Lunar Microgrid Trade Studies to Define Interface Converter Requirements

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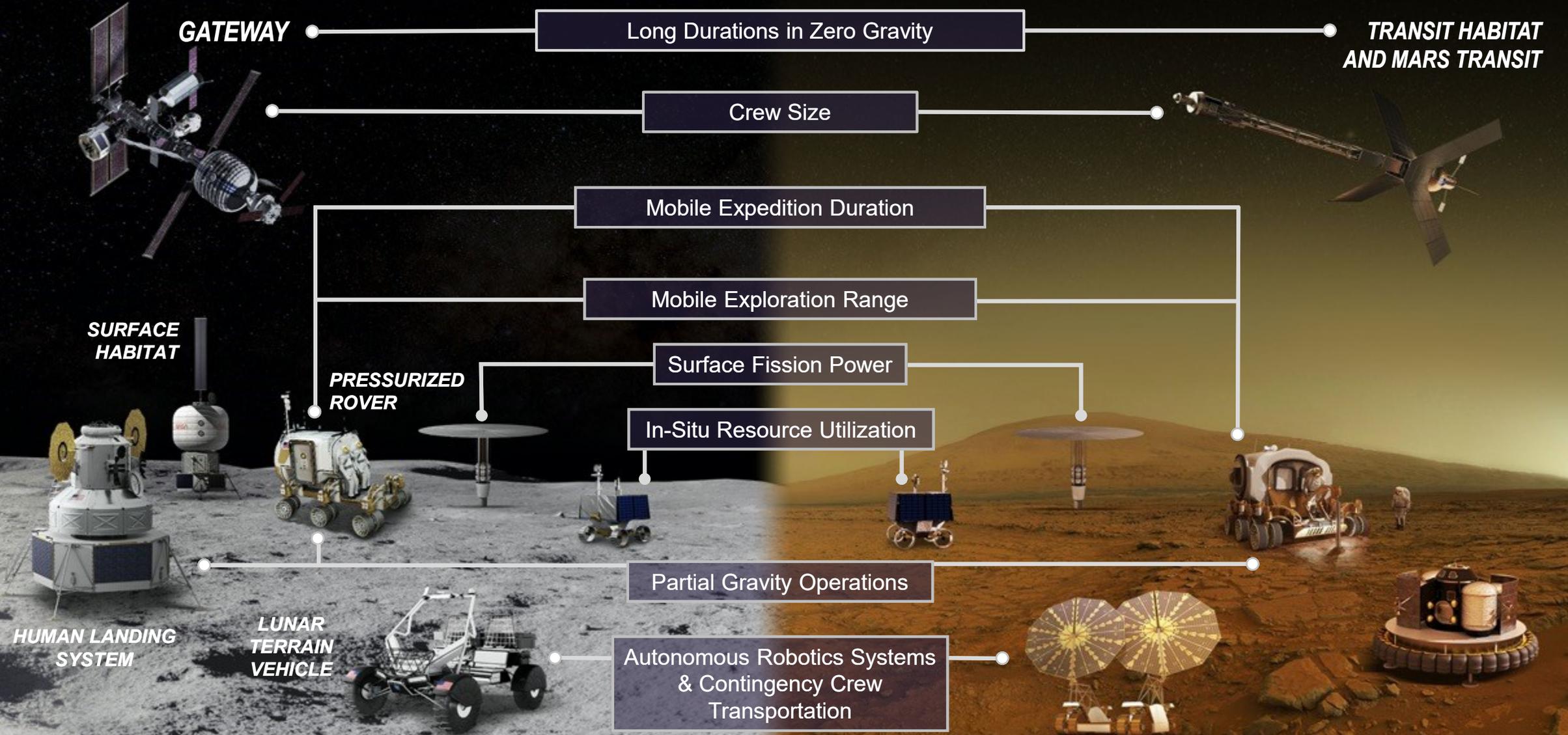
NASA Glenn Research Center

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Background

- NASA's long term vision includes crewed Mars missions

- Current focus is on Artemis program
  - Demonstrate key Mars enabling technologies
  - 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
  - Expansion necessitates planetary surface power grids

- NASA's STMD investing in R&D work for an Artemis grid
 - Microgrid Definition and Interface Converter for Planetary Surface (MIPS)

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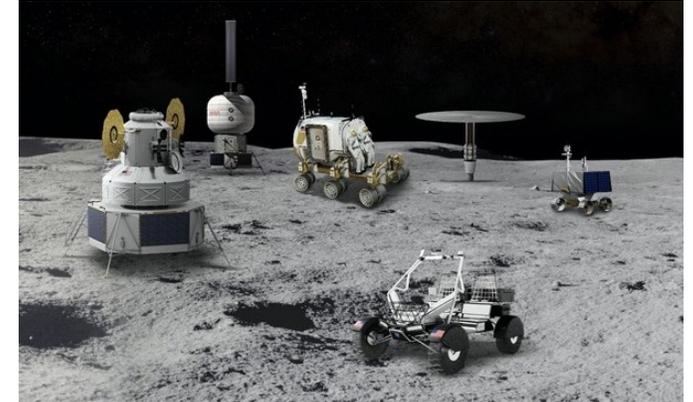
Moon to Mars Exploration

Operations on and around the Moon will help prepare for the first human mission to Mars

GATEWAY

TRANSIT HABITAT AND MARS TRANSIT

Long Durations in Zero Gravity

Crew Size

Mobile Expedition Duration

Mobile Exploration Range

SURFACE HABITAT

PRESSURIZED ROVER

Surface Fission Power

In-Situ Resource Utilization

HUMAN LANDING SYSTEM

LUNAR TERRAIN VEHICLE

Partial Gravity Operations

Autonomous Robotics Systems & Contingency Crew Transportation

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

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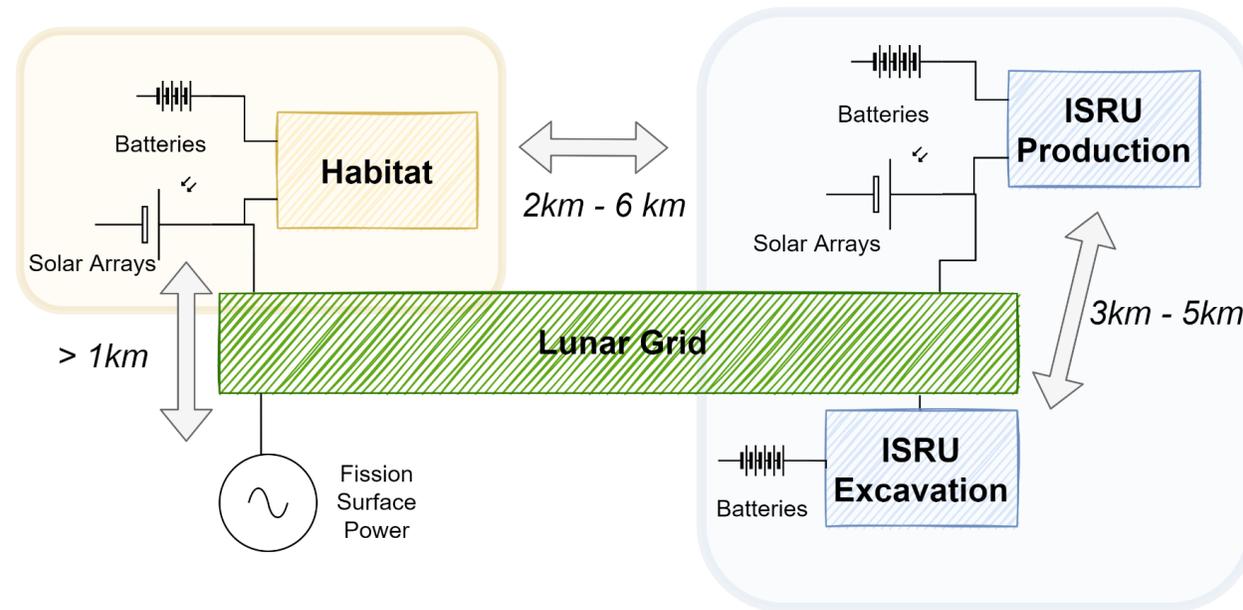
Artemis Grid Trade Study

- Electrical Power System—Sizing and Analysis Tool (EPS-SAT)
  - MATLAB-based tool for power system concept analysis
  - https://software.nasa.gov/software/LEW-20017-1

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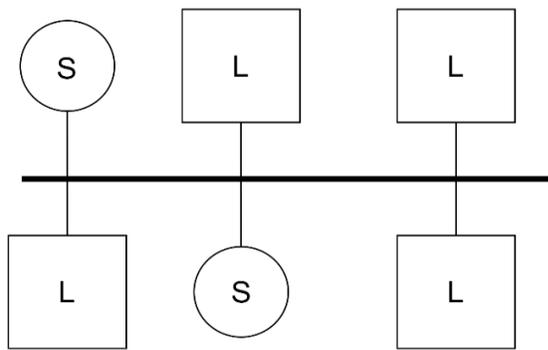
a) Radial Network
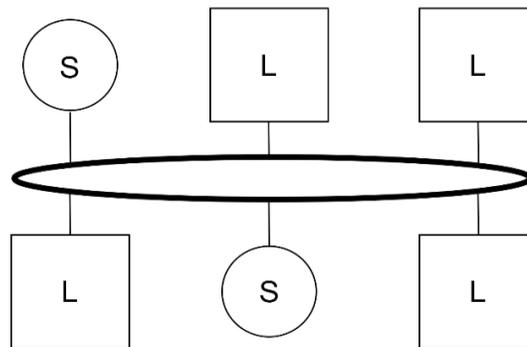
b) Ring Network
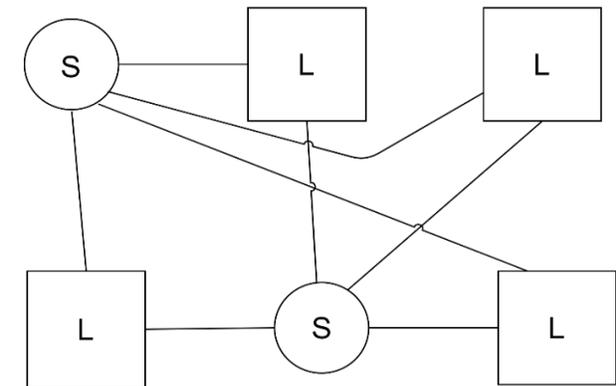
c) Mesh Network

Trade Study Assumptions

- **Cables**
  - Copper 10-14 AWG wires with ETFE insulation (~90% design efficiency at 40 kW)
  - Individual phase wires or bundle of parallel phase wires to be used per ampacity
  - Skin/proximity effect, inductance, and temperature effects modeled
  - Other effects (e.g. inductive, electrostatic regolith interactions) 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)

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

Cable

Converter

?

?

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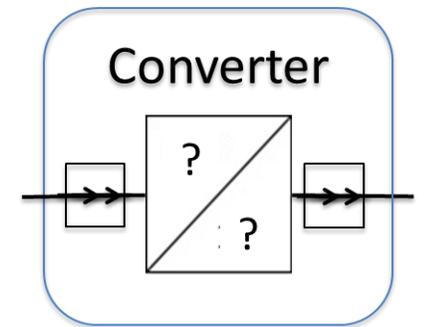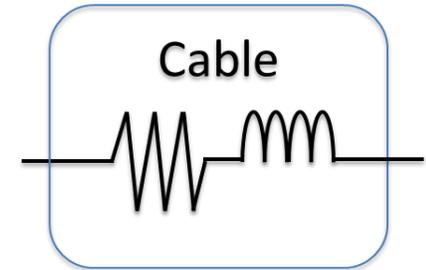
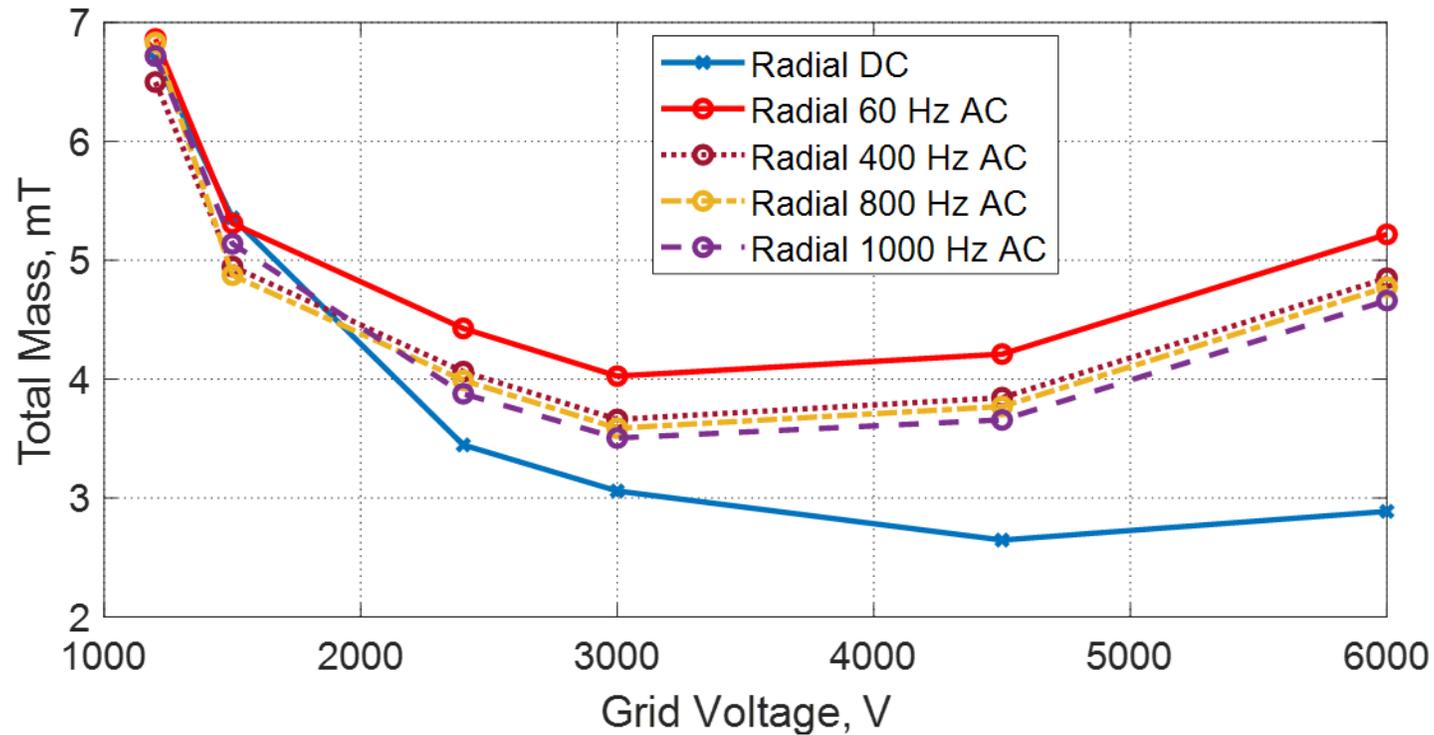# Radial Architecture

- **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

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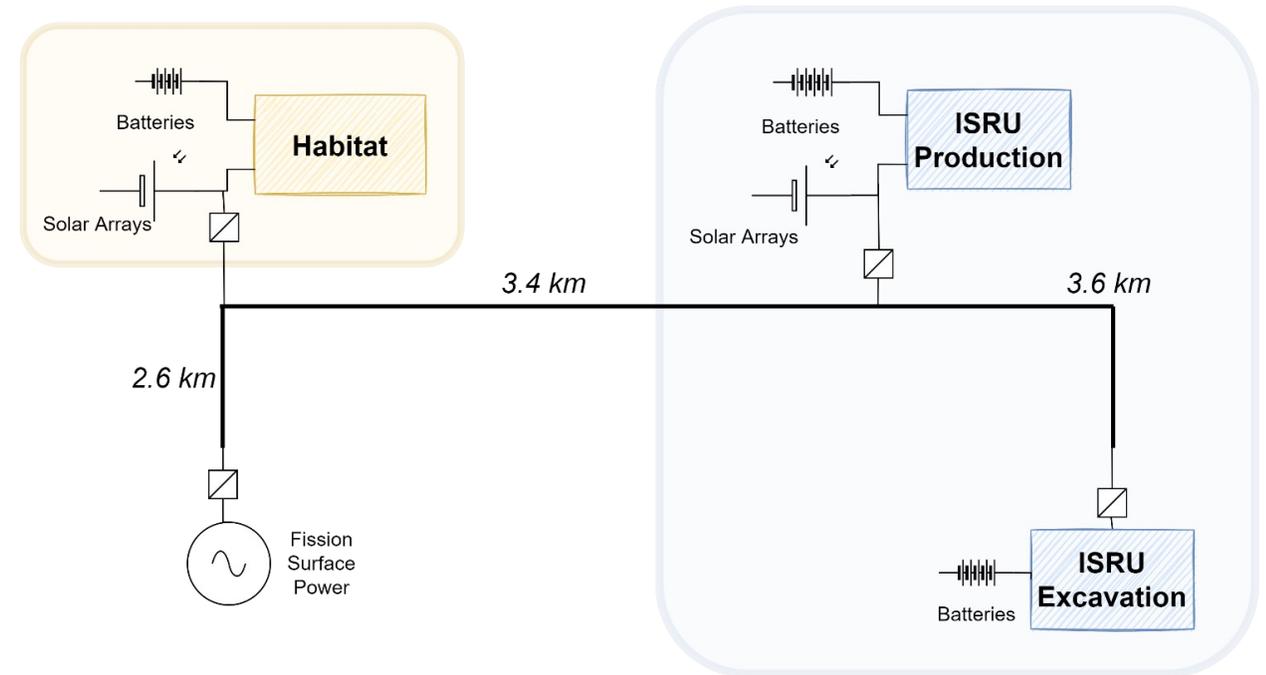
Radial Architecture Results

- 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

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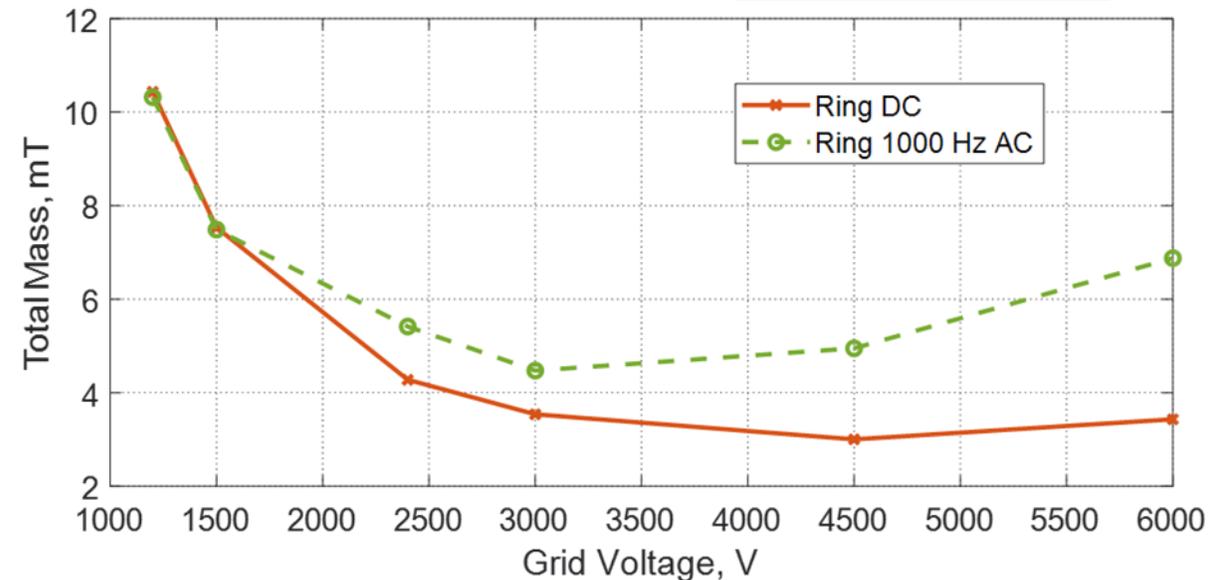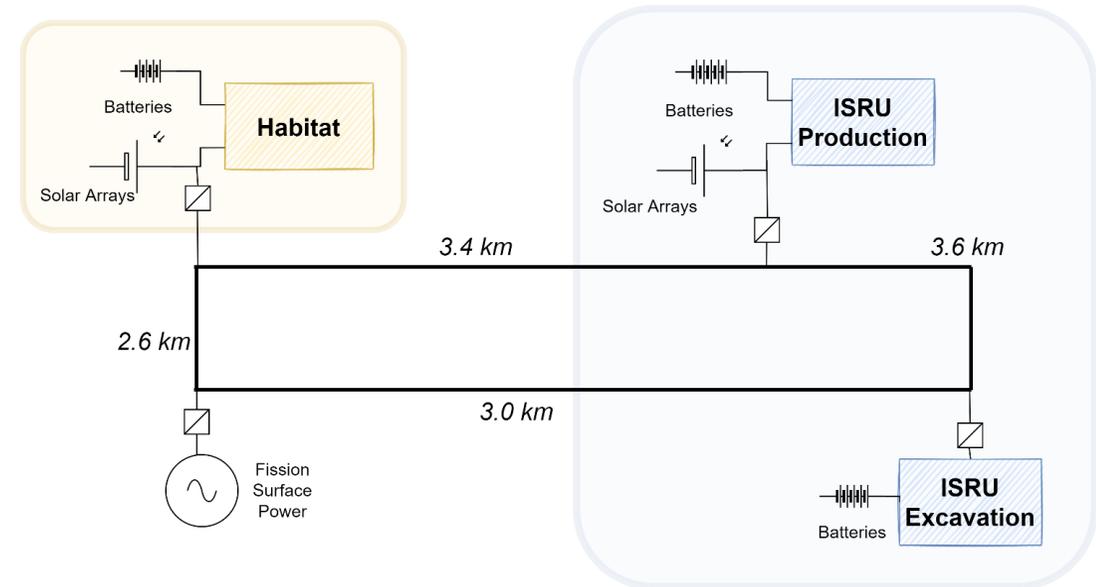
Mesh Architecture

- 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

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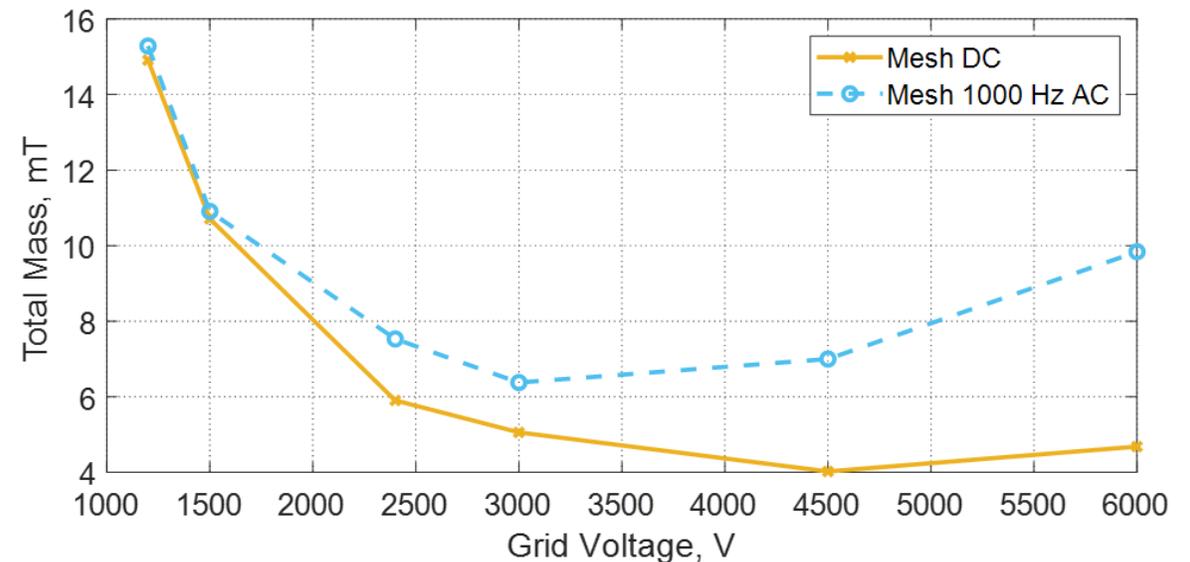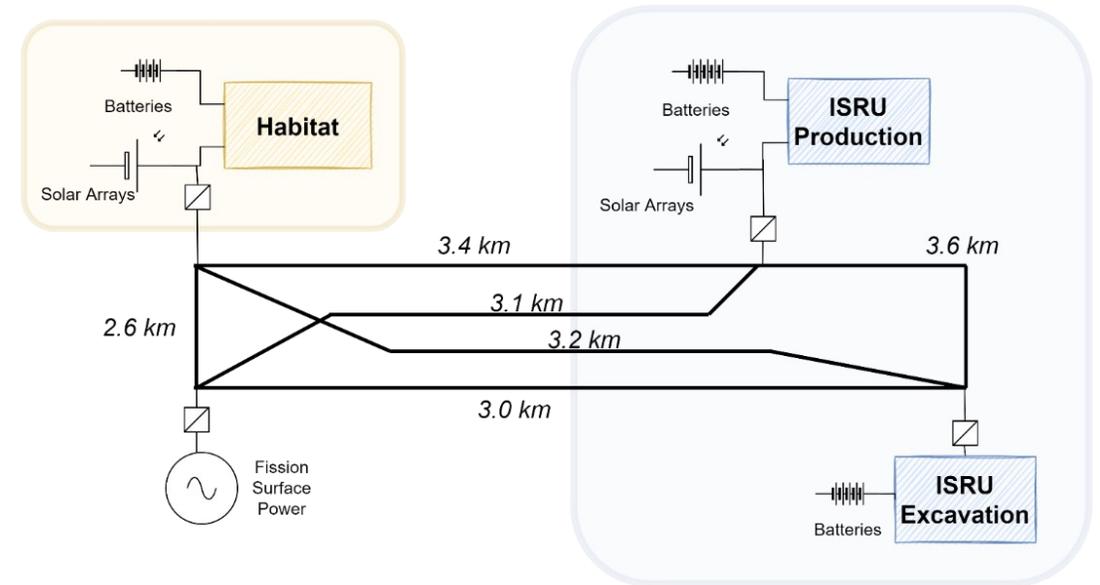
AC and DC Considerations and Trade Study Conclusions

- DC system significantly lighter than AC for voltages above 3-4 kV, otherwise marginal
  - However, DC grid practically limited to 1.2-1.5 kV, due to lack of high voltage rad-hard switches
 - AC easier to increase voltage and expand, as transformers can change voltage in AC-DC designs
- 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

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Ultimate Global Exploitation
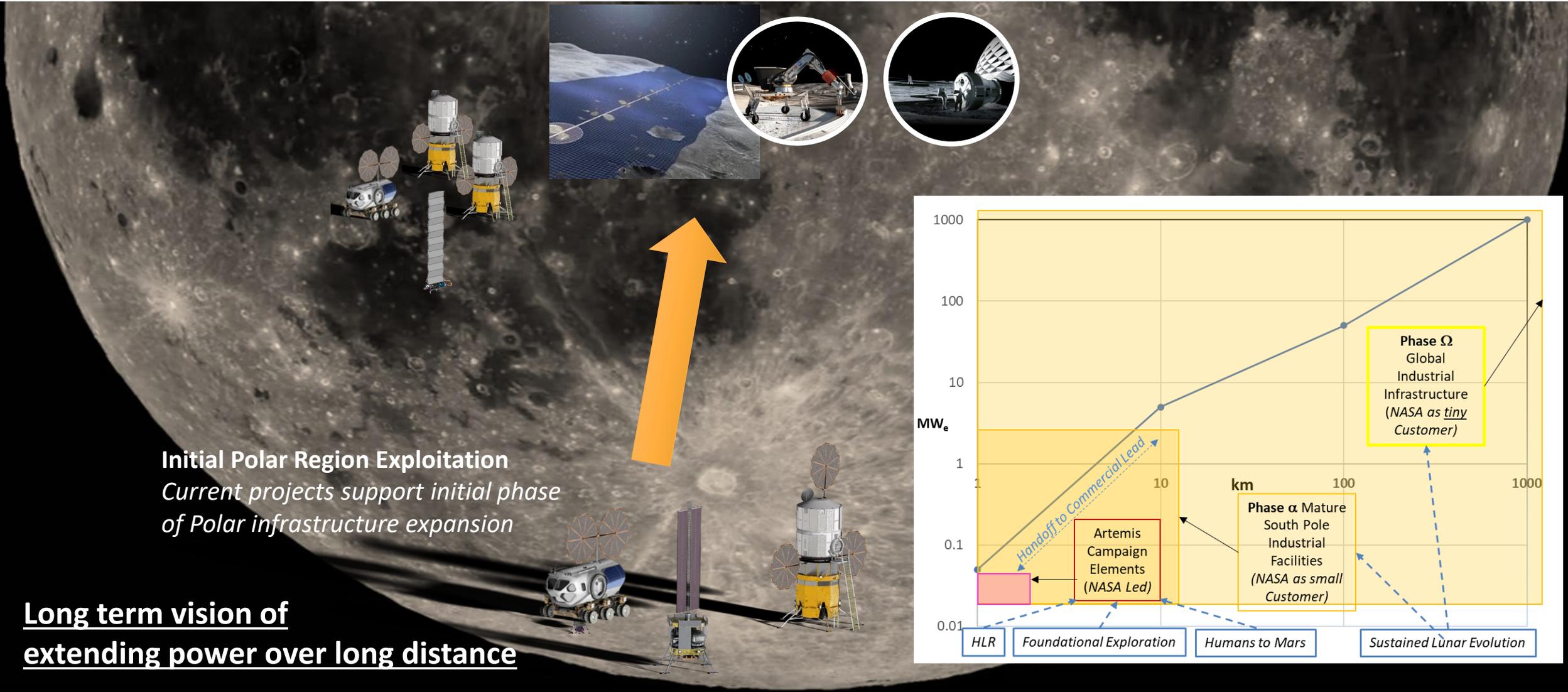
Initial Polar Region Exploitation
Current projects support initial phase of Polar infrastructure expansion

Long term vision of extending power over long distance

Handoff to Commercial Lead

Artemis Campaign Elements (*NASA Led*)

Phase α Mature South Pole Industrial Facilities (*NASA as small Customer*)

Phase Ω Global Industrial Infrastructure (*NASA as tiny Customer*)

MW$_e$

km

HLR | Foundational Exploration | Humans to Mars | Sustained Lunar Evolution

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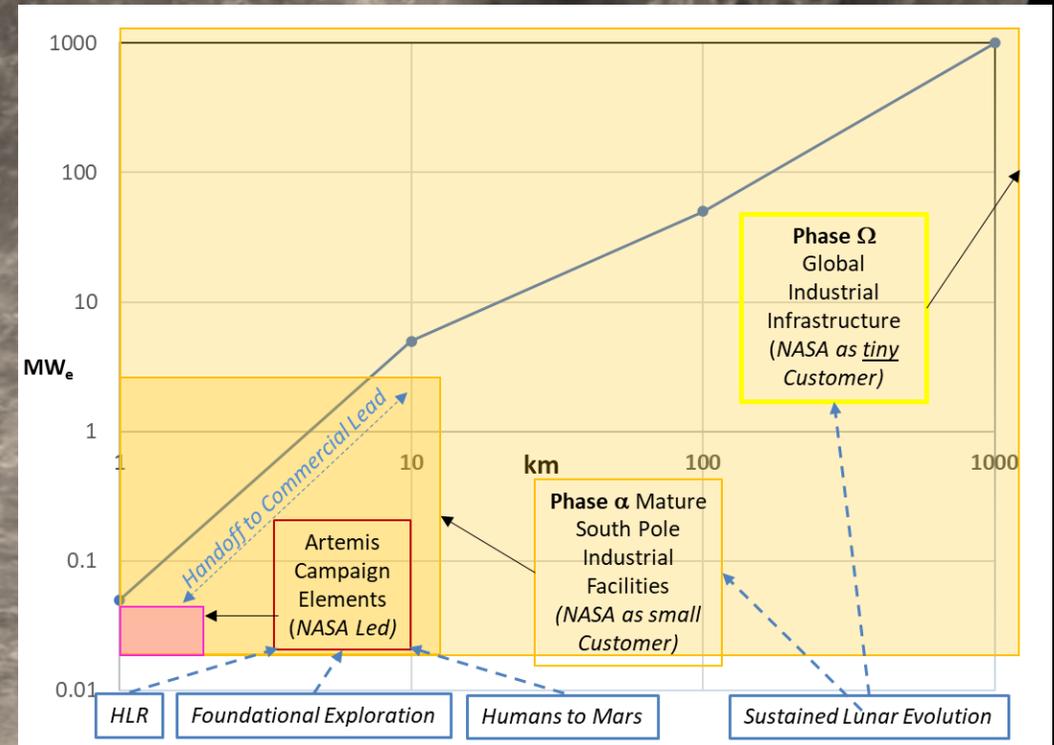
Initial Study for Grid Expansion Beyond Artemis

- Conducted follow-on studies for hypothetical expanded scale lunar power system
  - Envisions first big step beyond Artemis (beginning in-space manufacturing)
- Varying transmission system voltage, distance, and power
  - One power level per slide
    - 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

1 MW
10 km

In-Space Manufacturing

Space Manufactured Solar Generation

10 MW
50 km

100 kW
2 km

Artemis Base Camp

Commercial Habitat

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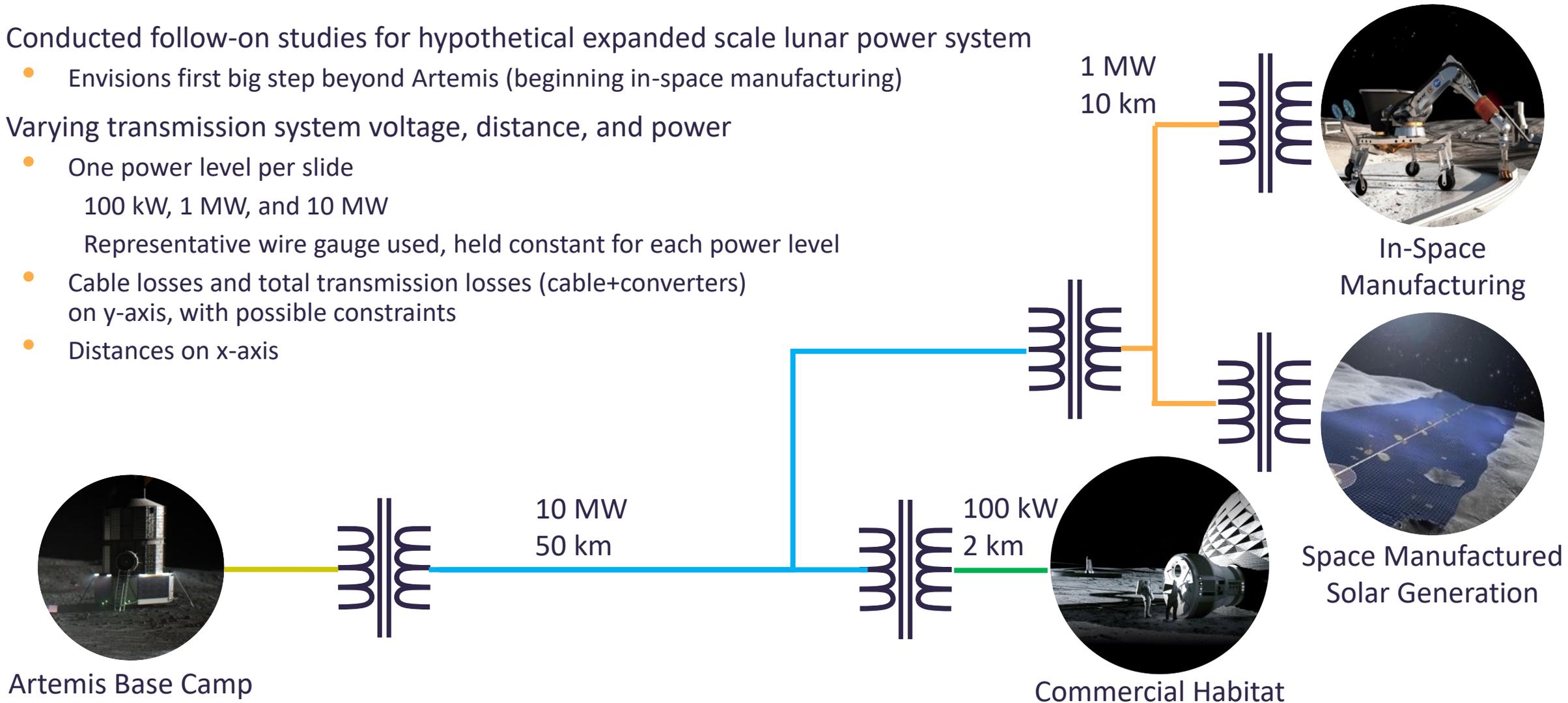
Voltage vs Distance at 100 kW

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

Losses assuming 8 AWG cable, carrying 100 kW at 1000 Hz

Legend:
- 3000 V
- 6000 V
- 9000 V
- 12000 V
- 15000 V
- 18000 V
- 3% Cable Loss Goal
- 10% Cable Loss Threshold

Commercial Habitat Bus

Cable Losses, %
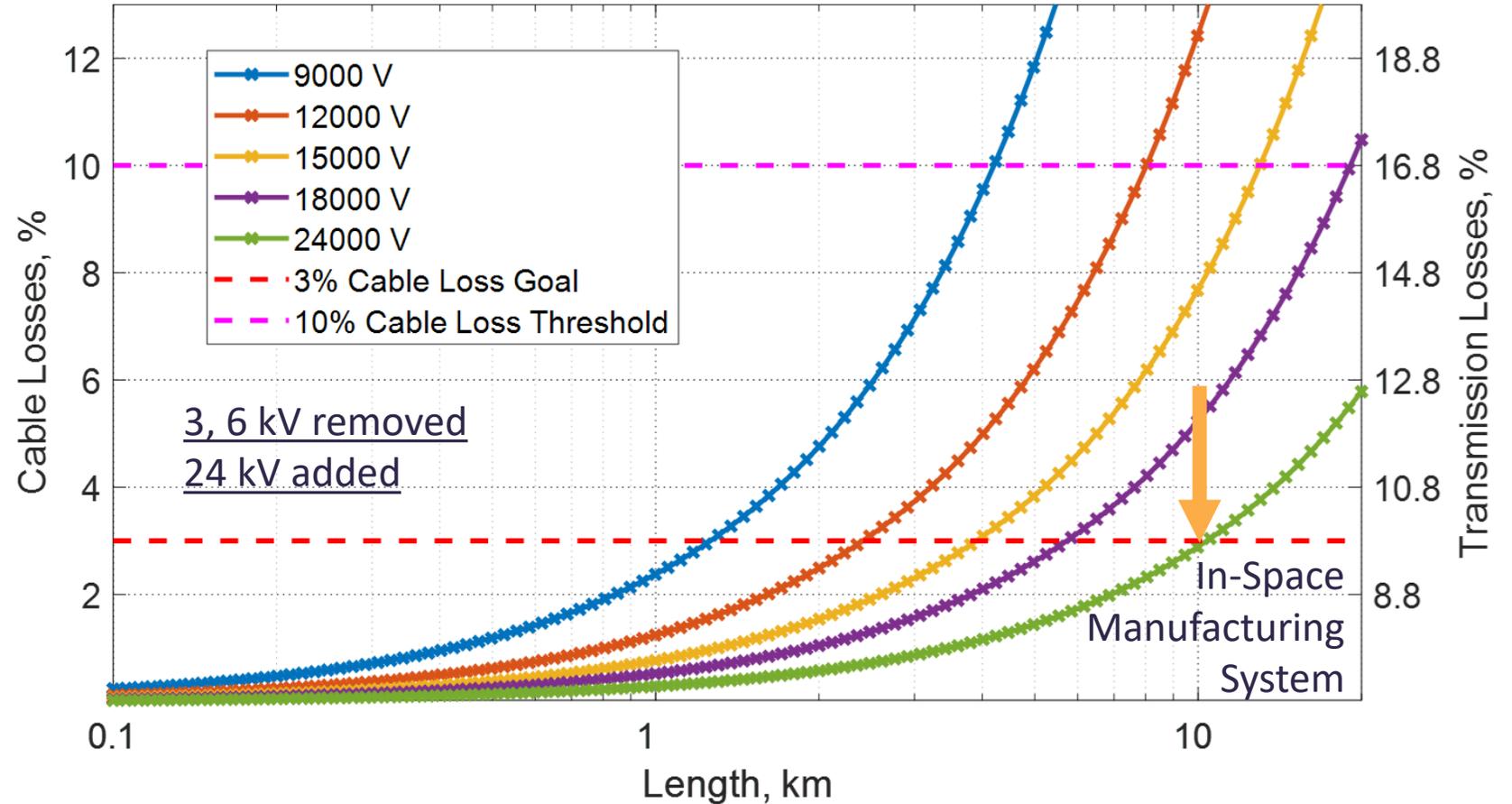Transmission Losses, %
Length, km

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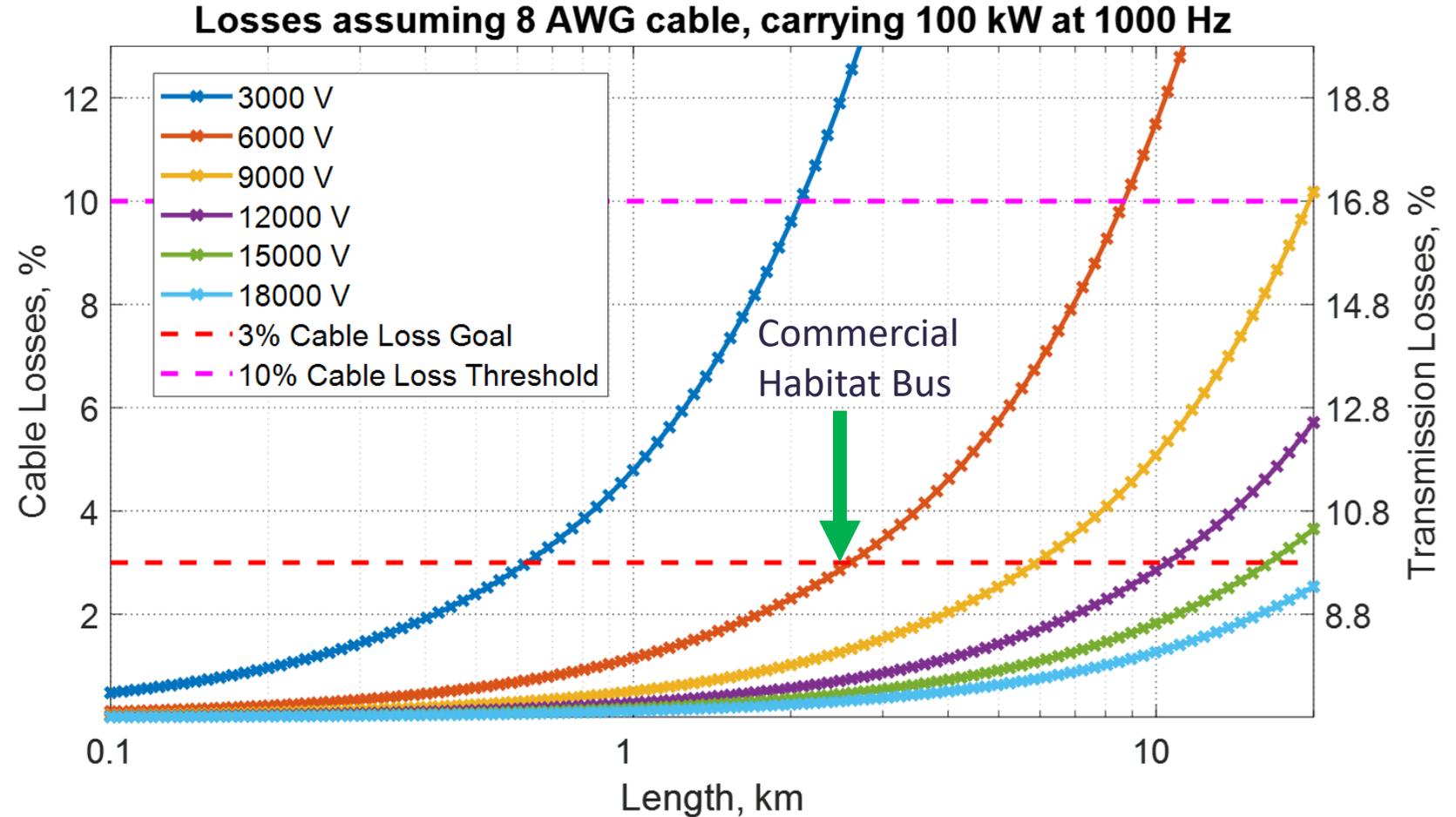
Voltage vs Distance at 1 MW

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

Losses assuming 4 AWG cable, carrying 1000 kW at 1000 Hz

Legend:
- 9000 V
- 12000 V
- 15000 V
- 18000 V
- 24000 V
- 3% Cable Loss Goal
- 10% Cable Loss Threshold

<u>3, 6 kV removed</u>
<u>24 kV added</u>

In-Space Manufacturing System

Cable Losses, % (vertical axis); Length, km (horizontal axis); Transmission Losses, % (right axis)
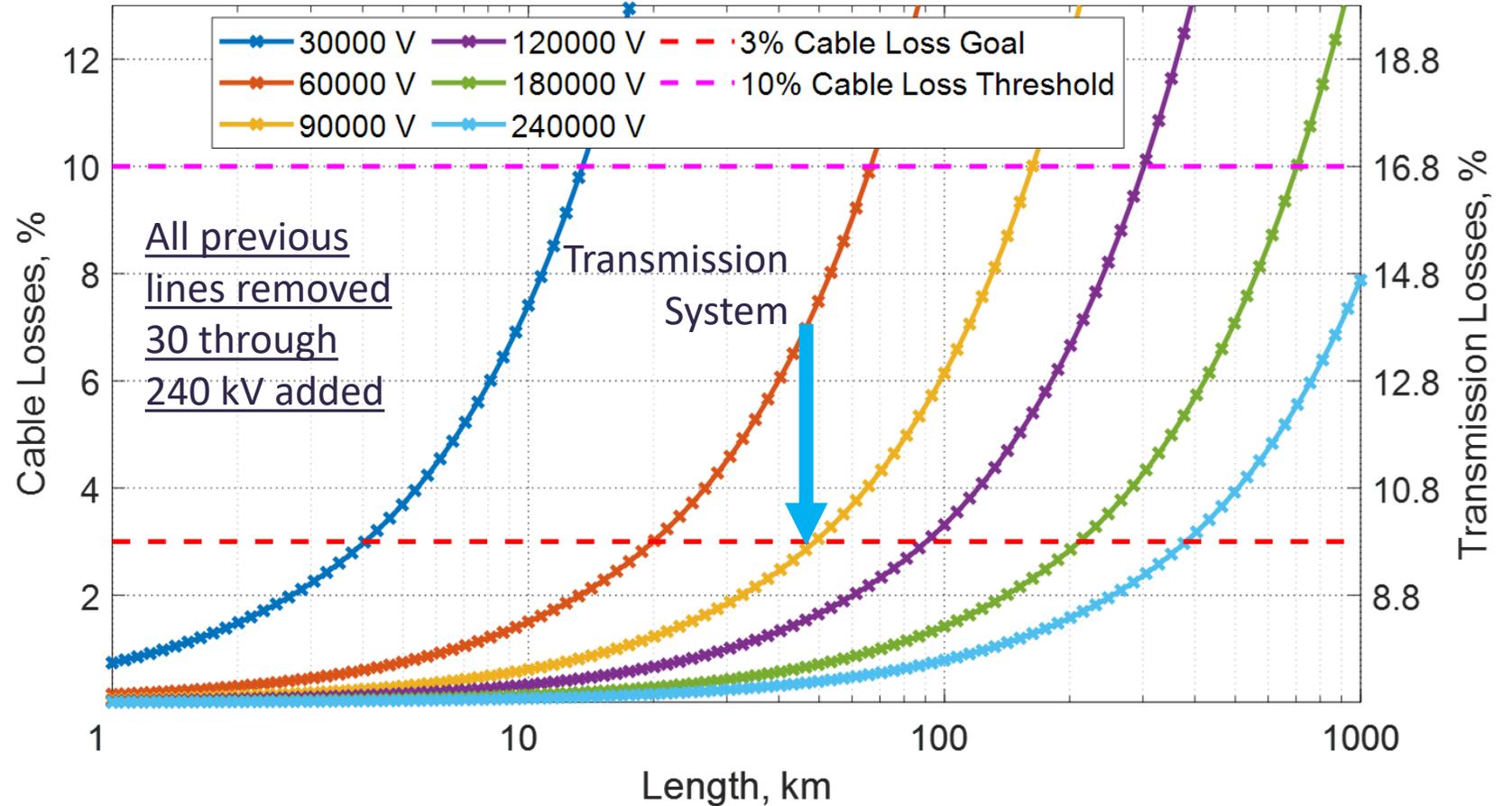
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Voltage vs Distance at 10 MW

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

Voltage regimes

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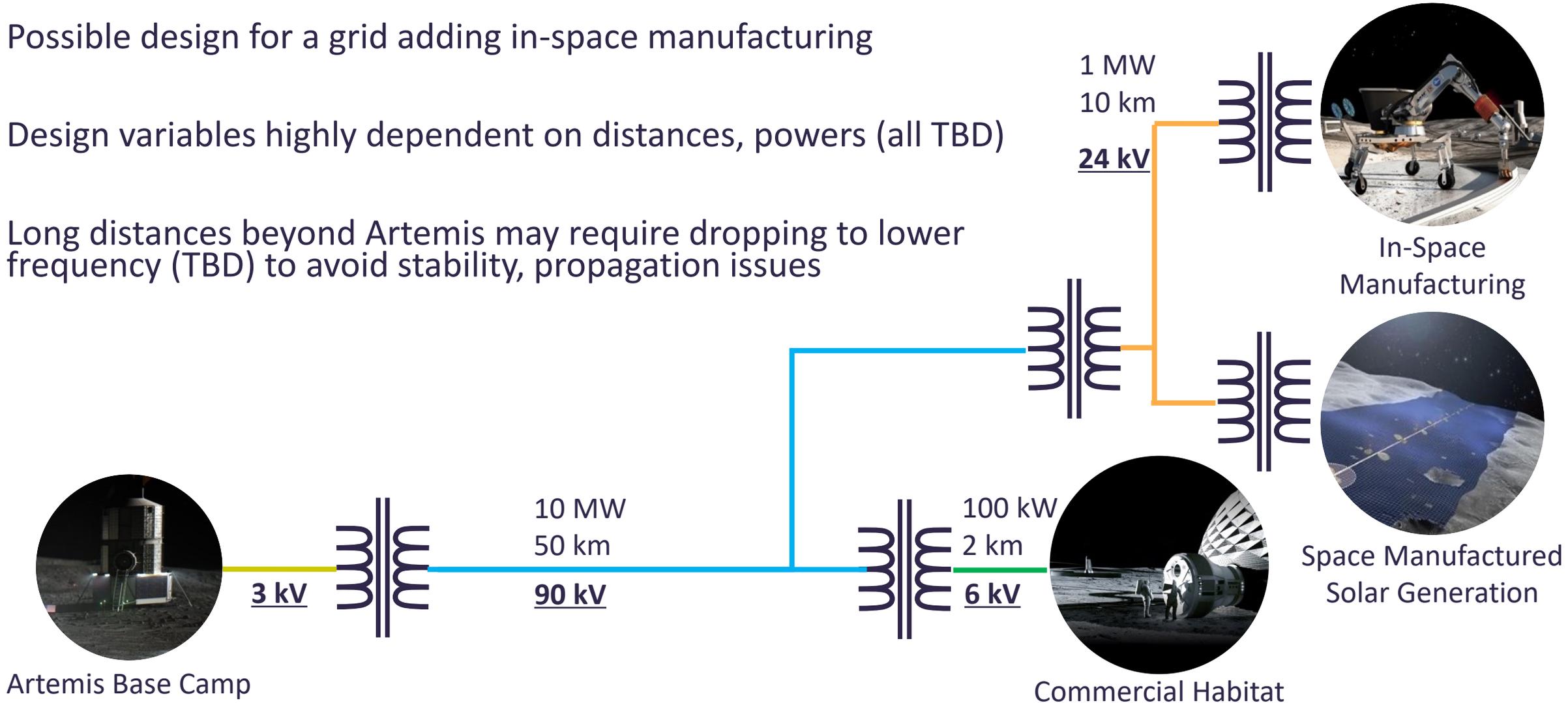 - up to 4 km
- 60 kV
  - up to 20 km
- 90 kV ←
  - up to 50 km
- 120 kV
  - up to 90 km
- 180 kV
  - up to 200 km
- 240 kV
  - up to 400 km

Losses assuming bare 4/0 cable, carrying 10 MW at 1000 Hz

Legend:
- 30000 V
- 60000 V
- 90000 V
- 120000 V
- 180000 V
- 240000 V
- 3% Cable Loss Goal
- 10% Cable Loss Threshold

All previous lines removed 30 through 240 kV added

Transmission System

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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

1 MW
10 km

24 kV

In-Space Manufacturing

Space Manufactured Solar Generation

10 MW
50 km

90 kV

100 kW
2 km

6 kV

3 kV

Artemis Base Camp

Commercial Habitat

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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

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