Powering Space

Delivering Affordable Energy for the Emerging cis-Lunar Economy

05 June 2019

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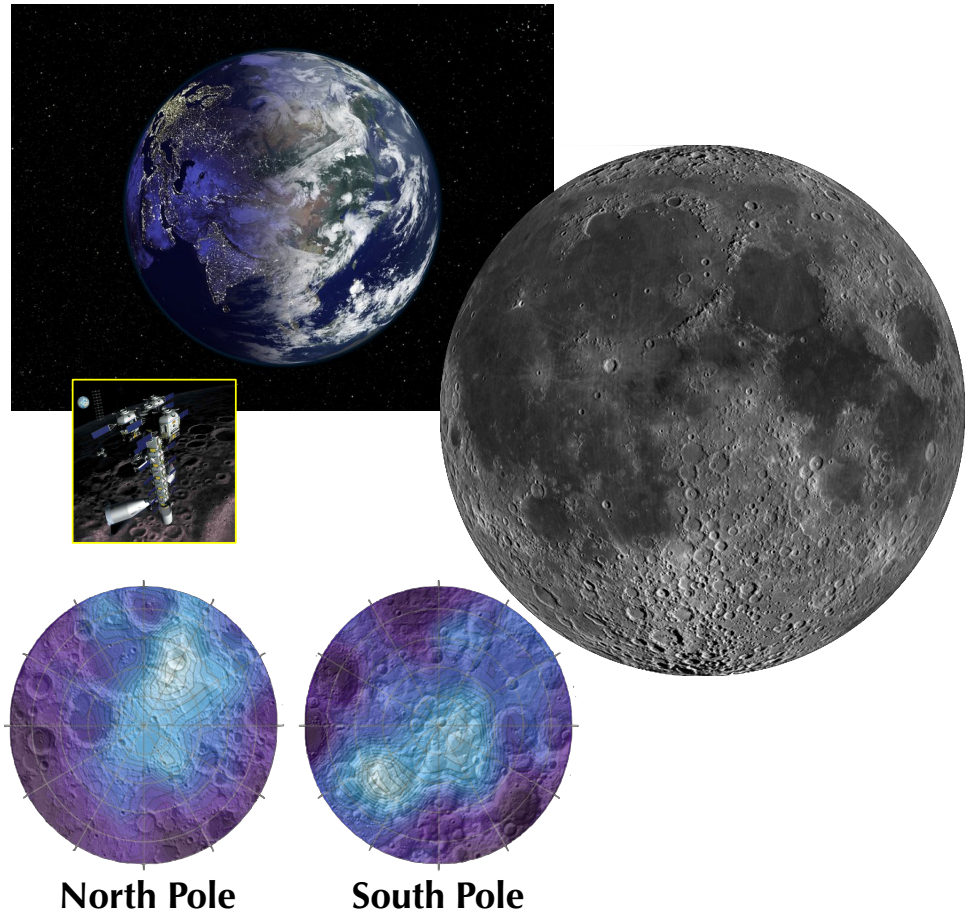
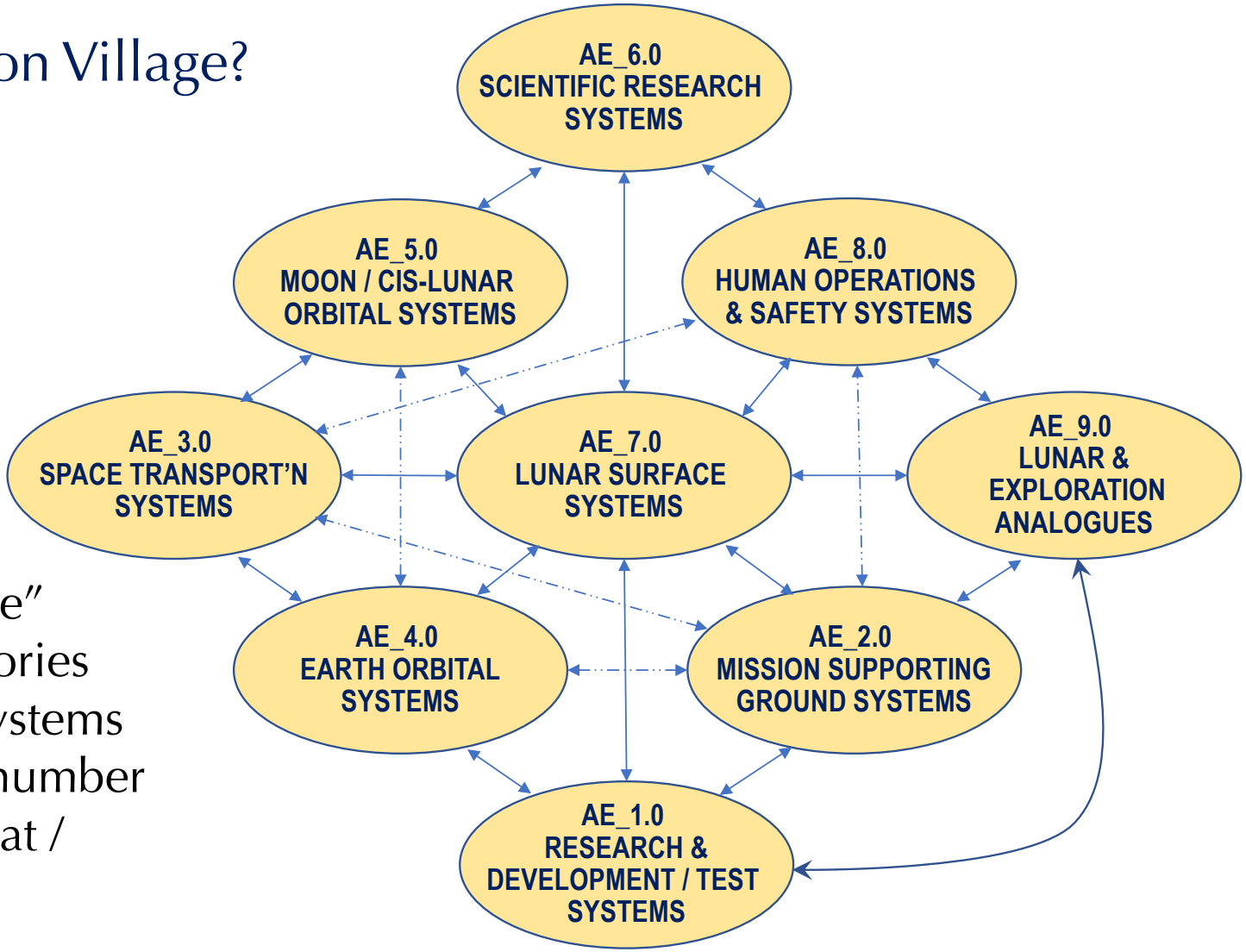
Scope of Cis-Lunar Markets

- "Geographic Scope" of the cis-Lunar Markets comprises:
  - Earth-to-Moon Transport & Operations
  - Cis-Lunar Space
  - Lunar Orbit
  - Lunar Surface: Polar Regions
  - Lunar Surface: Equatorial Regions, etc.

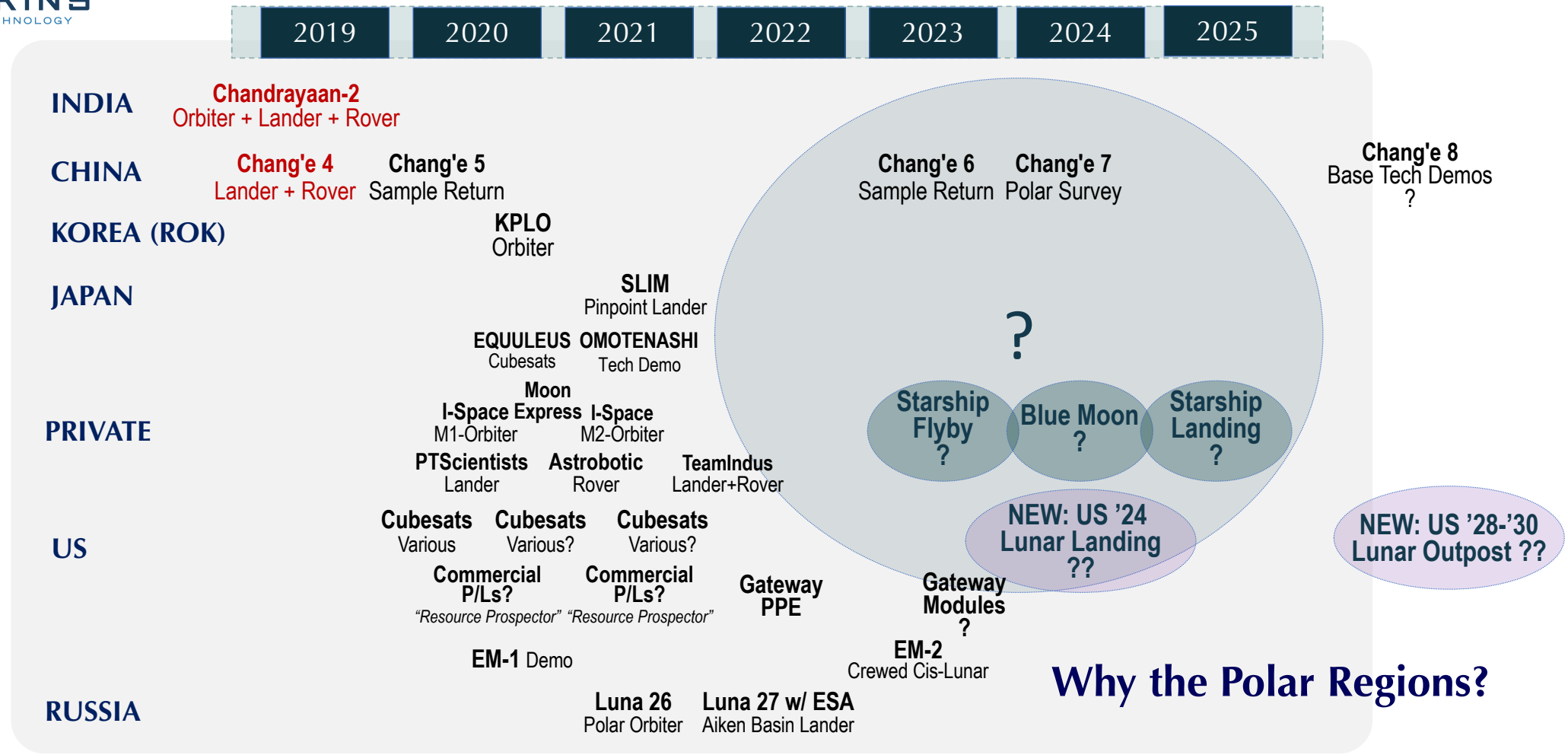


What is the Moon Village?



Many of these "Moon Village" Architectural Element categories involve various missions / systems that require power – and a number which will one day operate at / near the lunar polar regions

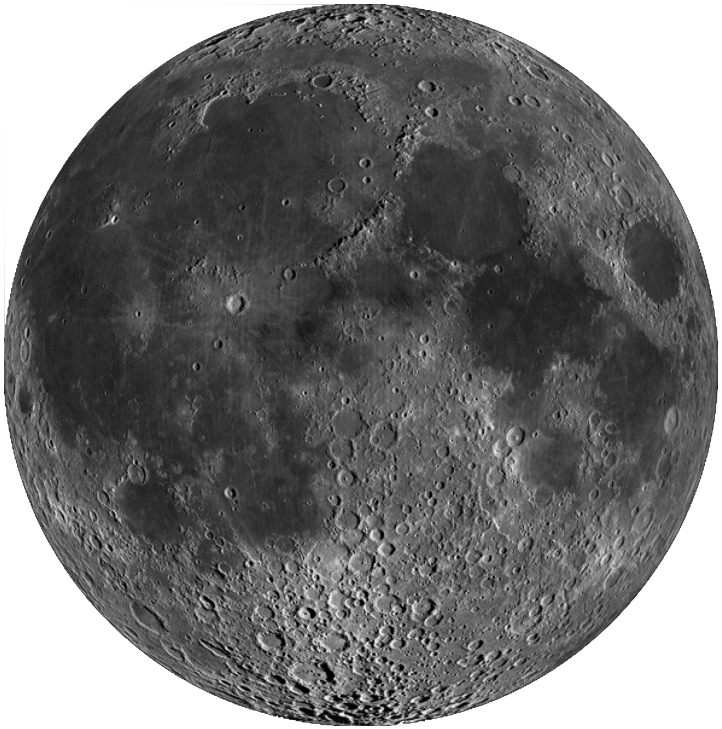
CURRENT Global Plans: Ambitious & Rapidly Changing



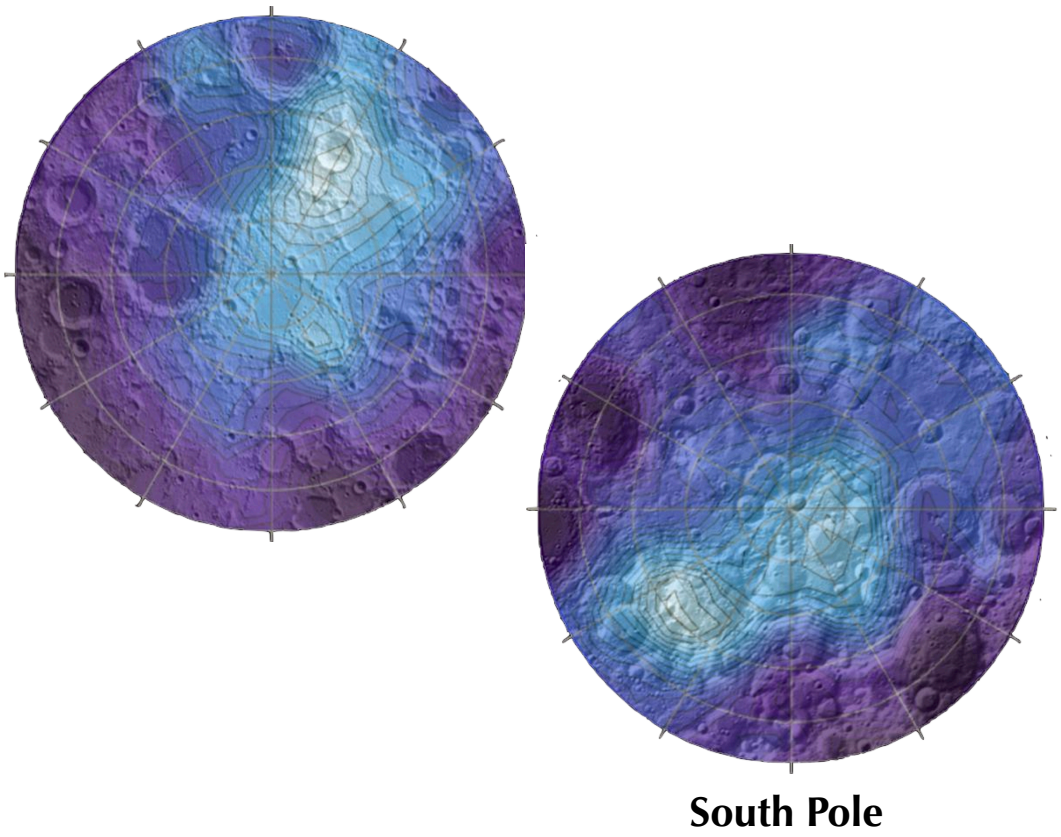
Why the Polar Regions?

Why the Polar Regions? (1 of 2)

- Earth is tilted at an angle of about 23.5° with respect to what is known as the "plane of the Ecliptic" (i.e., the plane defined by Earth's orbit around the Sun)
- This tilt accounts for the seasons we experience – in summer, the north pole is tilted toward the Sun and the weather in the northern hemisphere is warmer, and *vice versa* in the winter
- However, **the Moon is tilted at an angle of only about 1.5° relative to the plane of the Ecliptic**
- As a result, many canyons and craters at the Moon's poles are never illuminated by sunlight – and have been in shadow for billions of years
- Conversely, other locations at the poles – the rims of major craters, the ridges of mountain ranges, plateaus, etc. – are almost constantly in sunlight

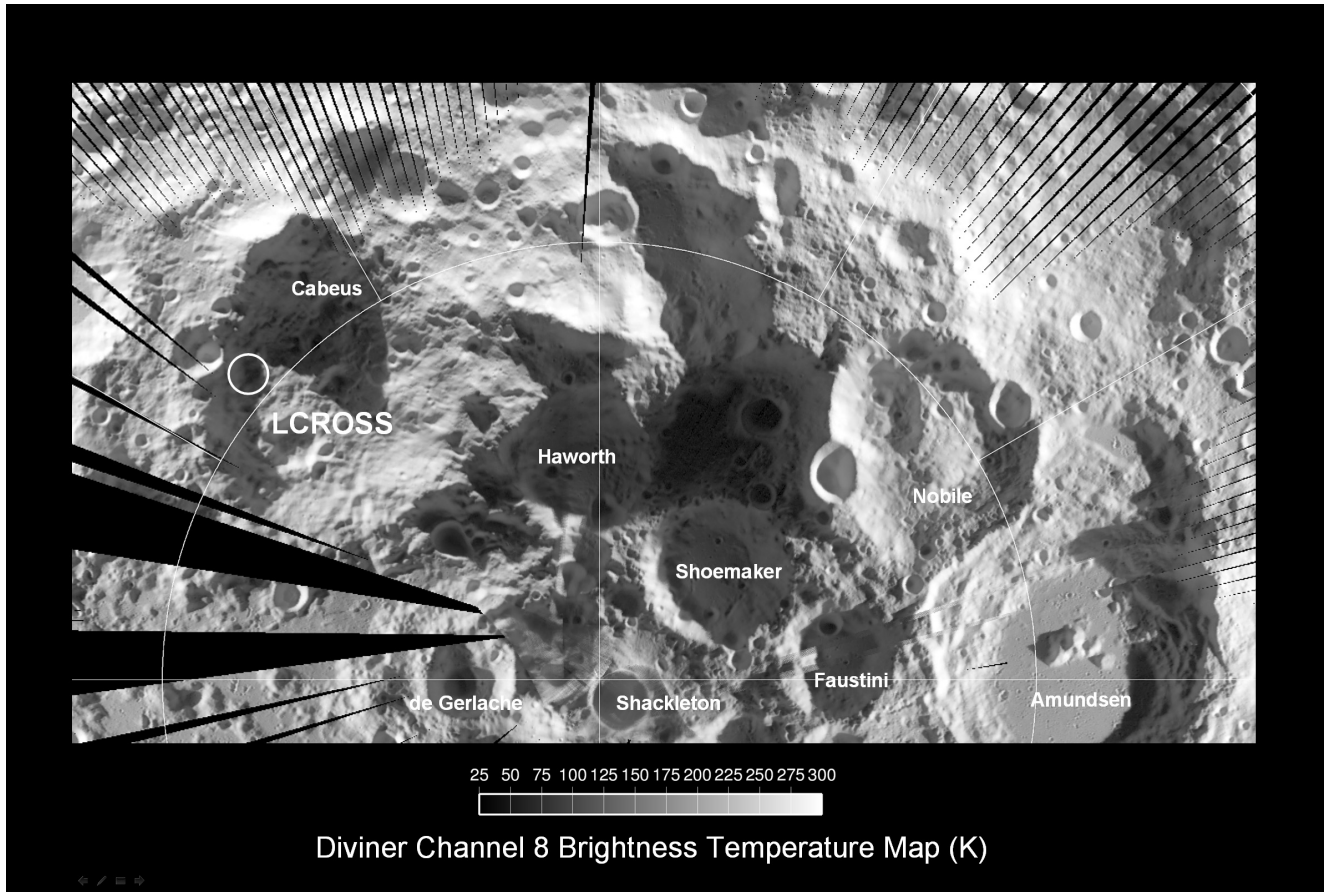


Why the Polar Regions? (2 of 2)



- During the past 20 years, various missions / probes have validated that vast amounts of volatiles – particularly water, probably in the form of ice – are captured in the extremely cold, permanently-shadowed regions at the North and South poles of the Moon
- The Moon's polar deposits of volatiles can be mined, and transformed into both propellants (Oxygen and Hydrogen) and life support logistics (air, water, etc.); as a result, they represent a significant potential resource for future exploration, commercial development and eventual settlement
- The US, China, Japan, India, Europe and others are all examining options for exploration and later extraction / use of these resources

A Specific Market Opportunity: Lunar Polar Energy



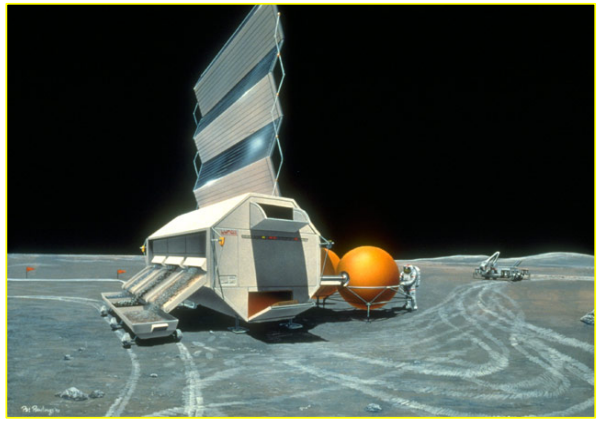
Market Opportunity:

High-Power Lunar Surface Operations at a key location of interest is the Polar Regions

Example: the South Pole

What is the Challenges / Solutions?

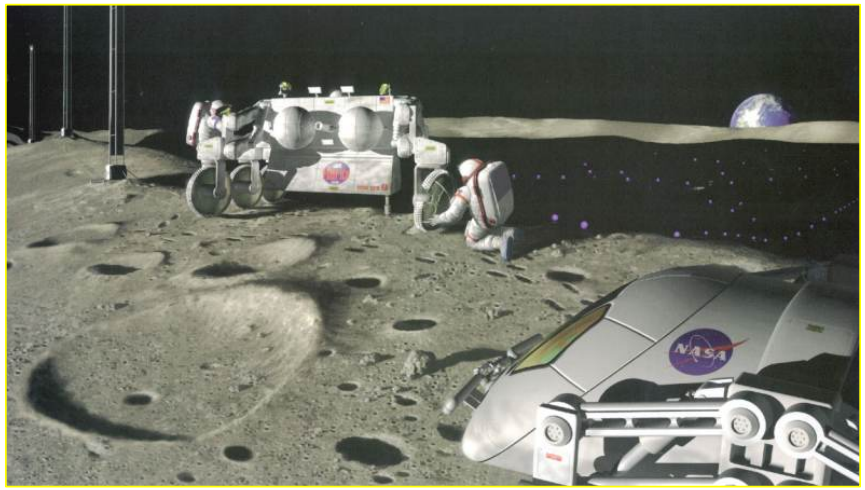
- Accomplishing mining, extraction and processing of lunar resources will require considerable **energy / power**
- The four principal options for energy in deep space / planetary missions are:
  - **Primary Batteries**, for very short duration missions – power up to 10s of Watts → X *Requires Regular Recharging*
  - **Radioisotope Thermoelectric Generators** (RTGs), for very long duration missions – power up to 100s of Watts, but very toxic radioactive materials → X *Costs are very High, and Permission to Launch Impractical*
  - **Solar Photovoltaic Arrays** (often with Batteries), for 1-20 year duration missions – power up to 10s of kilowatts or more, but only where the sunlight is available → X *There is no sunlight where the volatiles / water ice is deposited*
  - **Space Nuclear Reactors**, for missions up to 10 years duration – power ranging from 10-1,000 kW, but with radioactive materials that → √ *Potential Option; although system* becomes dangerously radioactive once the reactor is "turned on"



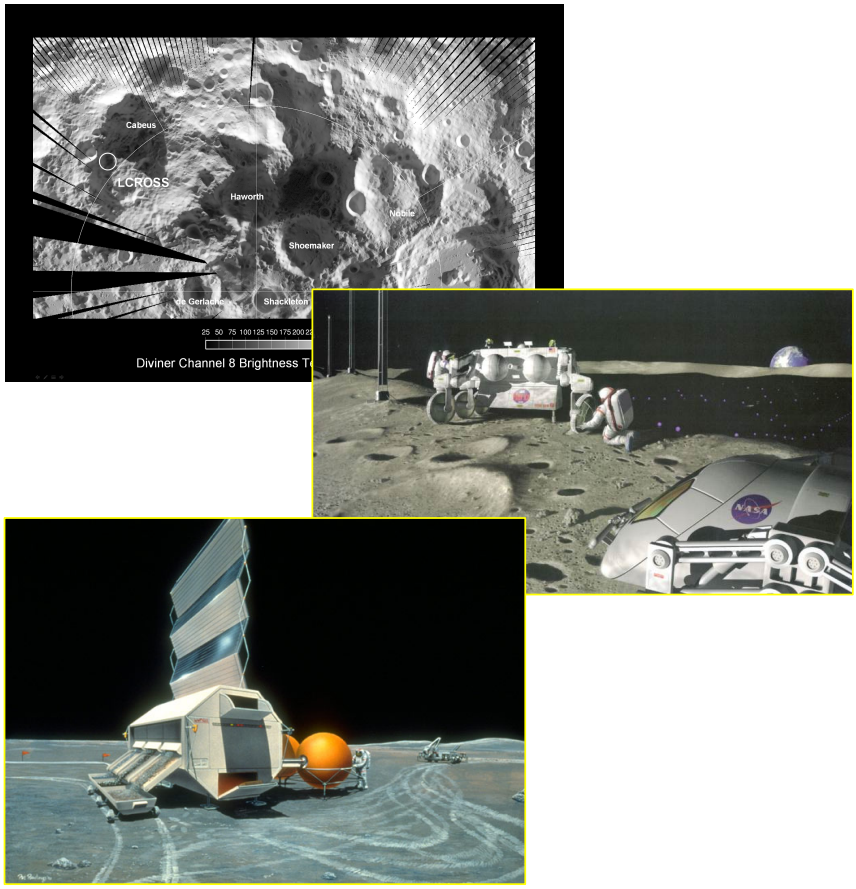
And, the permanently shadowed areas of the Moon's polar regions are 1,000s of meters lower in elevation, and 5-50 kilometers separated from sunlit locations → Conventional Power Cables are impractical

Another Option: Wireless Energy

- Harvest and/or Generate Power in one of the “Peaks of Eternal Light” (or similar) and wirelessly transmit it to systems / operations in the cold / permanently shadowed areas…
- The several new options for energy in deep space / planetary missions are:
  - **Reflectors**, for short range energy redirection, this can be highly interesting
  - **Solar Power with Wireless Power Transmission via Lasers**, often discussed for transmission to a single system
  - **Solar Power with WPT via Microwave Transmission**, often discussed for transmission to an area
  - **Space Nuclear Power with WPT via Laser or Microwave Transmission**, see above…

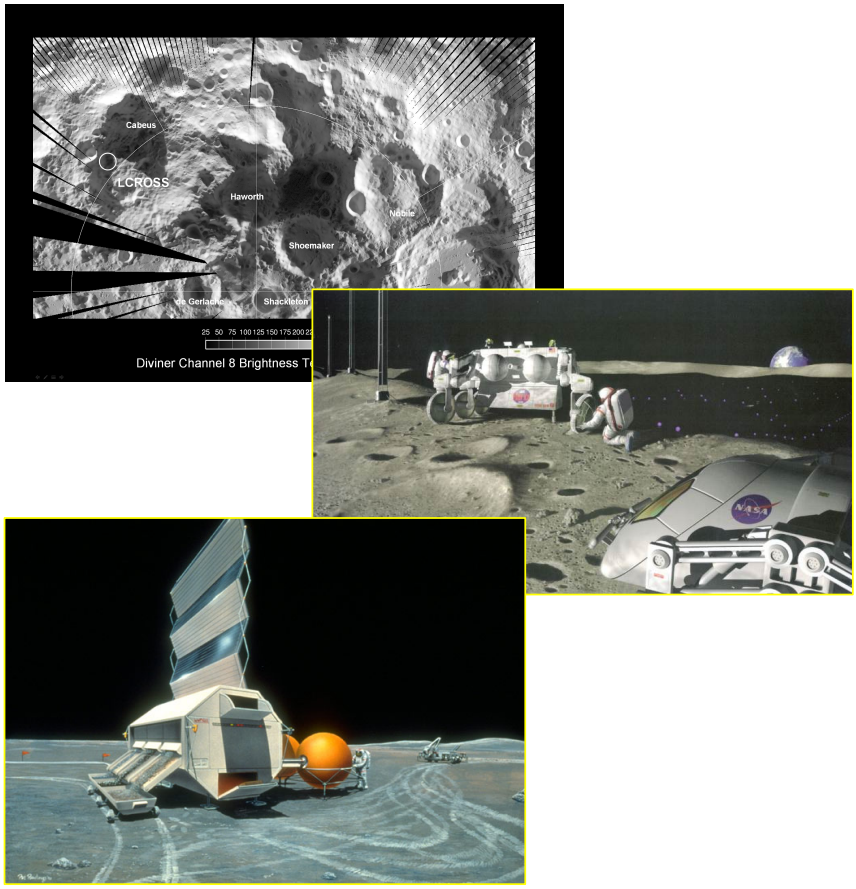


What are the Requirements for Polar Resources? (1 of 2)



- Types of "Users"
  - Mining / Ice Harvester Systems
  - Ice / Regolith Processing
  - Volatiles Processing Storage
  - Supporting "Systems" (e.g., Systems to support Occasional Astronaut Visitors)

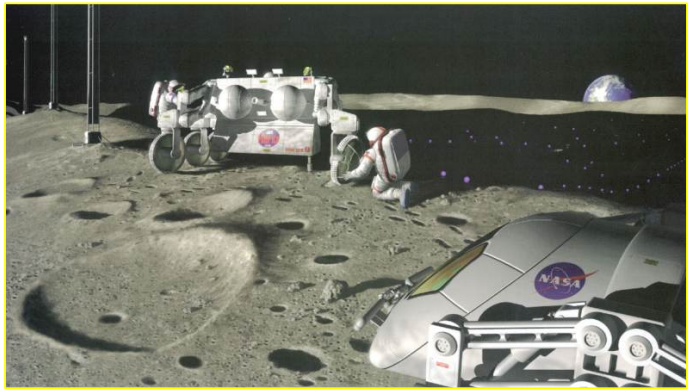
What are the Requirements for Polar Resources? (2 of 2)



- Power Levels
  - Individual systems ~ 2-20 kW (wag)
  - Aggregate SoS ~100-1,000 kW (added-up wags)
- Lifetime
  - Months to Decades (related to power level)
- Environments
  - In the Sun:
    - ✓ Vacuum, Temperatures @ ~240°K, Dry Dust, Human / Outpost Operations
  - In the Shadow:
    - ✓ Vacuum + Potential Outgassing, Temperatures @ ~50°K, Dry Dust + "Processed Dust", Occasional Human / Support Systems Operations

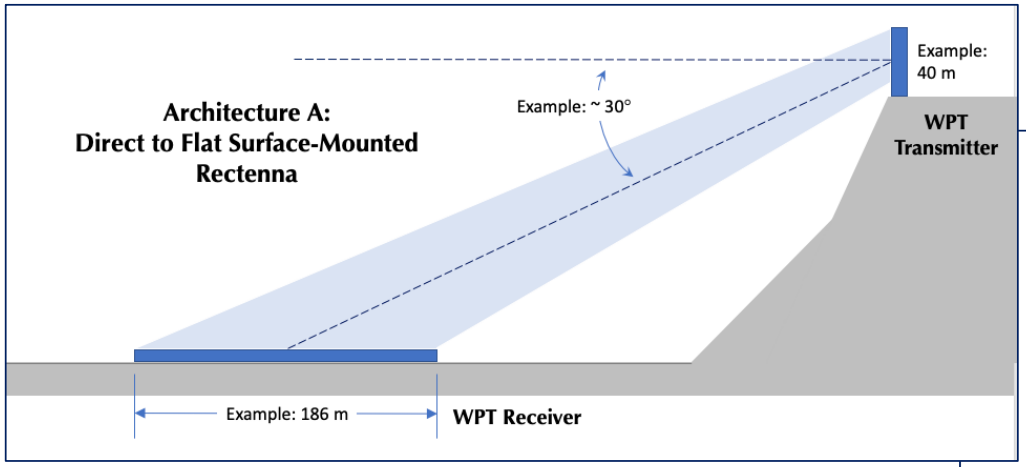
A New Option

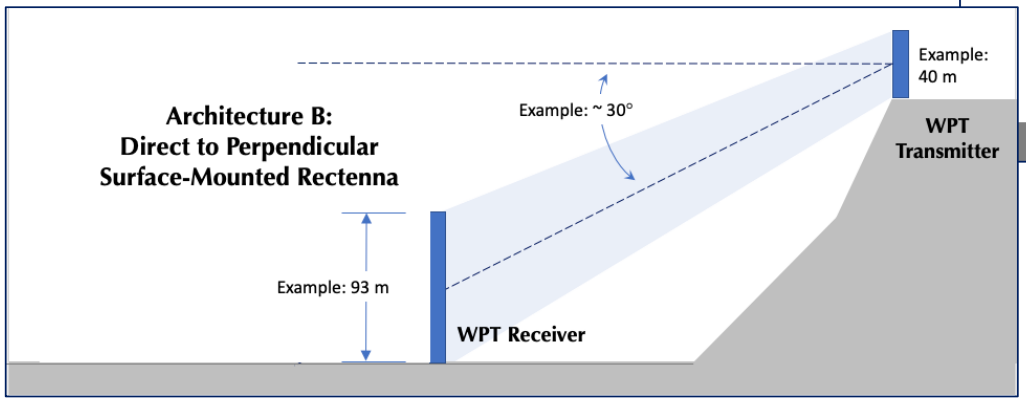
- Another option exists, however…**Lunar Surface-Based Space Solar Power**
- Solar energy can be harvested via photovoltaic (PV) arrays located in the sunlit high-lands, and transmitted wirelessly with good efficiency to receivers deep within the permanently-shadowed regions where the power is needed
- **Ranges: e.g. ~10-40 Kilometers…**

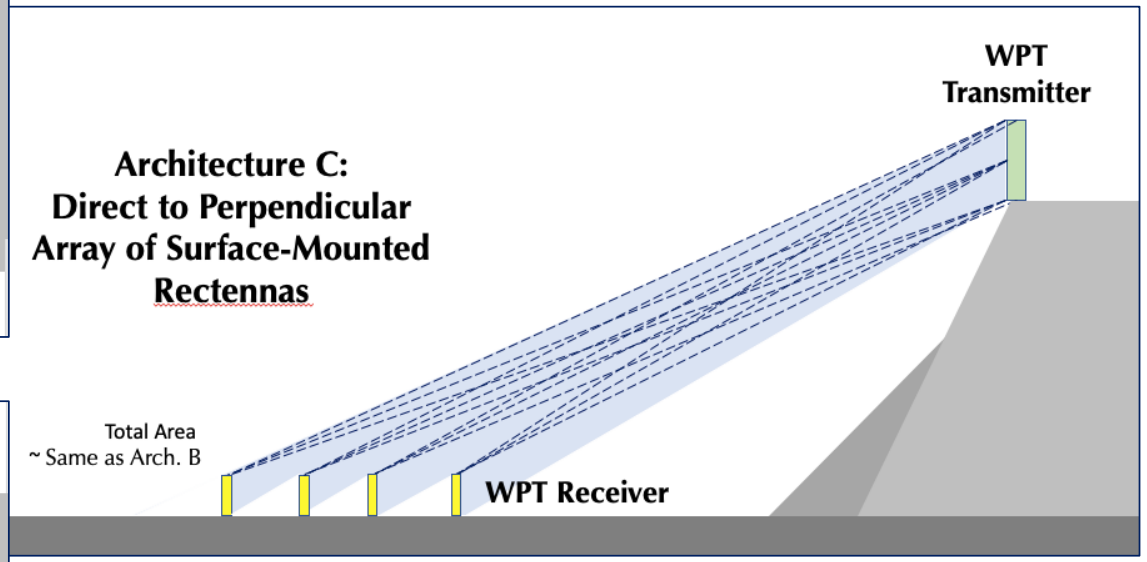


- The technologies to accomplish this exist in the laboratory -- and are ready to be applied to the challenge of Lunar polar power…

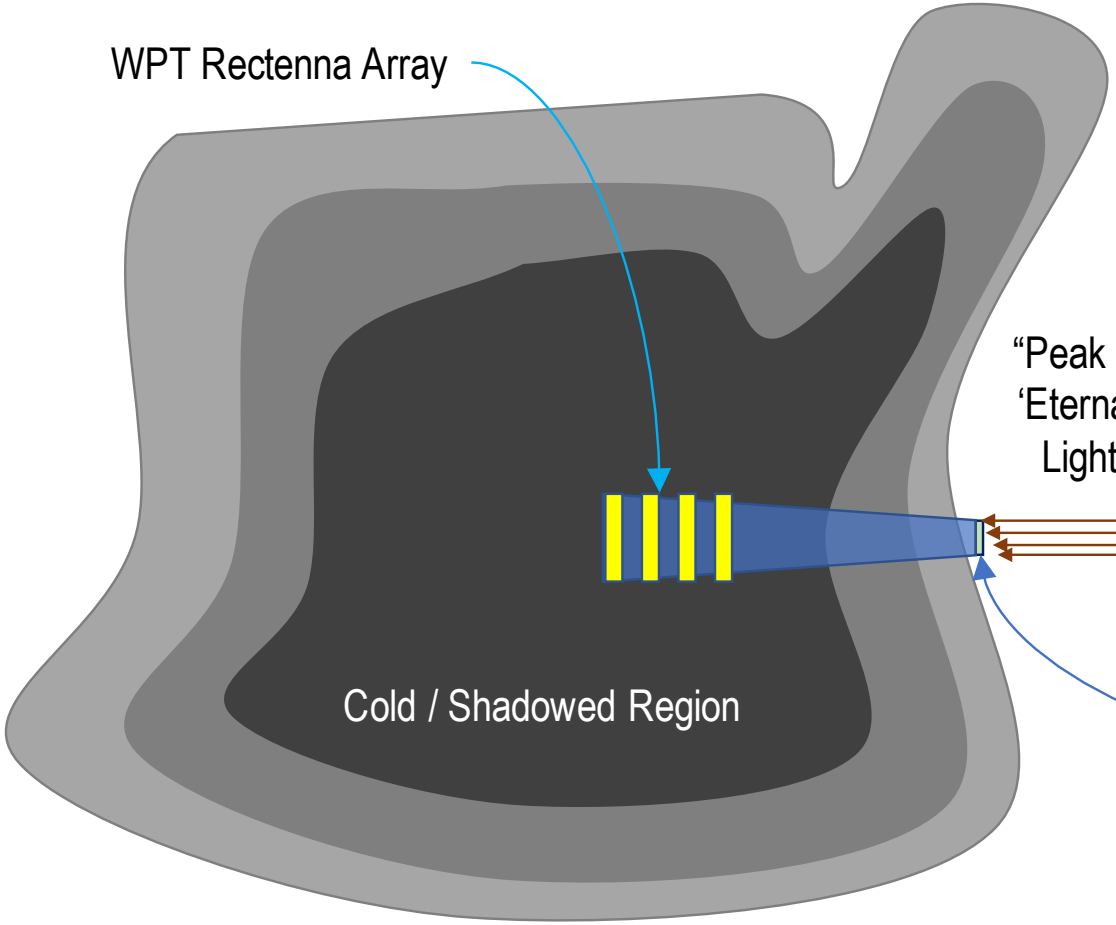
Lunar Surface-Based Space Solar Power Architectural Options







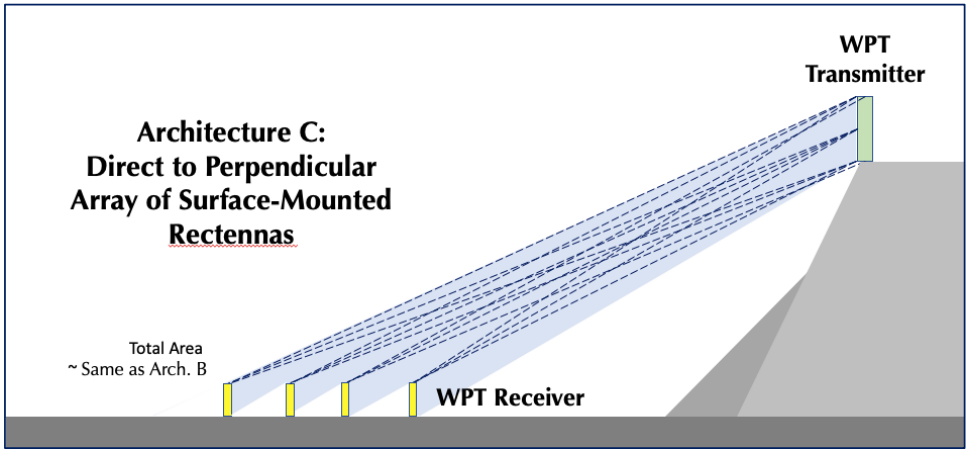
Lunar Surface-Based Space Solar Power Preferred Option



"Peak of 'Eternal' Light

Sunlight

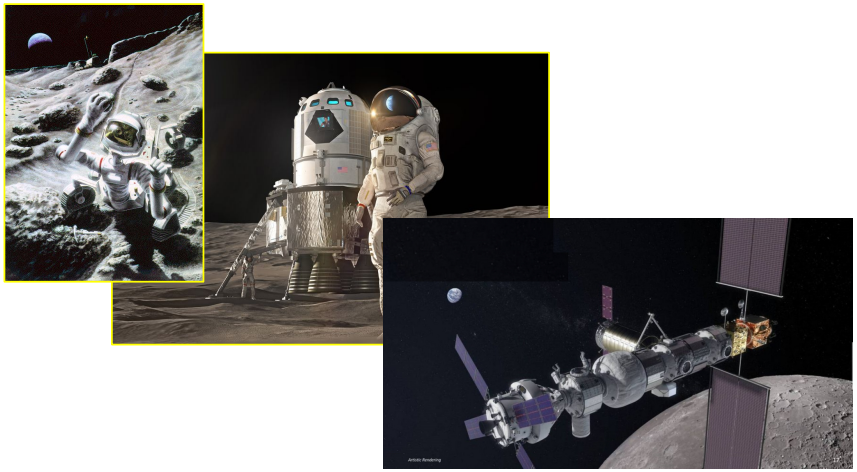
WPT Transmitter



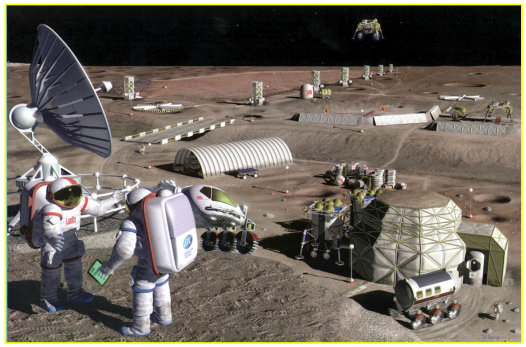
Costs @ Less than $100M (H/W) for 100 kW Delivered

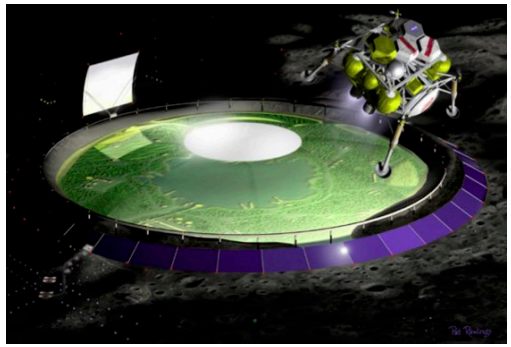
vs. ~ $1B (H/W) for 100kW Delivered for SP-100 Class SNRPS

Other Power Needs for Cis-Lunar Space - Examples



- Early
  - Robotic Missions
  - Cis-Lunar Orbiting Outposts (e.g., the Gateway)
  - Lunar Surface Sortie Human Missions
- Later
  - Cis-Lunar Orbiting Platforms
  - Lunar Surface Outposts
- Much Later: Settlements





- Locations:
  - Orbiting, Polar & Elsewhere
- Power:
  - kW Growing to MW Growing to 10s to 100s of MW

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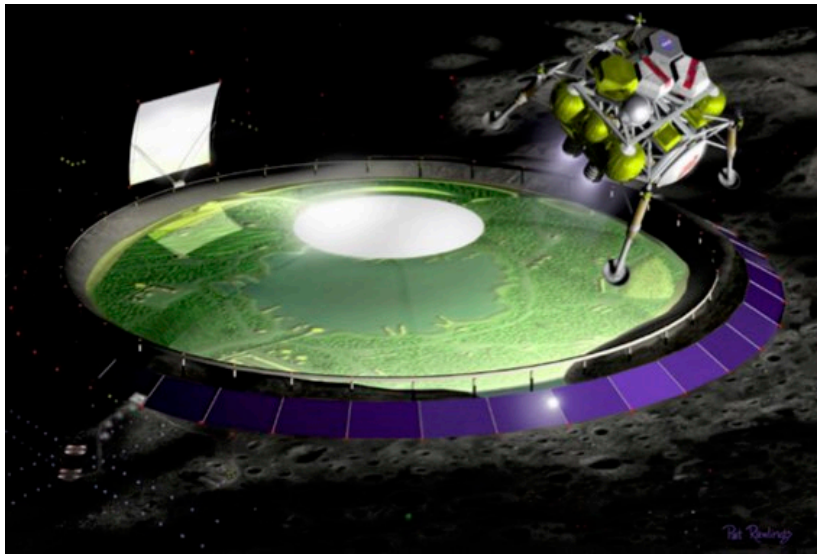
Highlight: Powering Settlements…

Minimum Number of People	**≥ 120**
Agricultural Area per Person	**~4,000 m^2 / person**
Peak Power Per Unit Area (for illumination, H_2O processing, etc.)	**~800 W / m^2**
Total Area Required	**~480,000 m^2**
Effective Settlement "Diameter"	**~800 m**
Settlement Power Required	**~350 ± MW**



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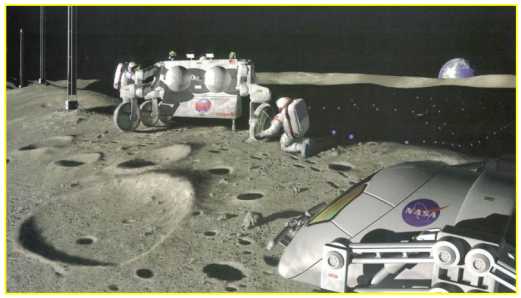
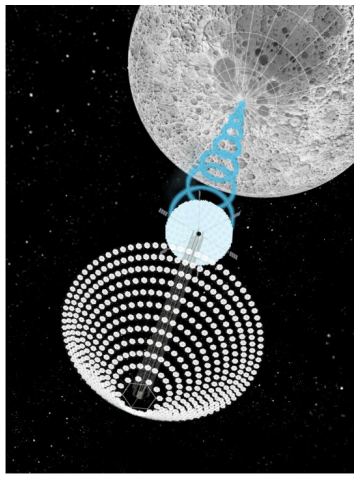
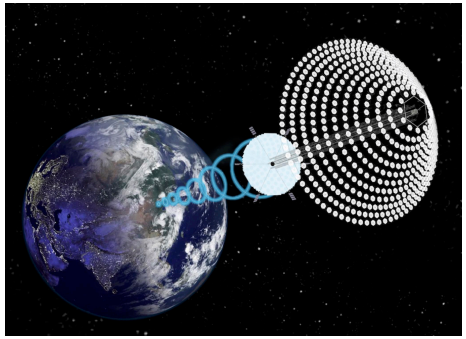
Pathways Forward

Powering Space → Powering Earth

Technology R&D → Demonstrations on Earth → Demos in Space →Demos on Moon → Operations on Moon --> Power Beyond







Closing

- Great demand / potential involving “powering” developments in Cis-Lunar Space
- Potential Funding Sources (US and International) …
  - Commercial Ventures
  - “COTS type” programs
  - Government Programs
    - ✓ Focused on the Moon
    - ✓ Relating to SSP/WPT

To Discuss Further: contact mankinspacetech@gmail.com

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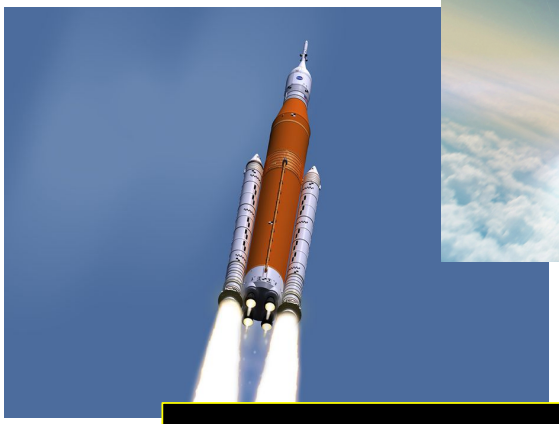
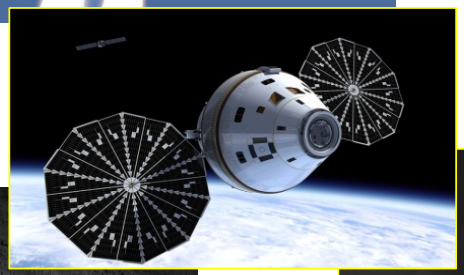
Back-Up Slides

What **Are** the "Cis-Lunar Markets"? EXAMPLES…

AE_3.0 / SPACE TRANSPORTATION SYSTEMS

- These Architectural Elements comprise a range of vehicles and facilities that are to be used for transporting lunar-related missions / systems to space, in space and to/from the surface of the Moon





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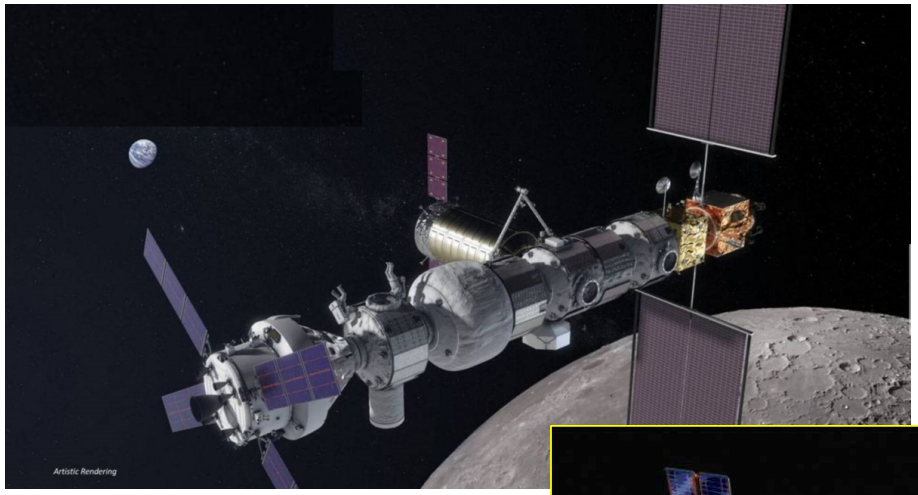


AE_4.0 / EARTH-ORBITAL SYSTEMS

- This category of AE comprises a range of vehicles and systems operating in Earth orbit (typically LEO, MEO and/or GEO) that support lunar-related missions / systems operations and capabilities.

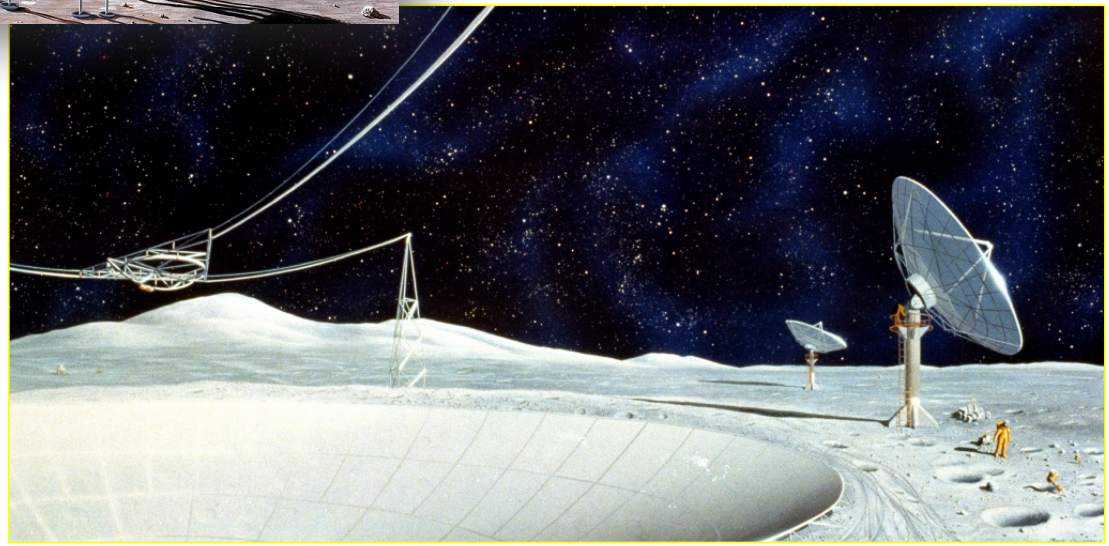
AE_5.0 / MOON / CIS-LUNAR ORBITAL SYSTEMS

- These AEs comprise a range of vehicles and systems operating in cis-Lunar orbit (typically a Libration Point, lunar orbit, etc.) that support lunar-related missions / systems operations and capabilities.

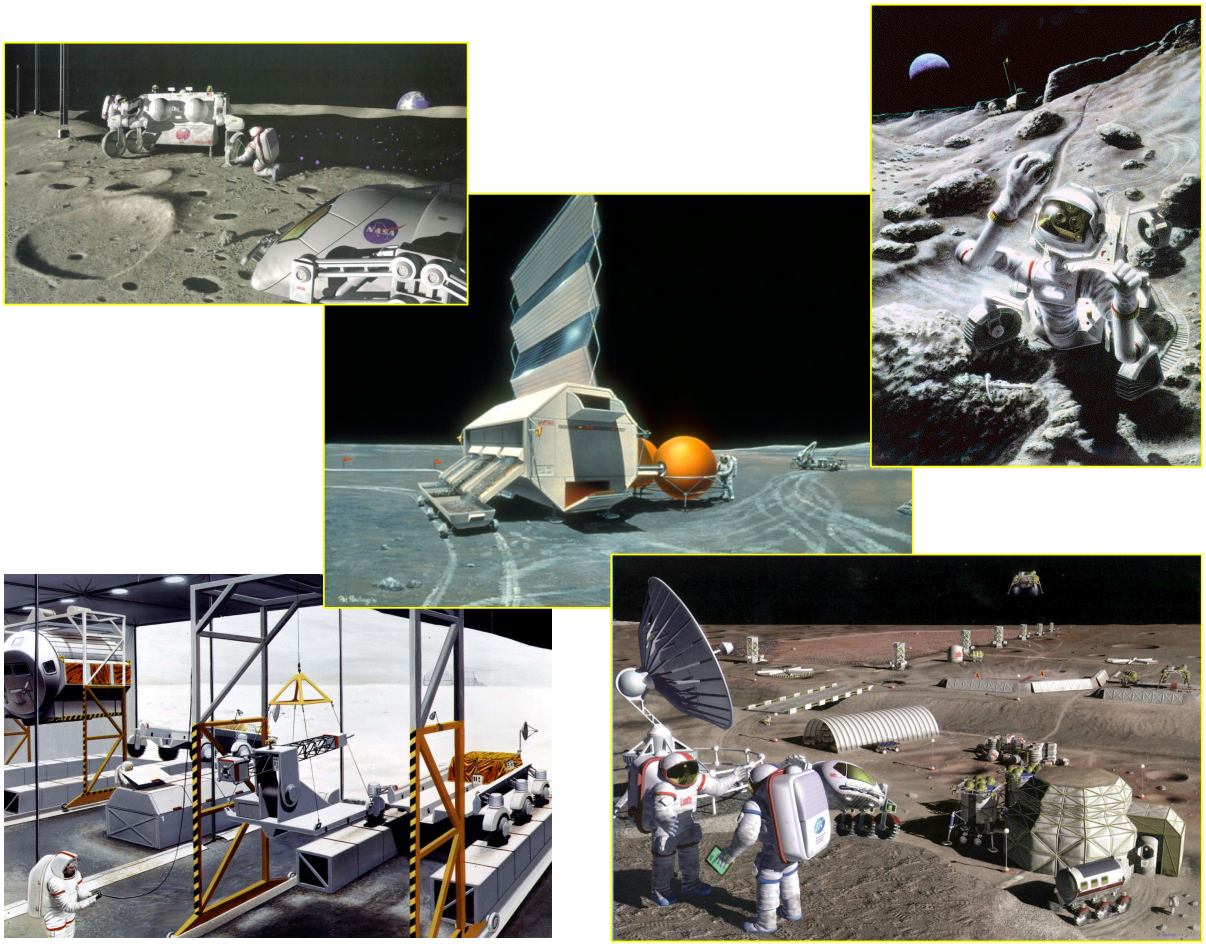
What **Are** the "Cis-Lunar Markets"? EXAMPLES…

AE_6.0 / SCIENTIFIC RESEARCH SYSTEMS

- This category comprises a systems, payloads and capabilities in space that accomplish scientific research programs, including those operating in Earth orbit, cis-Lunar space, or the lunar surface



What **Are** the "Cis-Lunar Markets"? EXAMPLES…



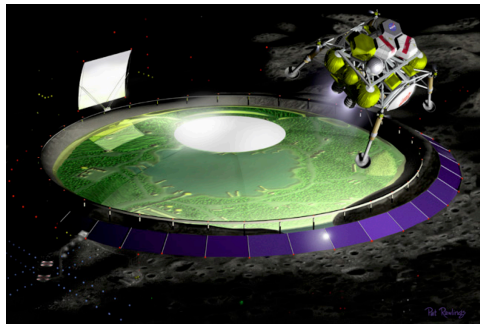
AE_7.0 / LUNAR SURFACE SYSTEMS

- This category of Architectural Elements comprises a wide range of systems, payloads and capabilities delivered to and/or operating on the surface of the Moon that accomplish various functional requirements for scientific, commercial and/or human exploration focused programs and/or projects

What **Are** the "Cis-Lunar Markets"? EXAMPLES…

AE_8.0 / HUMAN OPERATIONS & SAFETY SYSTEMS

- These AEs involve a diverse set of systems, payloads and capabilities in space that enable safe and/or affordable human presence and operations, including those operating in Earth orbit, cis-Lunar space, or the lunar surface.



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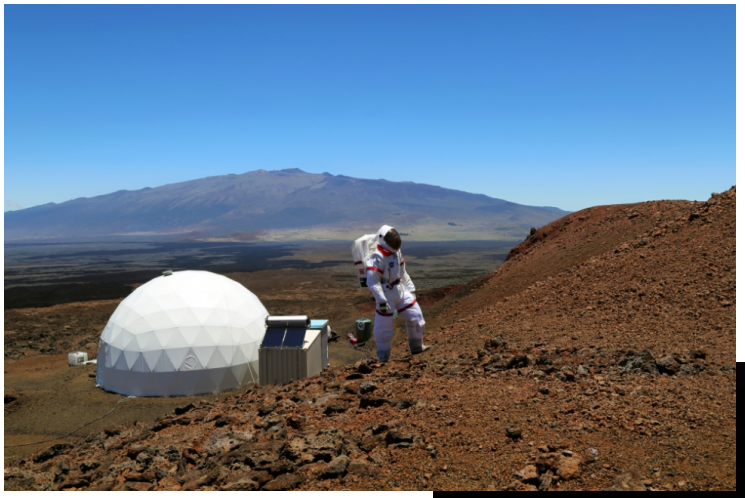

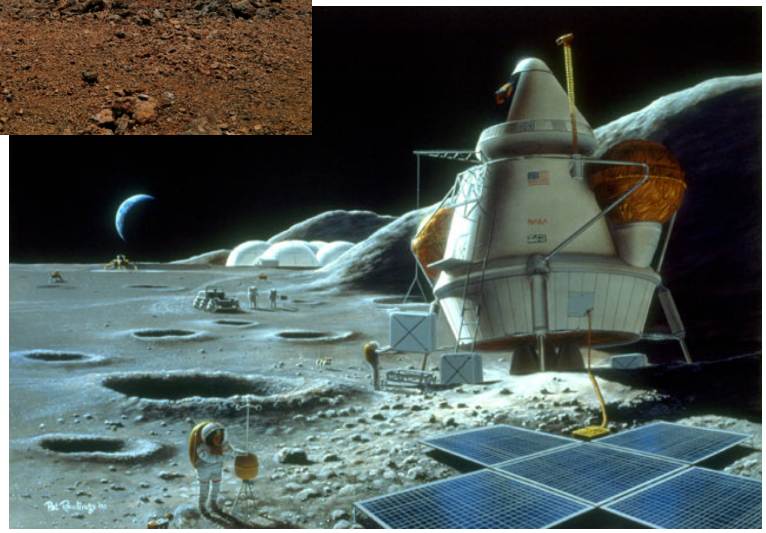

AE_9.0 / LUNAR & EXPLORATION ANALOGUES

- This category comprises "analogue" testbeds -- which are specialized capabilities to test concepts of operations -- including habitation human-systems design concepts, etc.

Lunar Surface-Based / Polar Space Solar Power
Case Study : 100 kW Delivered to Shadowed "Floor" (1 of 3)

WPT End-to-End Calculations		
Frequency	2,450,000,000	Hz
Wavelength	0.122364269	meters
Distance	25	km (Xmttr-Rcvr)
D (Xmttr)	40	meters
"Tau"	2.44	Parameter
Transmission Eff	99%	Percentage
Max Beam	96%	Beam Coupling
Required Beam	39%	Beam Intercepted
Xmttr DC Input	398,233	Watts
Xmttr DC-RF Eff.	80.00%	Percentage
Xmttr RF Output	318,586	Watts
RF-DC Efficiency	85%	RF-to-DC
D (Perpendicular Rcvr)	58	meters
RF Power @ Rcvr	117,647	Watts
DC Power @ Rcvr	100,000	watts

SSP Transmission System - in Permanently Illuminated Region		
Duration of each Lunar Day	708	hrs
% time SSP Array in the Sun	80.0%	percentage
Hours SSP Array in Sun	566.4	hrs
Average Temperature (PIR)	243	°K
Average Temperature (PSR)	40	°K
Insolation	1,368	W/m^2

SSP Receiver - in Permanently Shadowed Region		
% time WPT Receiving Energy	80.0%	percentage
Hours WPT Receiving Energy	566.4	hrs
Average Temperature (PSR)	40	°K
Insolation	1,368	W/m^2

Balance of Systems – Energy Storage in PSR		
Time of Storage	141.6	hrs
Storage at Receiver Required	14,160.0	kWh

Balance of Systems – Heliostats in PIR		
Total Area of Reflector Array	1,571	m^2
Area of A single Reflector	4	m^2
Efficiency of A Reflector	0.9	Percentage

Lunar Surface-Based / Polar Space Solar Power
Case Study : 100 kW Delivered to Shadowed "Floor" (2 of 3)

System / Module Sizing (1 of 2)

System Element Type	System Size	Module Size	
WPT Transmitter	1,256.6	1	m^2
WPT Receiver	2,671	1	m^2
PV Array	1,256.6	4	m^2
Heliostat Array	1,570.8	4	m^2
Energy Storage	14,160	100	kWh

System / Module Sizing (2 of 2)

System Element Type	Number of Modules	Module Mass (kg)	System Mass (kg)
WPT Transmitter	1,257	2	2,513
WPT Receiver	2,671	2	5,342
PV Array	314	4	1,257
Heliostat Array	393	4	1,571
Energy Storage	142	8	1,133

System / Cost Estimate

System Element Type	Cost Estimation Relationship ($/kg)	System H/W Cost ($,M)	Transport Cost (@ $50K/kg)
WPT Transmitter	$1,977	$4.97	$126
WPT Receiver	$692	$3.70	$267
PV Array	$2,018	$2.54	$63
Heliostat Array	$2,018	$3.17	$79
Energy Storage	$1,441	$1.63	$57
TOTAL	N/A	**$16M**	**$591M**

$1,800

Lunar Surface-Based / Polar Space Solar Power
Case Study : 100 kW Delivered to Shadowed "Floor" (3 of 3)

- Assumed Lifetime: 10 years
- Baseline Alternative Solution: Space Nuclear Reactor Power System
  - SP100 or Prometheus type; tailored for Lunar Surface Deployment
  - Mass: ~6,000 kg (including lander / radiator / etc.)
  - Cost: ~$2,000 M (including transport, operational engineers, etc.)
  - LCOE: ~$225 / kWh
- Lunar Surface Based SSP System
  - Estimated Cost: ~$607M (including $16M SSP System Hardware Cost)
  - EXAMPLE Economic Performance
    - ✓SSP System Hardware "Sales" Price: ~ $1,200M
    - ✓LCOE: ~$204 / kWh
    - ✓Simple Profit: ~ 75:1 (neglects cost of money, etc.)