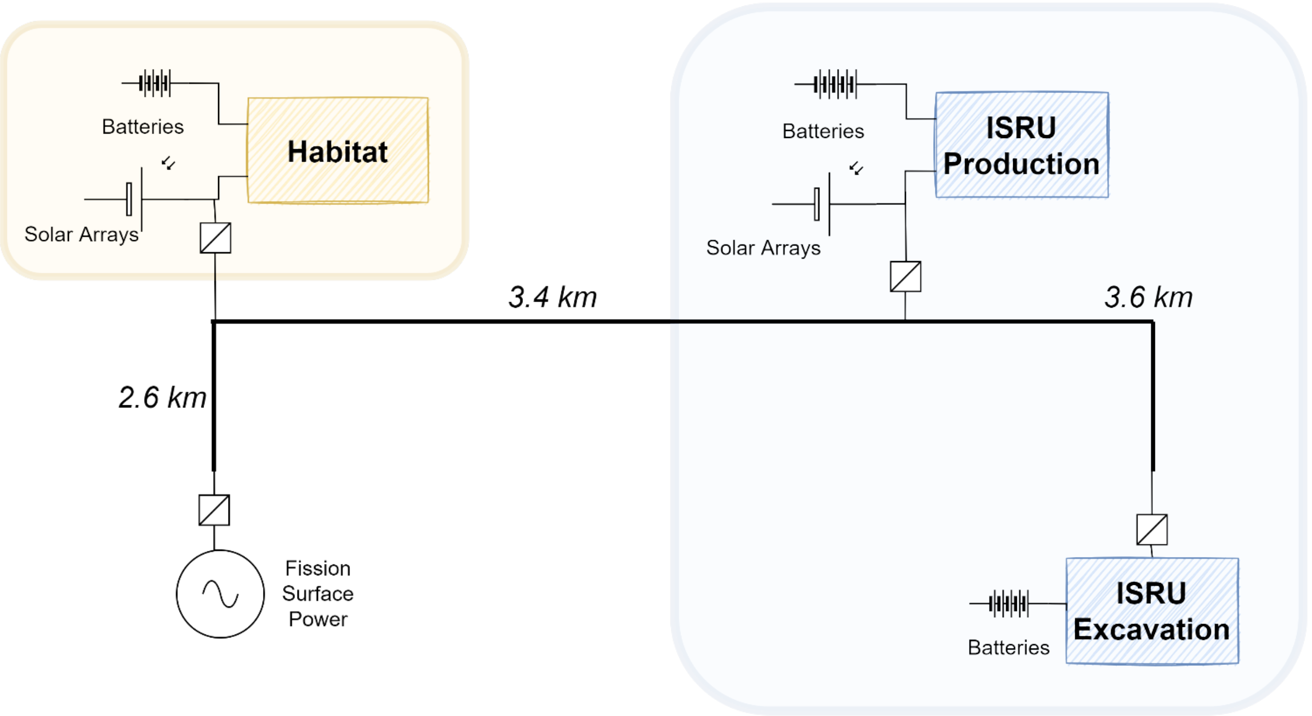
- <u>**Constant design efficiency for each voltage**</u>





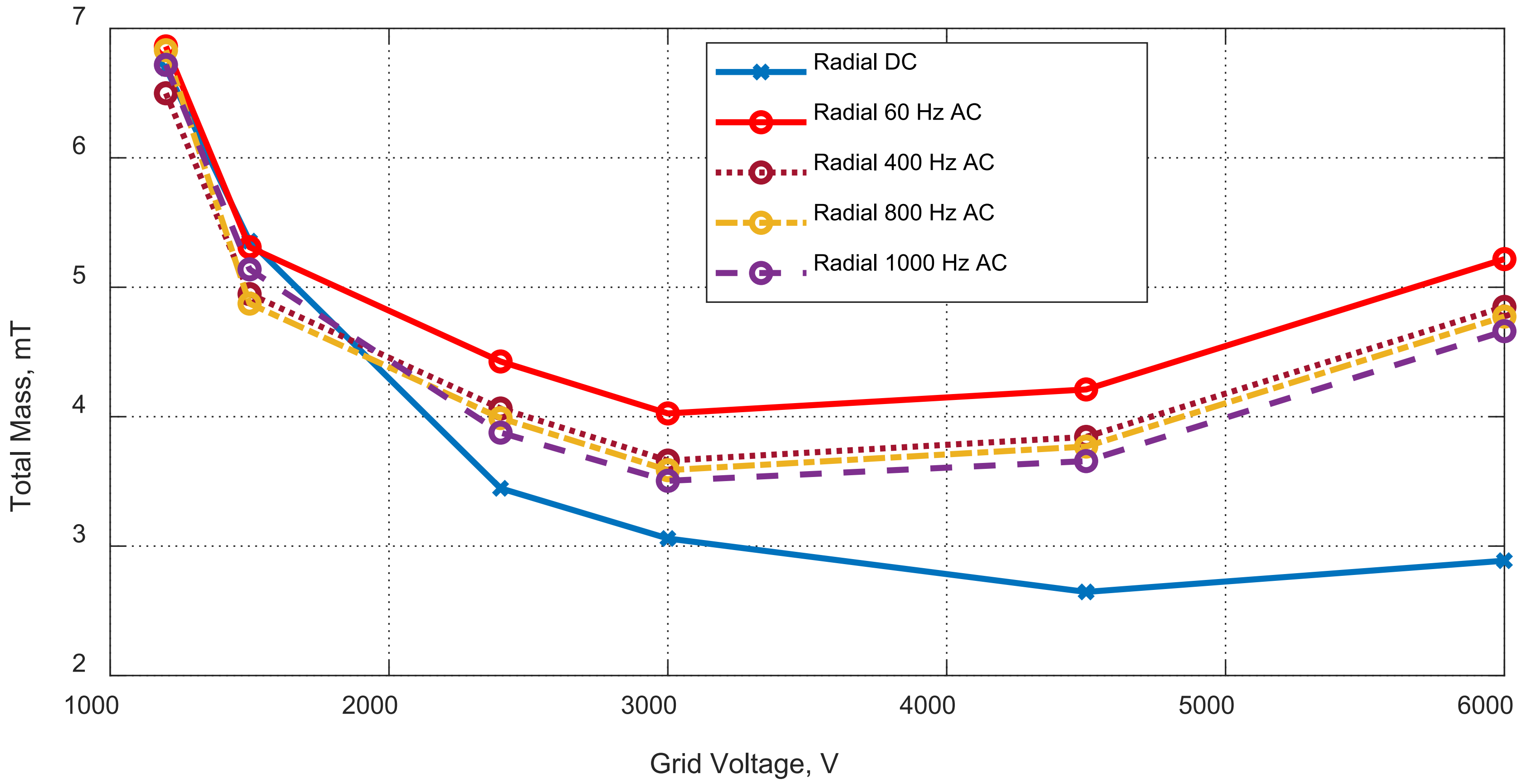
Radial Architecture

- **Radial System Assumptions**
  - Assume high voltage bus is near habitat
    - Brings ISRU and FSP power to habitat, to serve as a backup
  - Excess FSP power can flow to ISRU if habitat power needs are satisfied first
- **Radial Advantages**
  - Simple (lower implementation cost)
  - Lightweight
- **Radial Disadvantages**
  - Lack protection / redundancy during failure



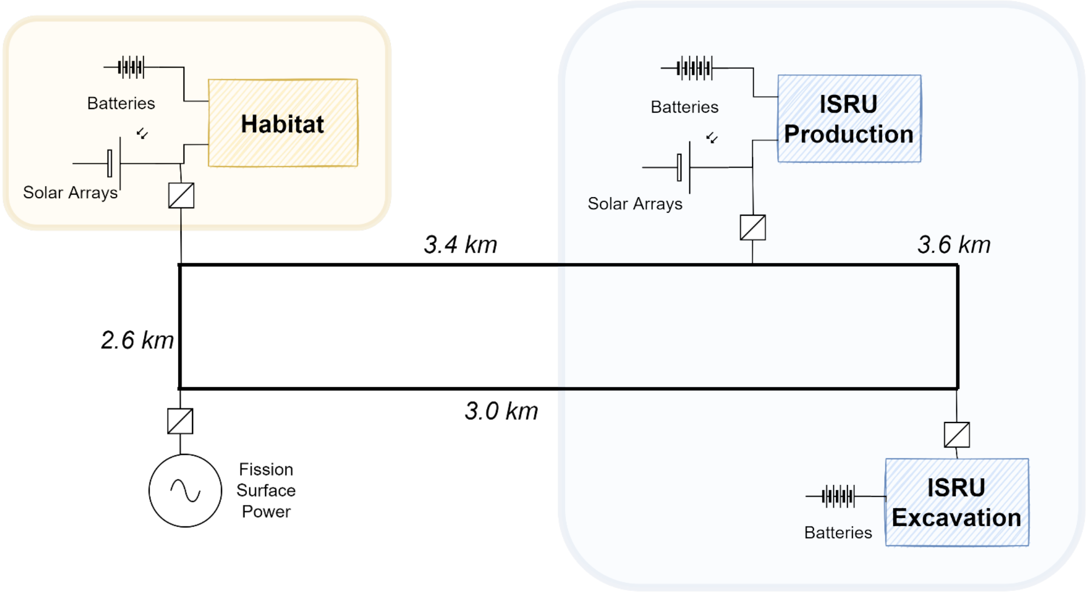
Radial Architecture Results

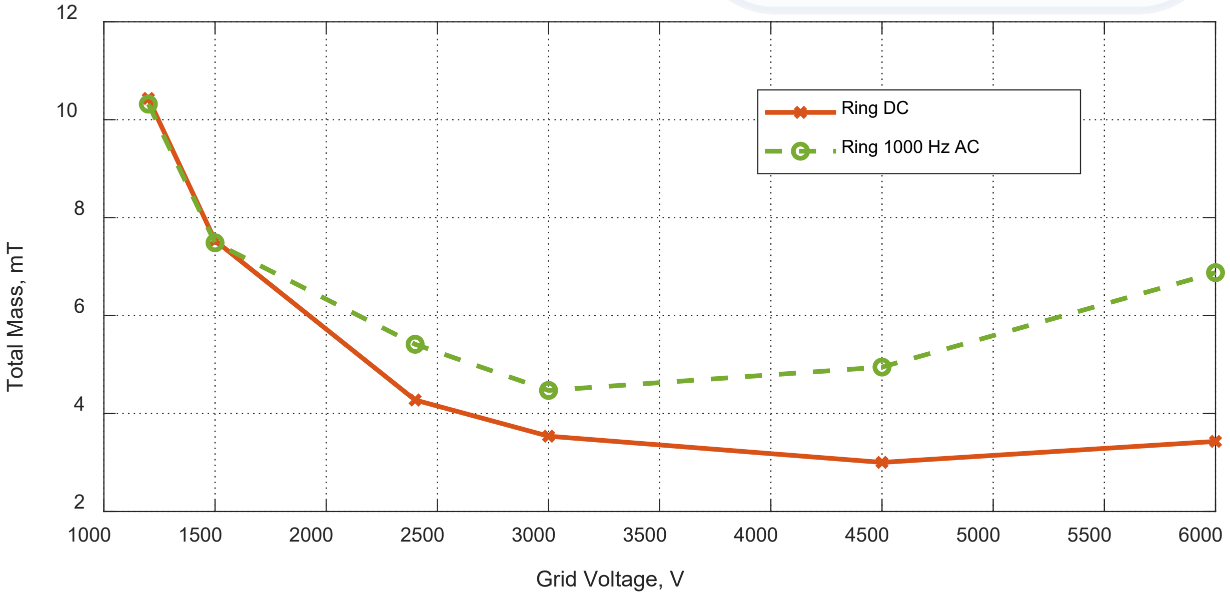
- **Total transmission mass (converter + cables) versus grid voltage**
  - AC options showing various frequencies
    - 1 kHz had lowest mass (will only present the 1 kHz going forward for AC)



Ring Architecture

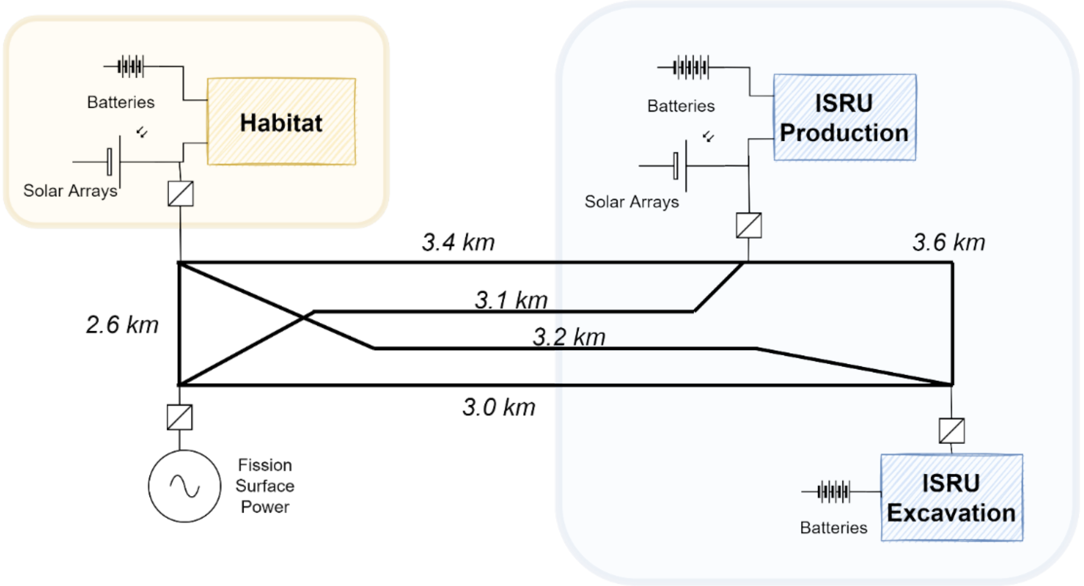
- **Ring architecture adds a second tie line between FSP and ISRU**
  - Assume FSP to Habitat line matches overall grid power type
- **Ring Advantages**
  - Adds single line tolerance for only one more tie line
  - Adds more efficient path for FSP power to get to ISRU mining which has no power of its own
- **Ring Disadvantages**
  - ~50% heavier than radial network
  - Can only lose one line and maintain ability to transmit power between any two assets

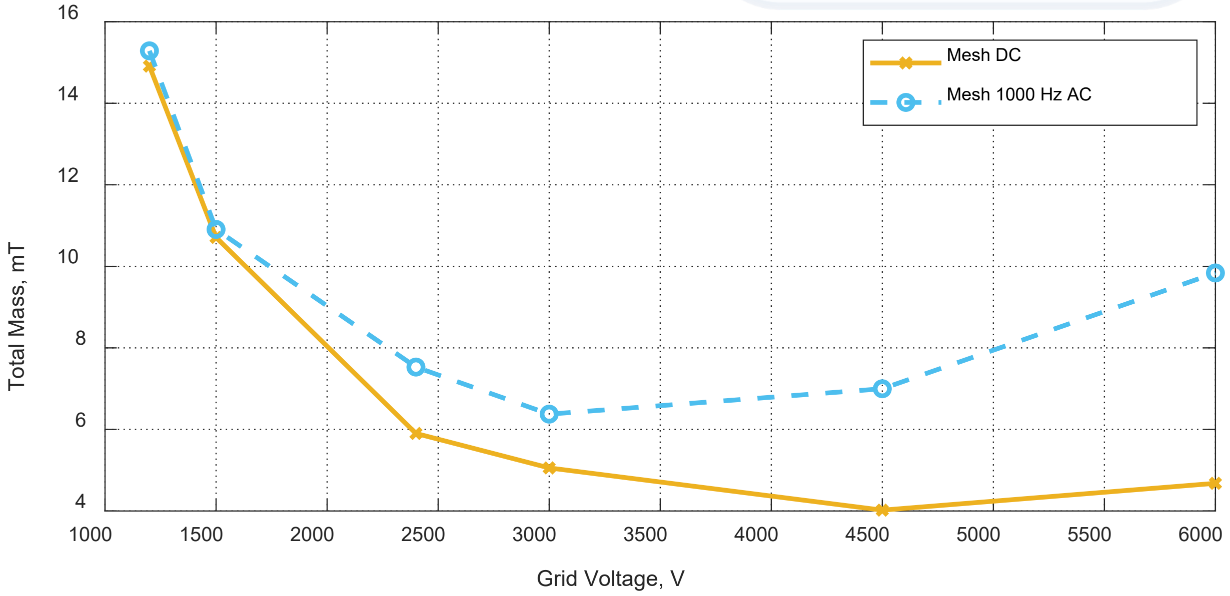




Mesh Architecture

- **Mesh adds two additional tie lines**
  - FSP to ISRU Production
  - Habitat to ISRU Mining
- **Mesh Advantages**
  - Additional lines add more efficient paths to transmit power throughout network
  - Dual line fault tolerance
- **Mesh Disadvantages**
  - ~100% heavier than radial network
  - ~50% heavier than ring





AC and DC Considerations and Trade Study Conclusions

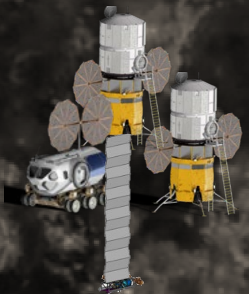
- **AC vs DC**
  - DC transmission significantly lighter than AC for voltages above 3-4 kV
    - However, DC grid practically limited to 1.2-1.5 kV, due to lack of high voltage rad-hard switches
    - Requires 4-5 series 300 V series stages, more stages likely prohibitive
  - AC easier to increase voltage and expand, as transformers can change voltage in AC-DC designs
  - Easy to standardize AC converter switch voltage ratings on the low voltage side of transformer
    - These facts drove team to select AC

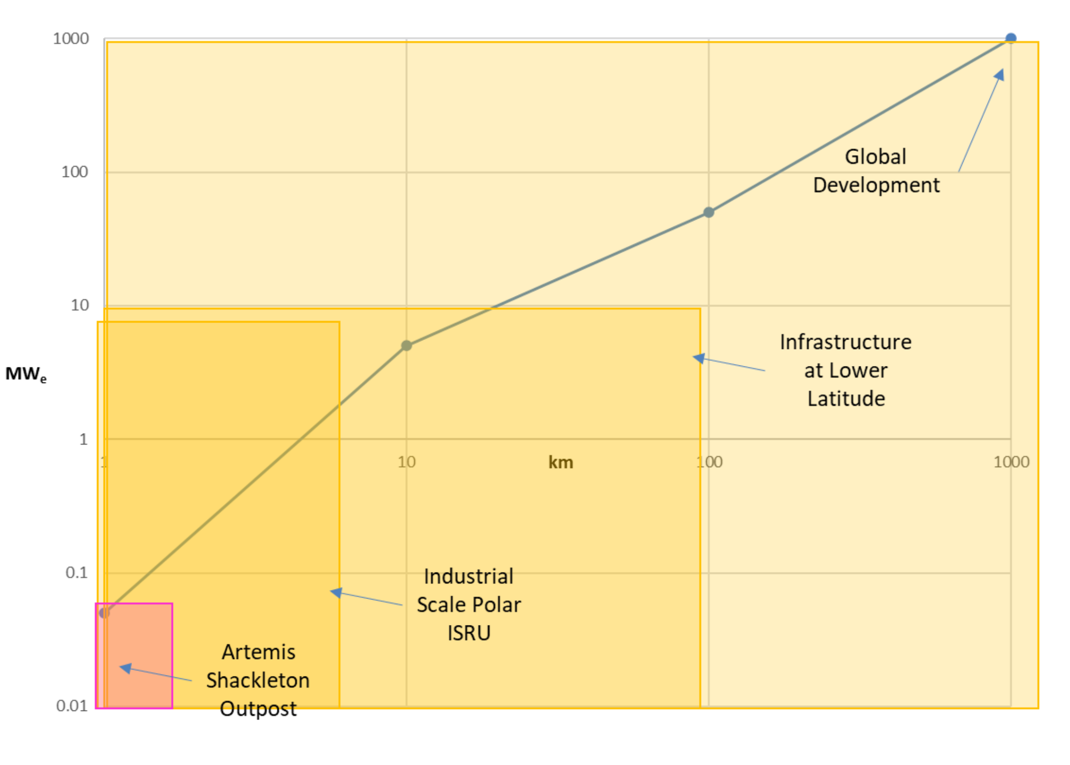
- **Study trends highlighted**
  - 3 kV AC is mass optimal feasible design solution
  - Architectures with more tie lines (ring, mesh) show higher fault tolerance and mass
  - Architecture selection should be made by mass and fault tolerance requirements/constraints

- **Buildup of a lunar surface microgrid will likely start small**
  - Start with radial and expand over-time to achieve increased reliability (fault tolerance)

- **Desirable to explore possible grid expansions toward global exploitation**

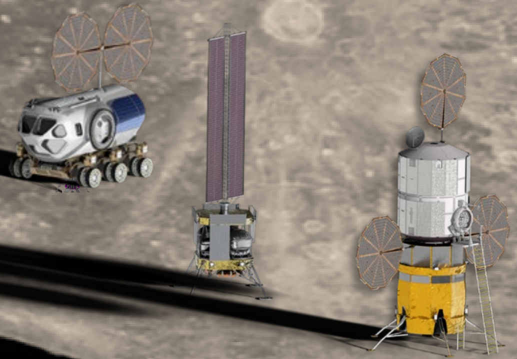
Ultimate Global Exploitation





Initial Polar Region Exploitation

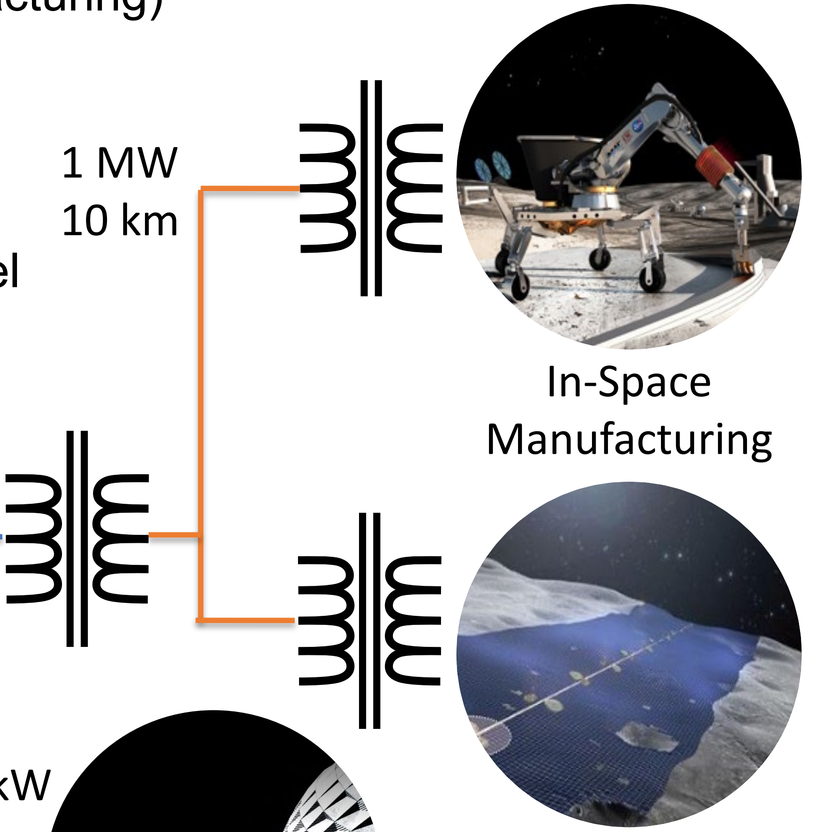
Current projects support initial phase of Polar infrastructure expansion

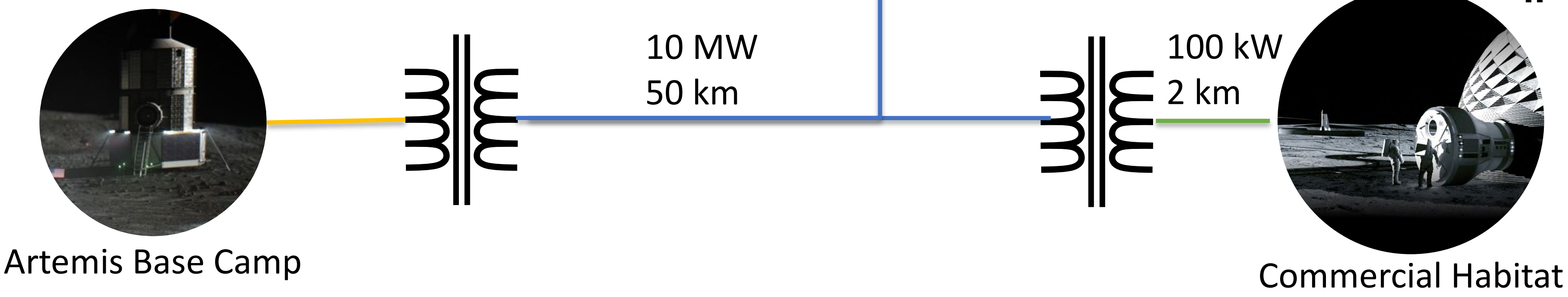


Long term vision of extending power over long distance

Initial Study for Grid Expansion Beyond Artemis

- **Conducted follow-on studies to envision expanded scale lunar power transmission system**
  – Envisions first big step beyond Artemis (beginning in-space manufacturing)
- **Varying transmission system voltage, distance, and power**
  – One power level per slide
    - 20 kW (Artemis scale), 40 kW, 100 kW, 1 MW, and 10 MW
  – Representative wire gauge used, held constant for each power level
  – Cable losses and total transmission losses (cable+converters) on y-axis, with possible constraints
  – Distances on x-axis



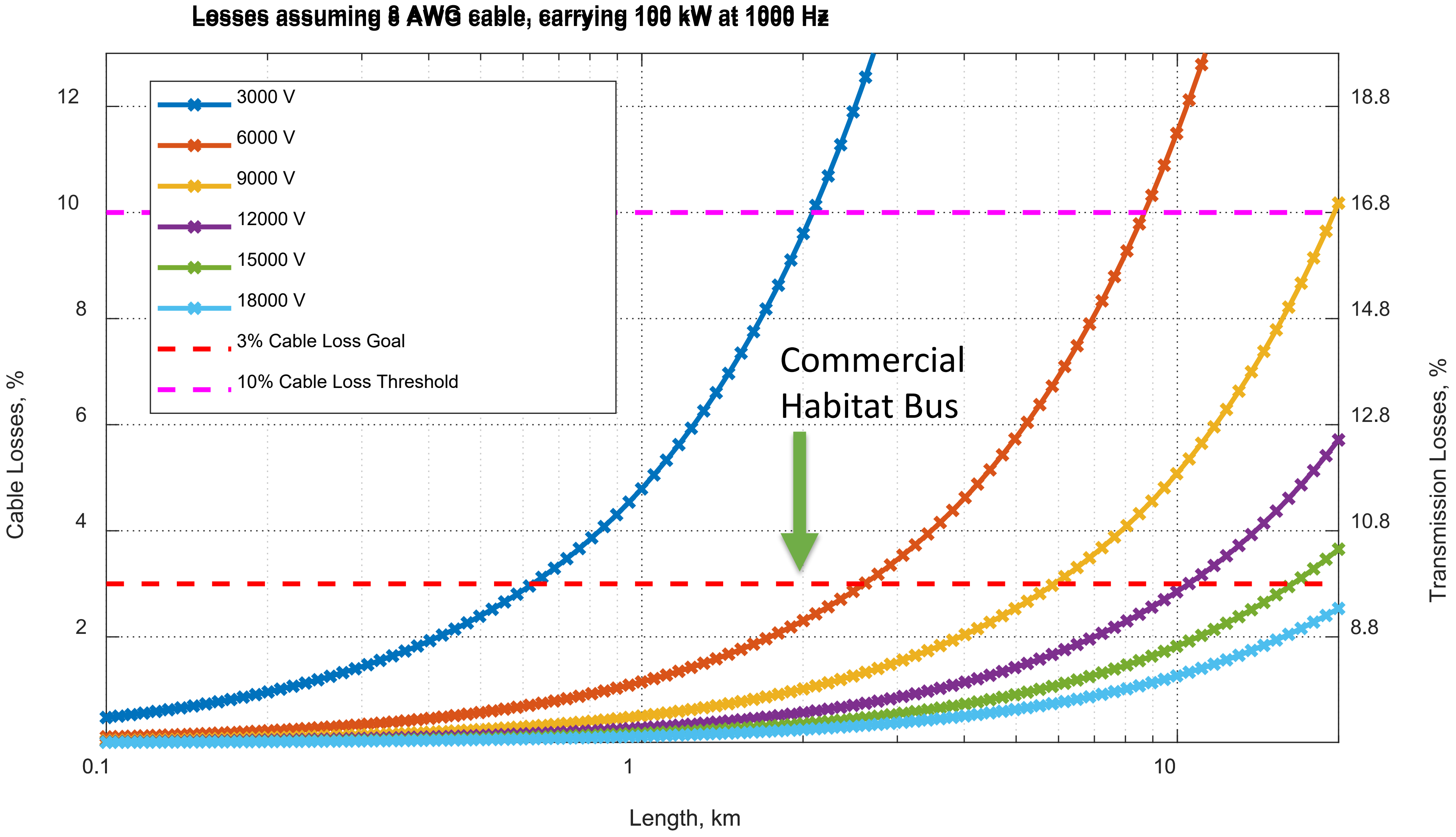


Voltage vs Distance at 100 kW

- **Distribution or low power transmission (using insulated cable)**

Voltage regimes

- **3 kV**
  - up to 600 m
- **6 kV**
  - up to 2.5 km
- **9 kV**
  - up to 6 km
- **12 kV**
  - up to 10 km
- **15 kV**
  - up to 15 km
- **18 kV**
  - up to 20 km

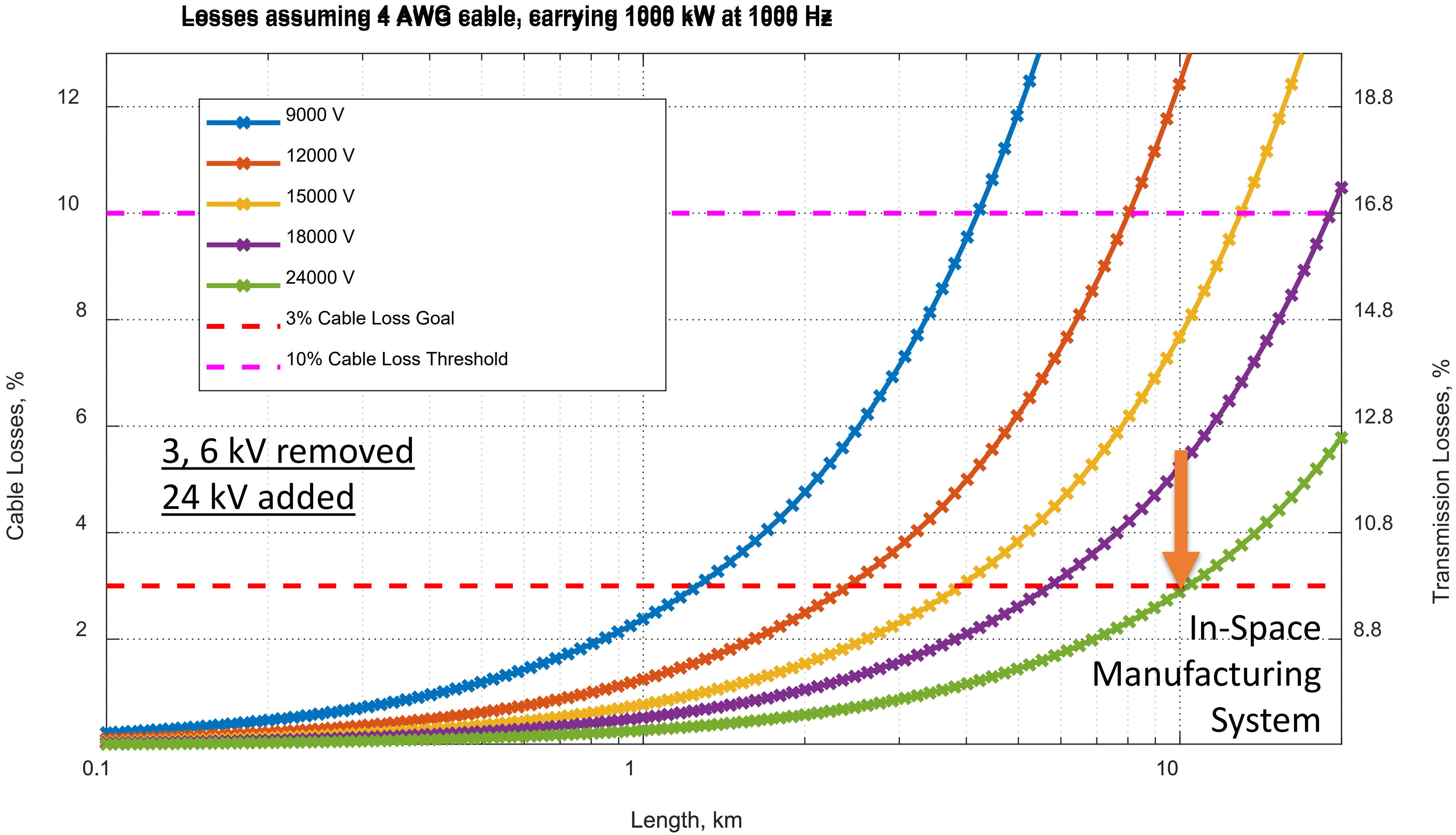


Voltage vs Distance at 1 MW

- **Inter-regional, medium power transmission (using insulated cable)**

Voltage regimes

- **9 kV**
  - up to 1 km
- **12 kV**
  - up to 2.5 km
- **15 kV**
  - up to 4 km
- **18 kV**
  - up to 6 km
- **24 kV**
  - up to 10 km

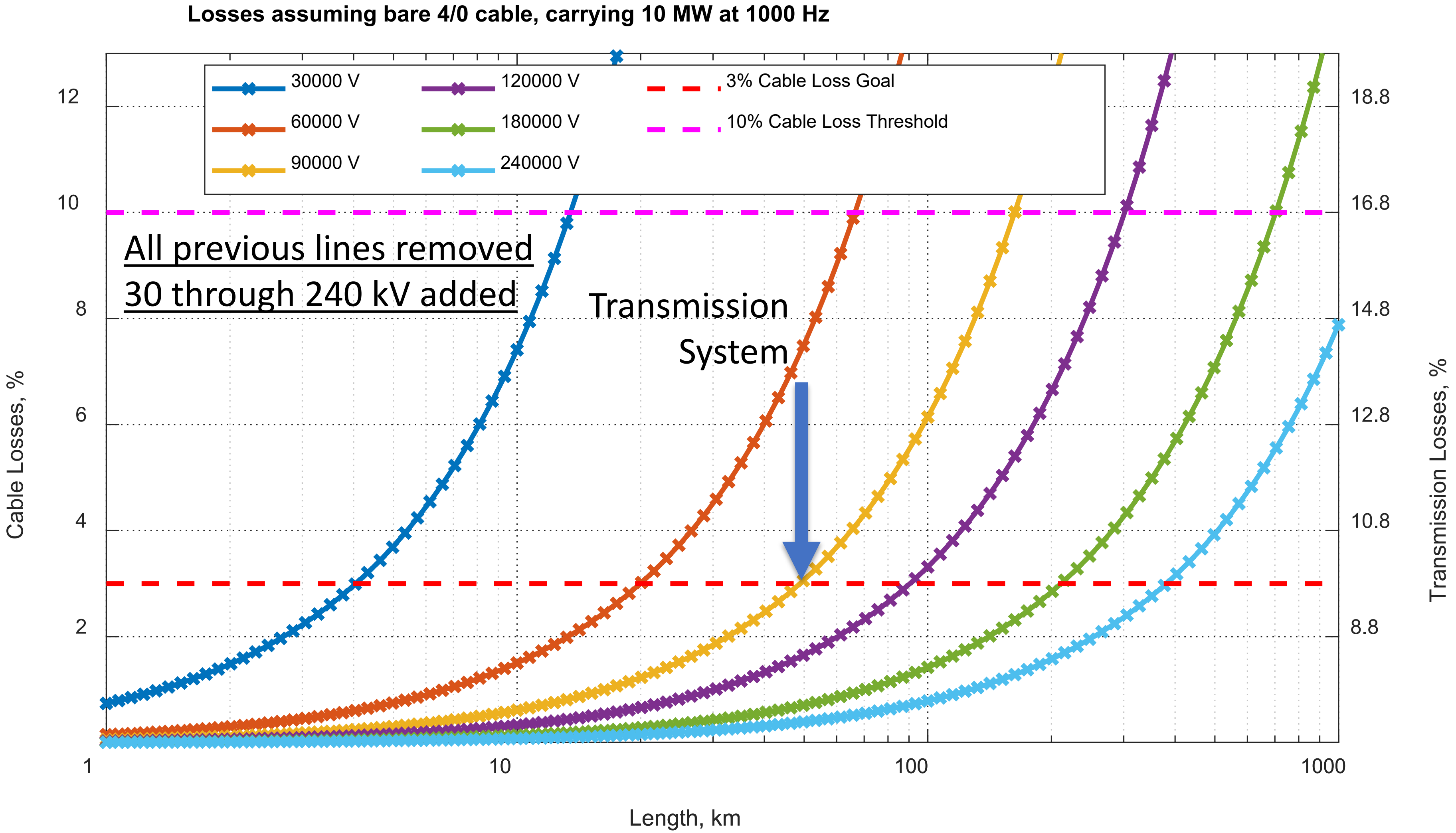


Voltage vs Distance at 10 MW

- **Initial extra-regional/global transmission (using uninsulated cable)**

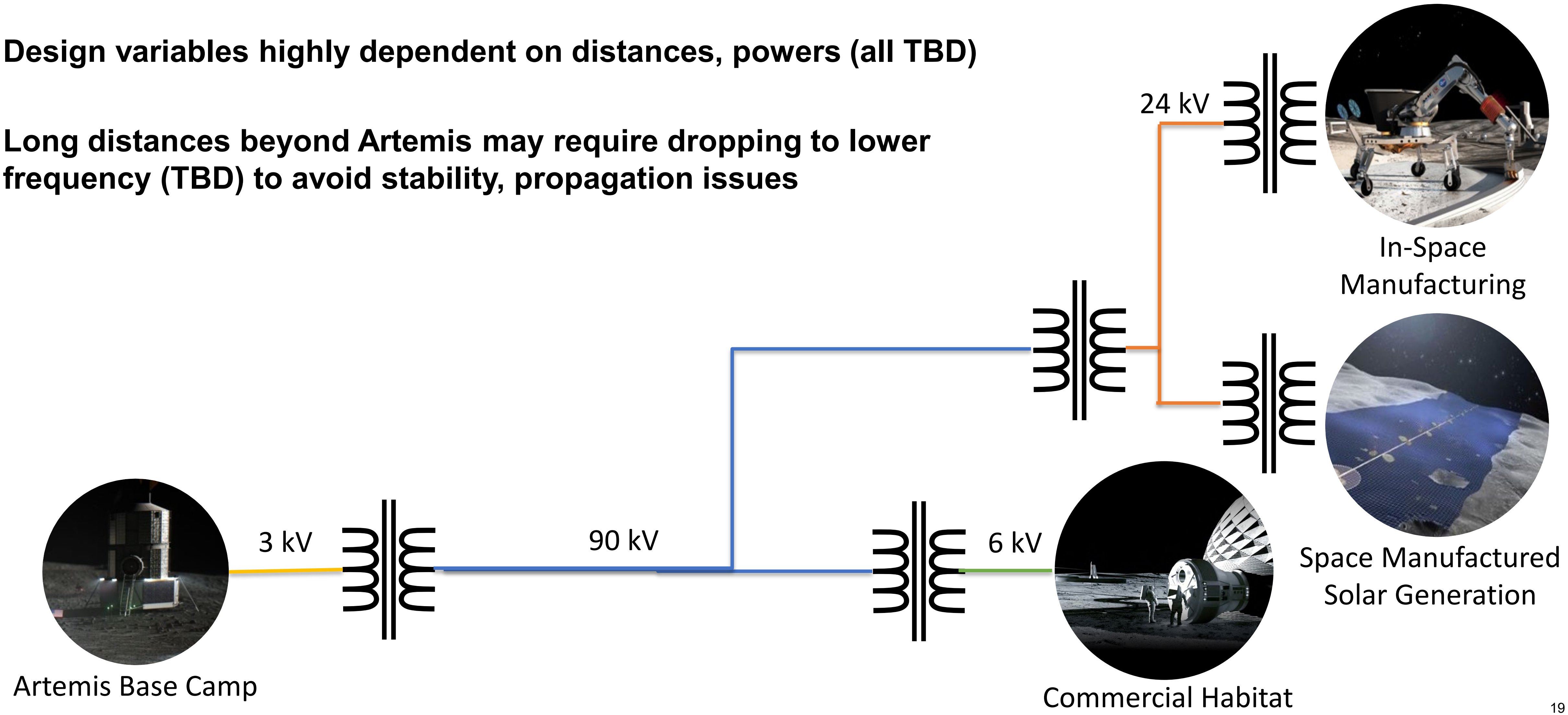
Voltage regimes

- **30 kV**
  - up to 4 km
- **60 kV**
  - up to 20 km
- **90 kV**
  - up to 50 km
- **120 kV**
  - up to 90 km
- **180 kV**
  - up to 200 km
- **240 kV**
  - up to 400 km



Initial Study for Grid Expansion Beyond Artemis

- **Possible design for a grid adding in-space manufacturing**
- **Design variables highly dependent on distances, powers (all TBD)**
- **Long distances beyond Artemis may require dropping to lower frequency (TBD) to avoid stability, propagation issues**



Summary

- **Artemis scale grid trade studies conducted to inform grid and interface converter design**
  - AC selected for ease of increasing voltage, extensibility
  - 3 kV AC selected as mass optimal solution

- **Follow on studies conducted exploring possible expansions of the Artemis grid**
  - Focus on in-space manufacturing

- **Grids become necessary for planetary surface operations as they grow to include more assets dependent on each other for power**
  - NASA investing in initial R&D work for these grids

Thank you