Program Update
10-Year Lunar Architecture (LunA-10) Capability Study

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Briefing prepared for LSIC Spring Meeting

April 25, 2024

DARPA

LunA-10 consortium of industry, arranged by (initial) services

These groupings change across the program based on proposed technical areas/products

Market Analysis and Cislunar Logistics:

FIREFLY AEROSPACE

Power:

BLUE ORIGIN

HONEYBEE ROBOTICS

FIBERTEK, INC.

Mining & ISRU:

CISLUNAR INDUSTRIES

SIERRA SPACE

HELIOS

Communications, Position, Navigation, and Timing:

crescent

REDWIRE

Transit and Mobility:

NORTHROP GRUMMAN

SPACEX

Construction & Robotics:

GITAI

ICON

These companies are here today to answer your questions

What direction is DARPA exploring?

Push from individual self-service to commercial multi-service

Push from government as a sole sponsor to commercial as a customer

For a given service or unit: what are the inputs/outputs/limitations?

What DARPA-hard technical challenges must be surmounted to create a sustainable lunar economy by 2035?

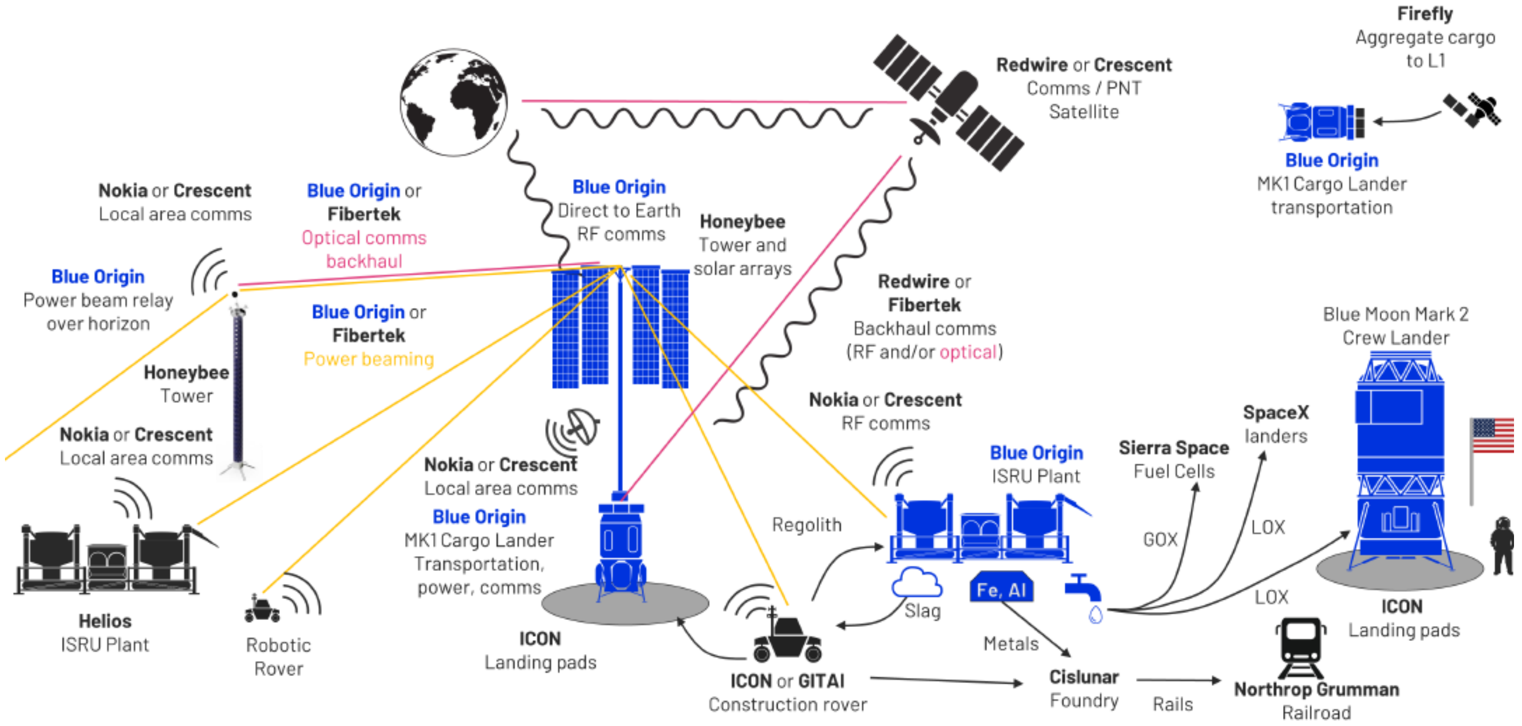
A fast and furious summary of over 25,000 person-hours of labor

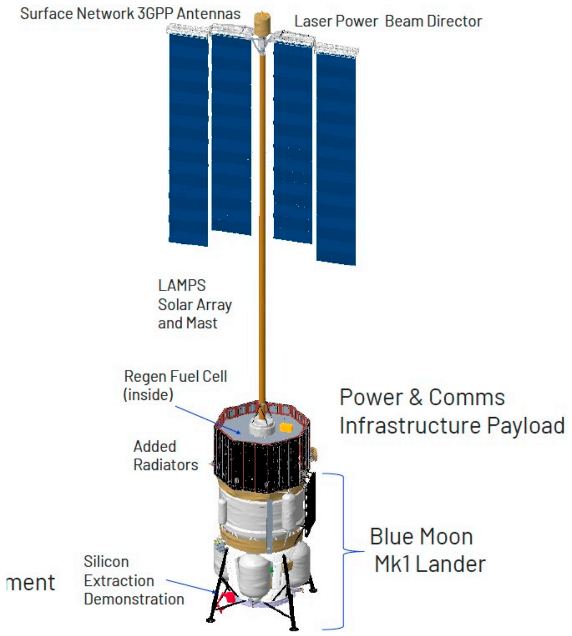
Blue Origin: lander, power, comms and ISRU

Three complementary, multi-service commercial systems:

1. Lander node as payload host and Infrastructure Platform
2. Laser-enabled Wireless power framework
3. ISRU for Construction, Mining and Energy

Features	Capability
Solar Array	> 10 kWe
Mast	20 m mast on ~10 m lander (total 30 m above surface)
3GPP Telecom Service	25 Mbps bps up to > 10 km range, max range ~100 km
Regen Fuel Cell Augmentation Kit	1.5 MWh, 7.8 kW_e over 192 hrs
Laser Power Transmitter	~1 kW_e delivered to 10+ km,
Silicon Extraction Experiment	Demonstrate production of silicon from regolith
Heat Rejection Augmentation Kit	Added Radiator area for payload power

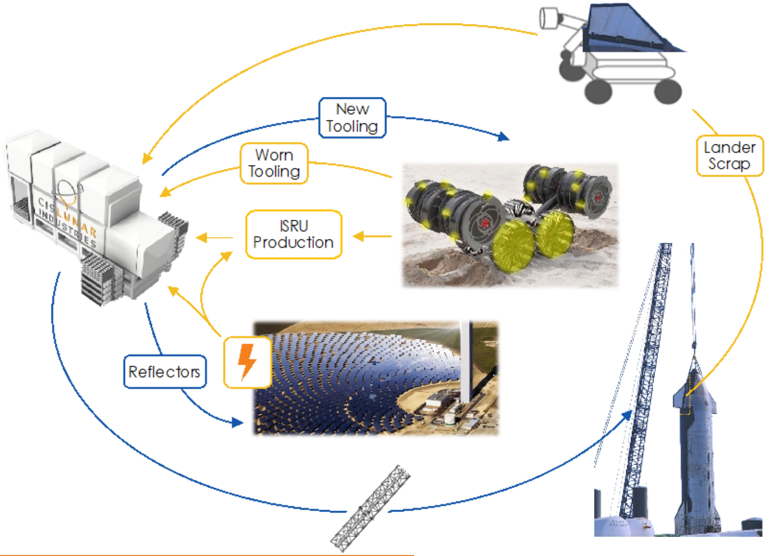


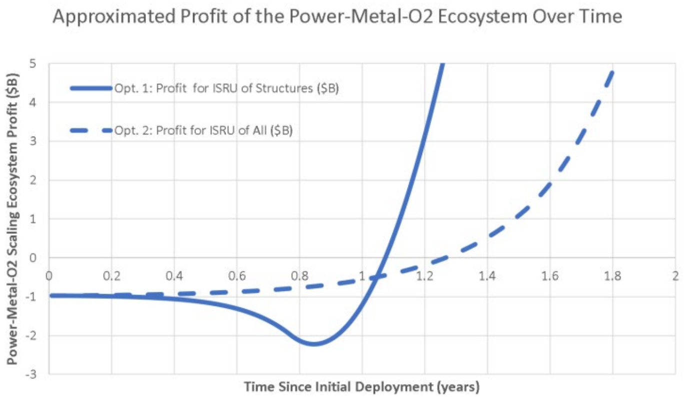


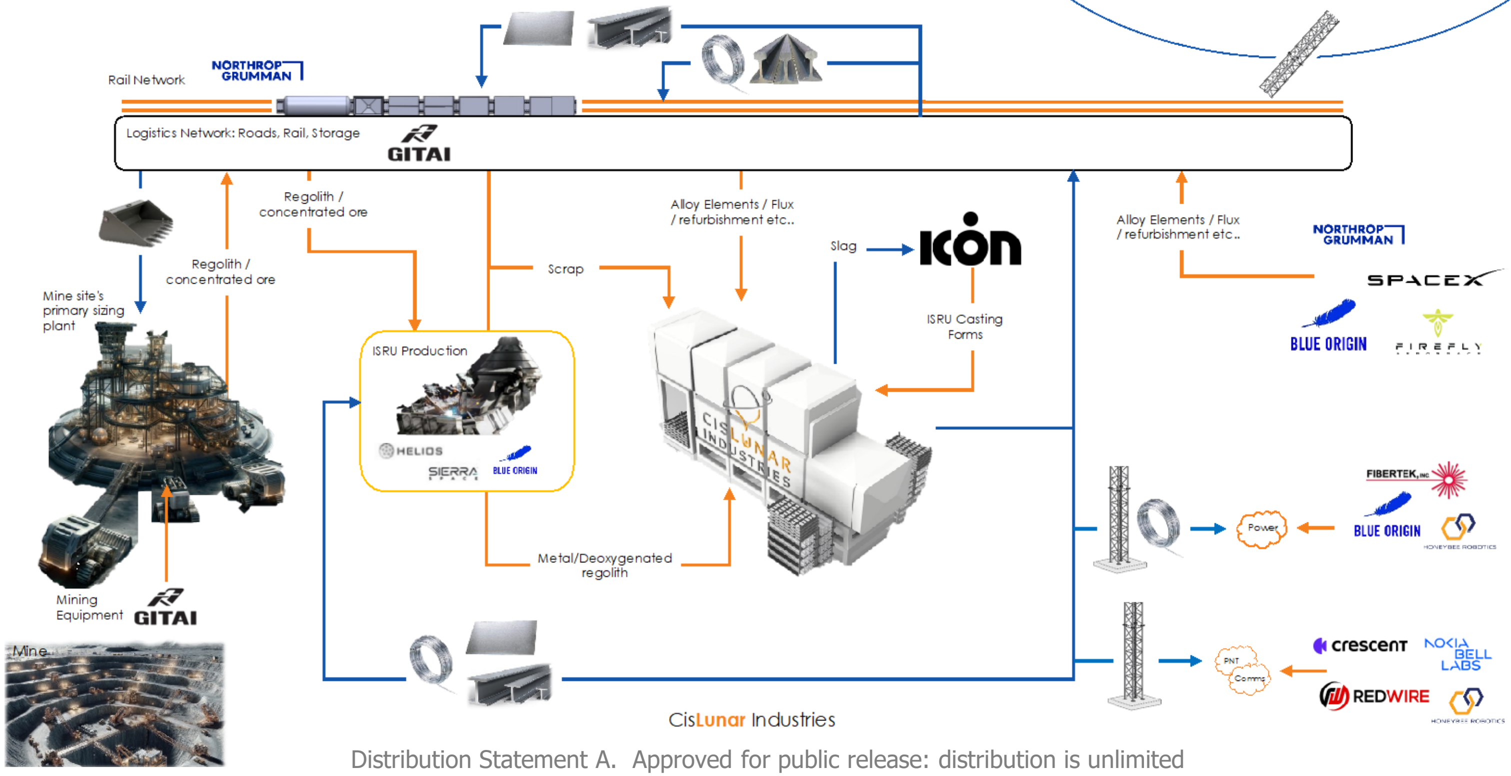
CisLunar Industries: metal extraction and recycling on the Moon

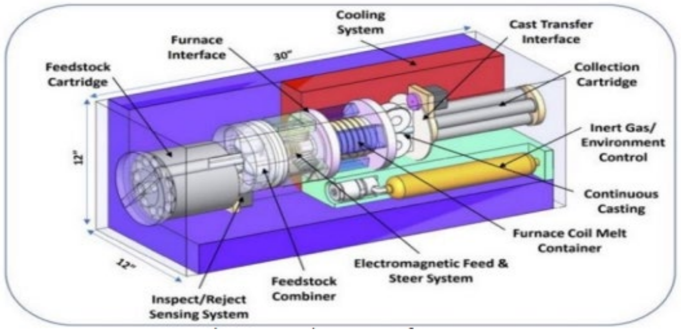
Building infrastructure and enabling sustainable mining operations:

- Inputs: ISRU metals (Al, Fe), scrap, slag, alloying elements
- Outputs: Ingots, beams, sheet metal, extruded wire and other metal-based products needed for the lunar economy





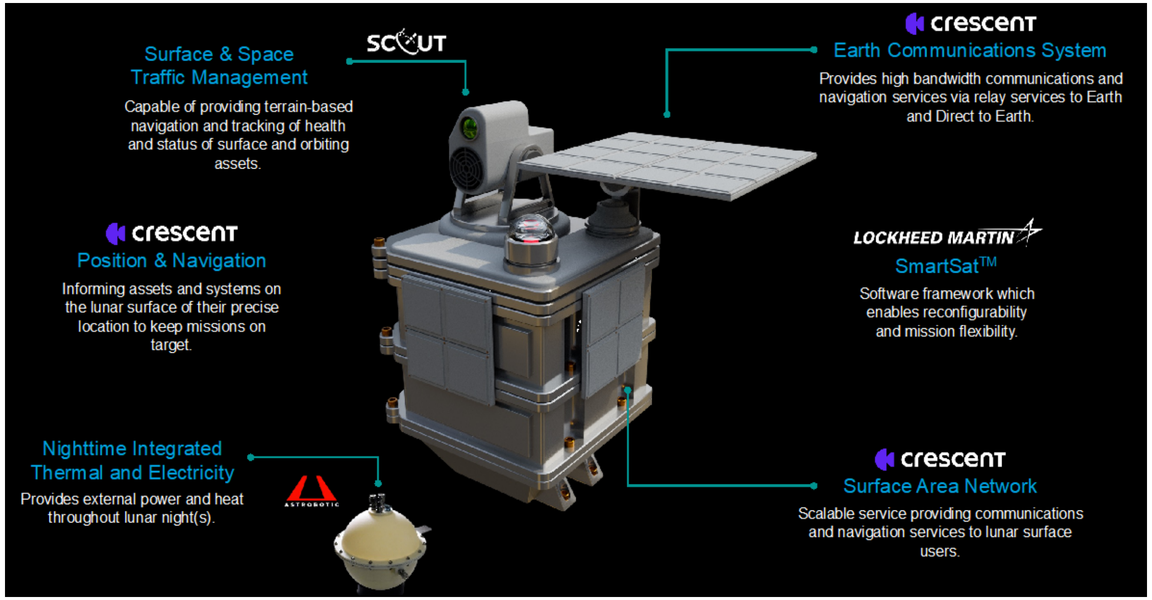


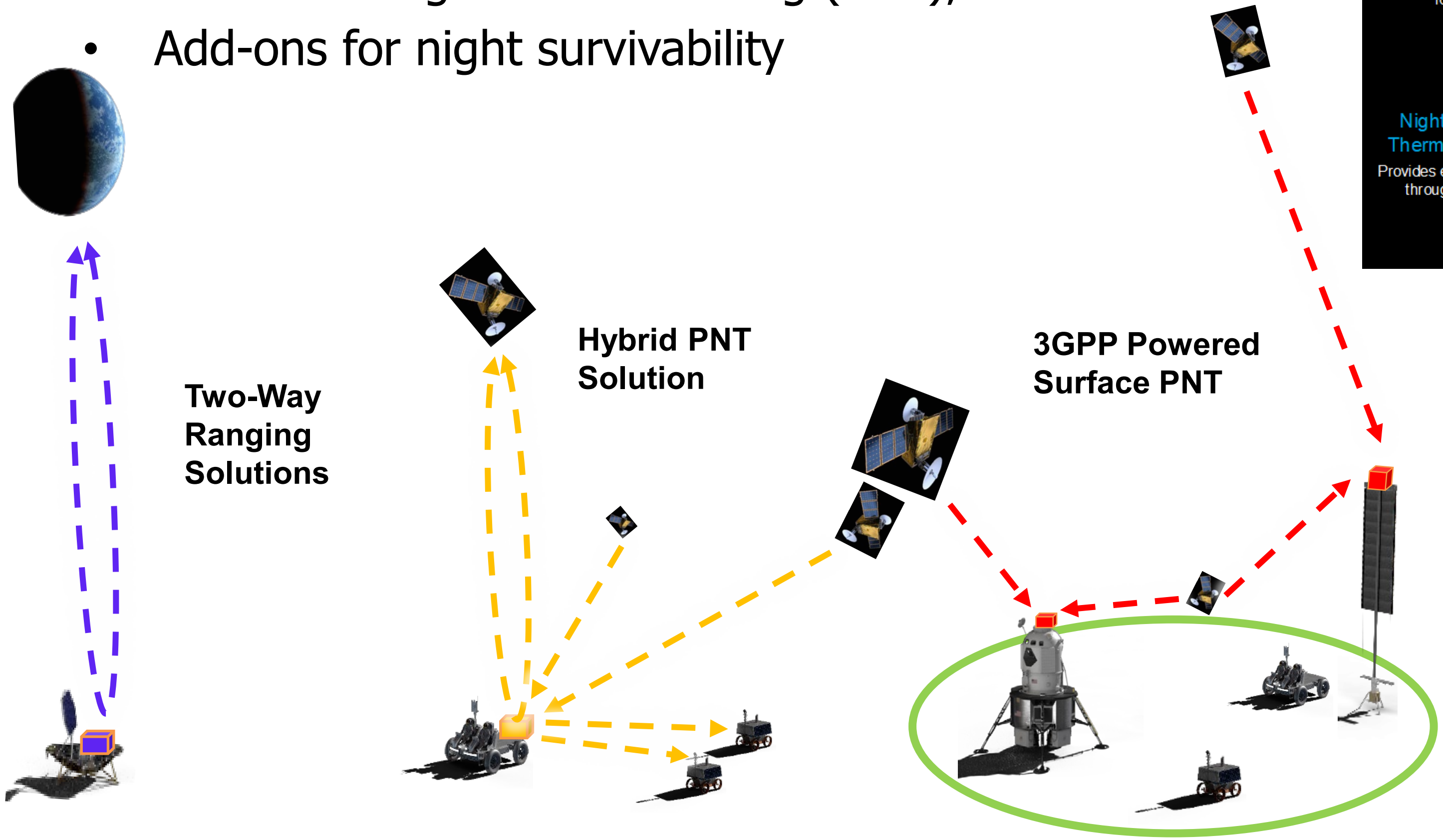


Crescent Space: scalable, night-survivable Comms, PNT and STM

Scalable, commercially commoditized unit for:

- Surface area networking (SAN),
- Space traffic management (STM),
- Direct-to-Earth comms,
- Position Navigation and Timing (PNT),
- Add-ons for night survivability



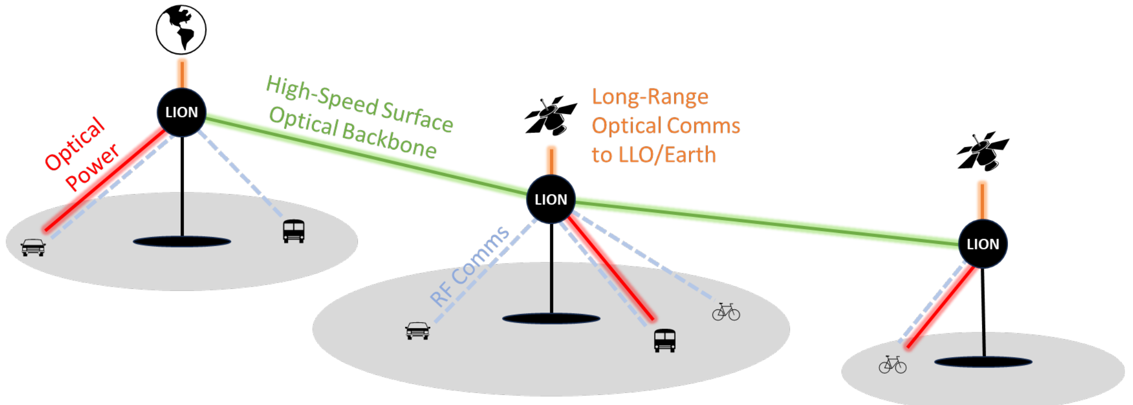


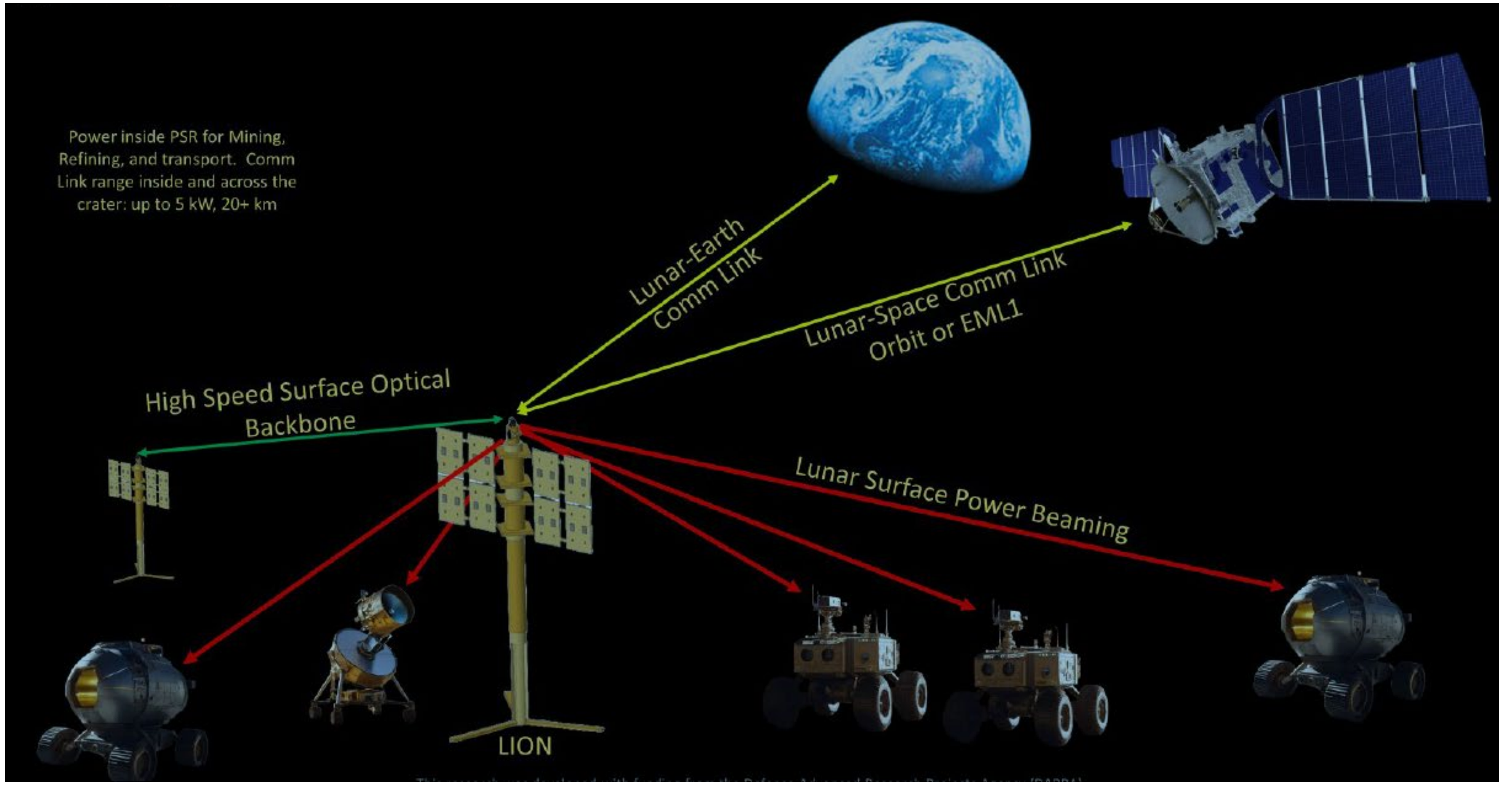
MUST-MVP	MUST-SAN	MUST	MUST-HEAVY
• <0.7 kg • <20 W	• <0.75 kg • <40 W	•<1.5 kg (+12 STN and STM) •<60 W (+40 STN and STM)	• <20 kg • <125 W

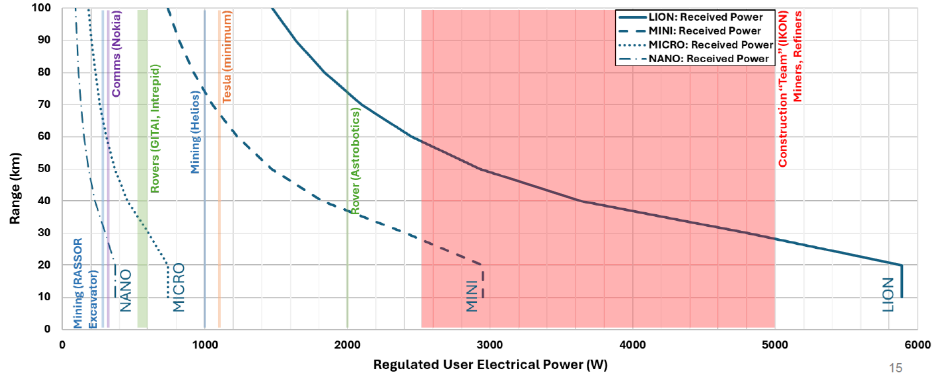
Fibertek: Lunar Infrastructure Optical Node (LION)

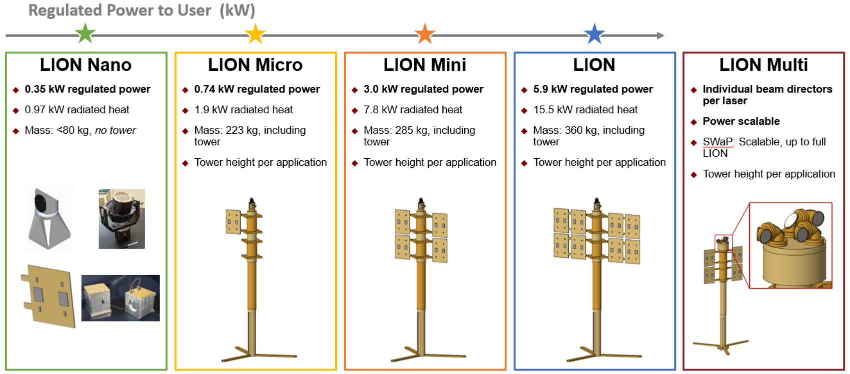
Scalable, modularized unit for surface power and connectivity to mobile users:

- Power beaming across the lunar surface
- High-speed surface optical back-bone
- Direct-to-earth communications link
- Lunar-to-orbit communications link





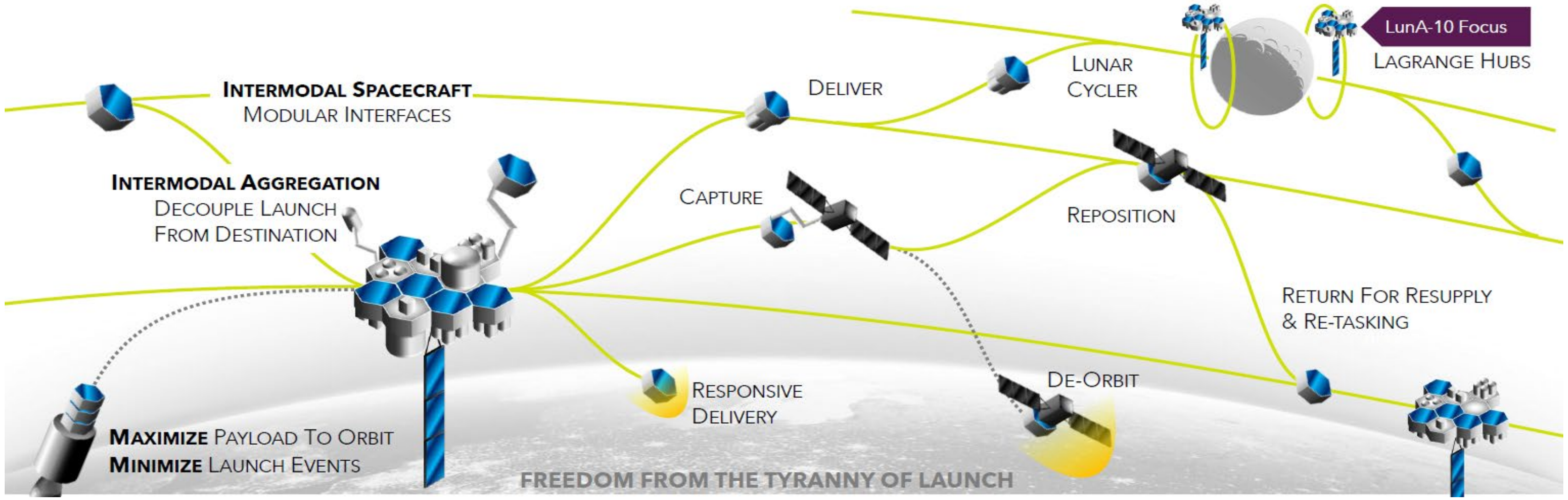


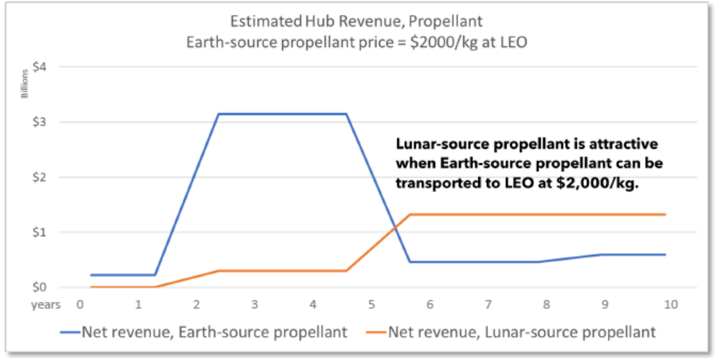


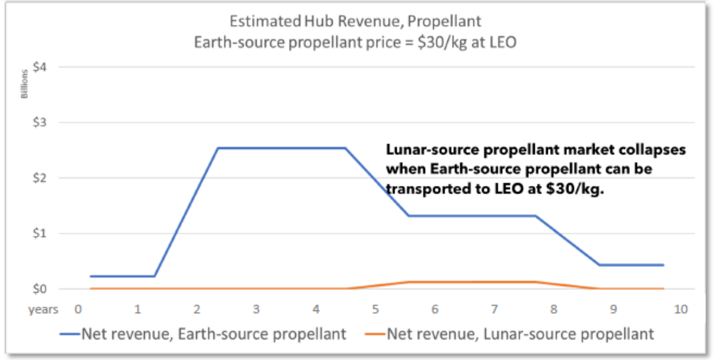
Firefly Space: a cislunar aggregation hub for propellant and spacecraft

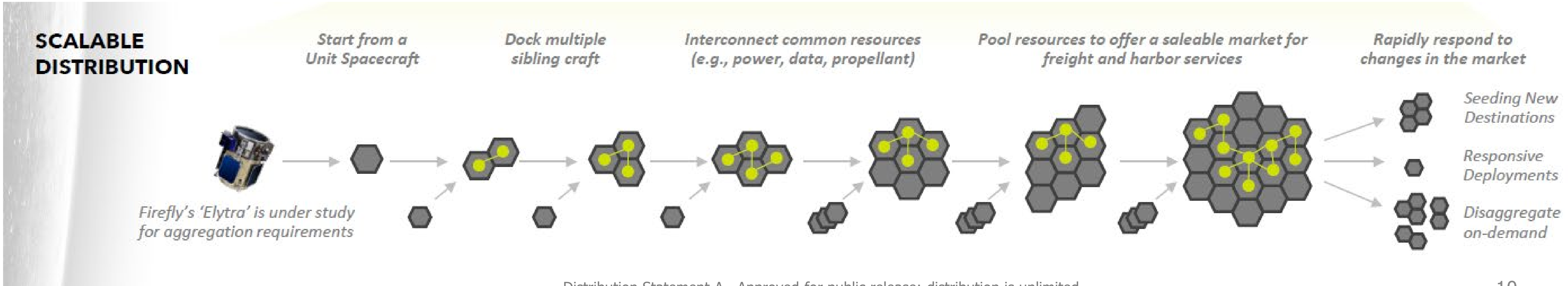
Design of a lunar harbor for in-space logistics

- Cost modelling based on propellant demand and price





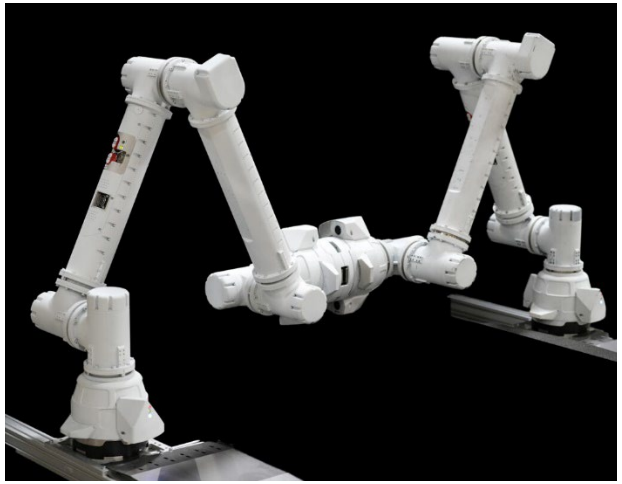


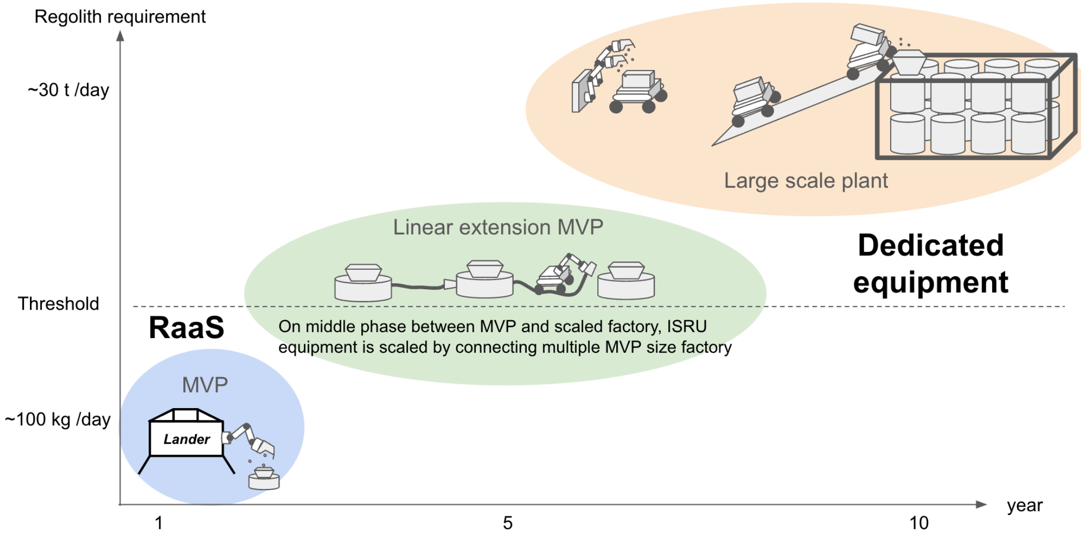


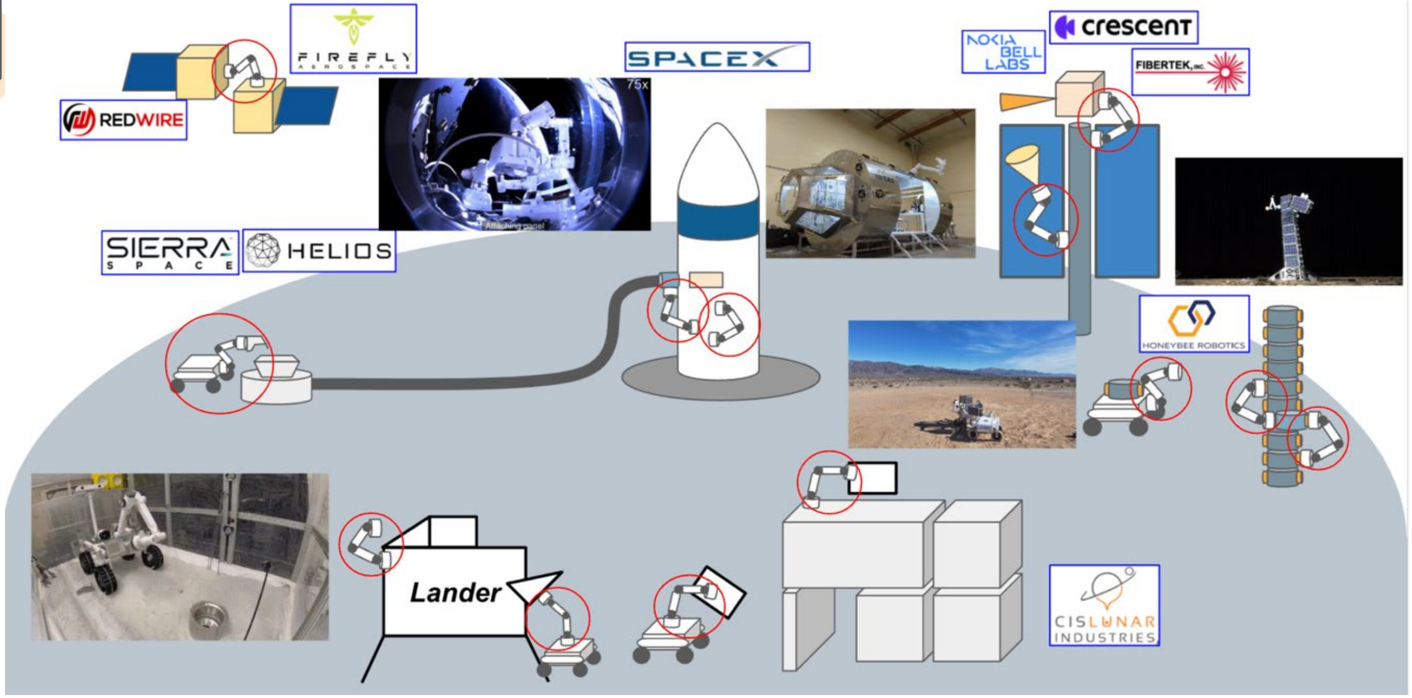
GITAI: Robotics as a Service (RaaS) for construction labor

Robotic labor charged in $/hour will:

- Enable the construction of lunar infrastructure including ISRU, power equipment, and transportation networks
- Provide maintenance as components fail or reach end-of-life
- Controllable from earth with no astronaut necessary







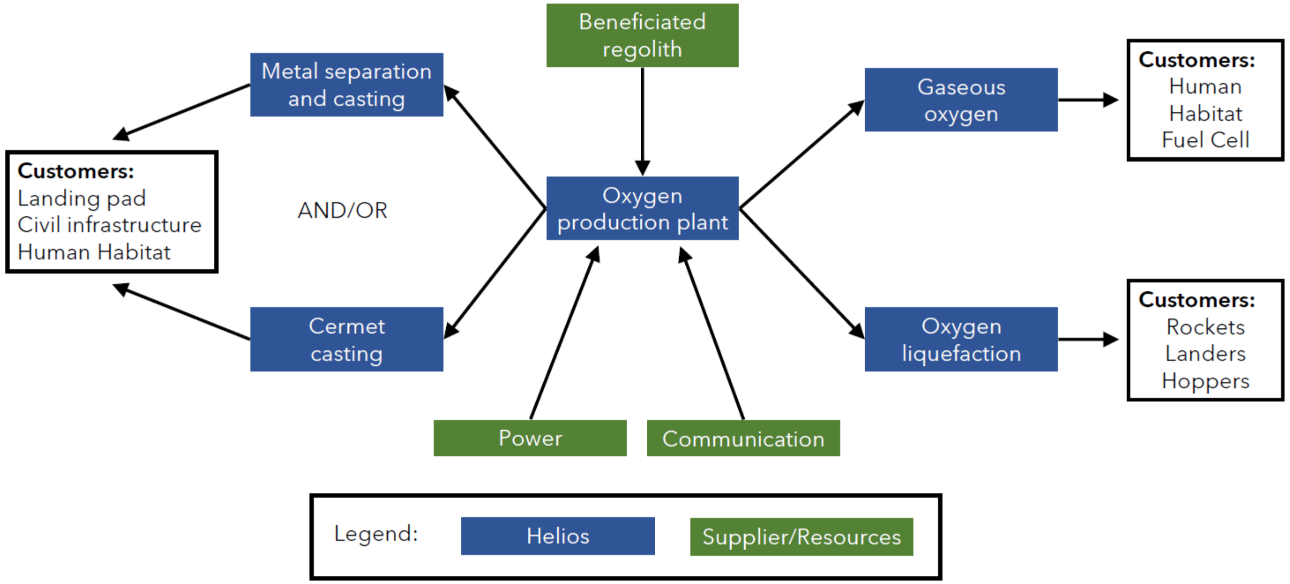
Modular inchworm arms integrated with rovers for mobility

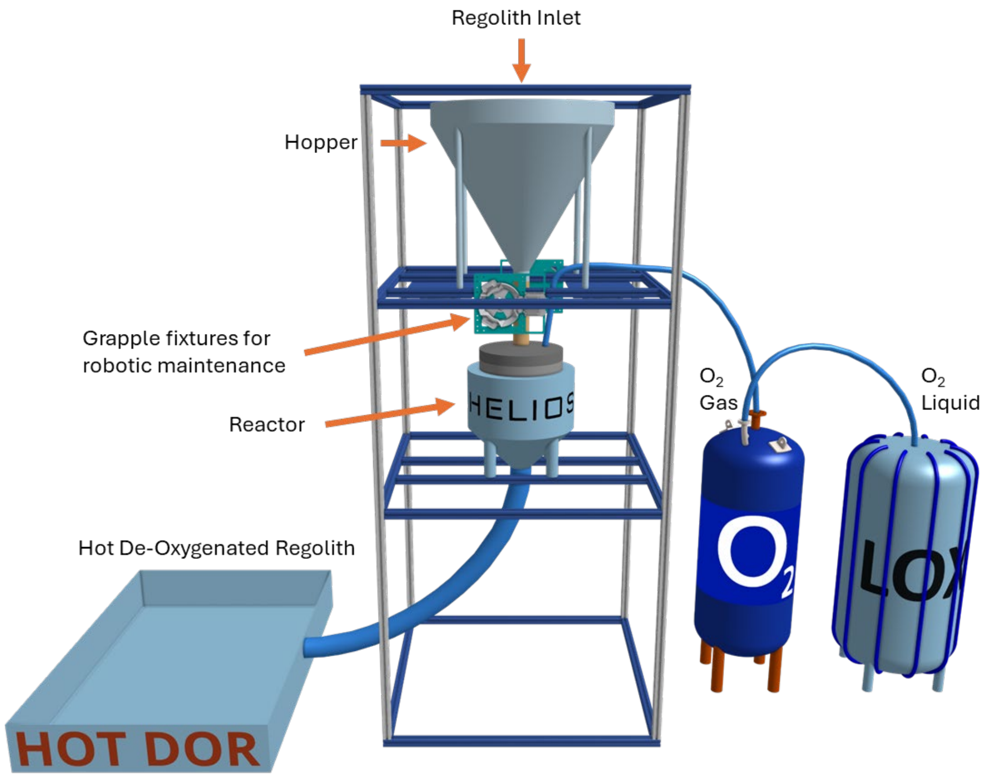
Helios: ISRU plant to produce LOX propellant at scale

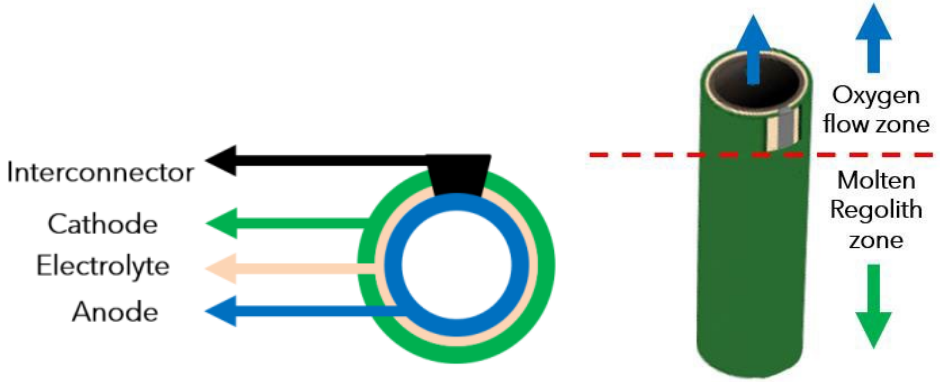
Scalable process for Solid Oxide Electrolysis to extract oxygen from regolith

Products include:

- Gaseous O2
- Liquid O2 (LOX) propellant
- De-oxygenated regolith for further metal refinement & processing



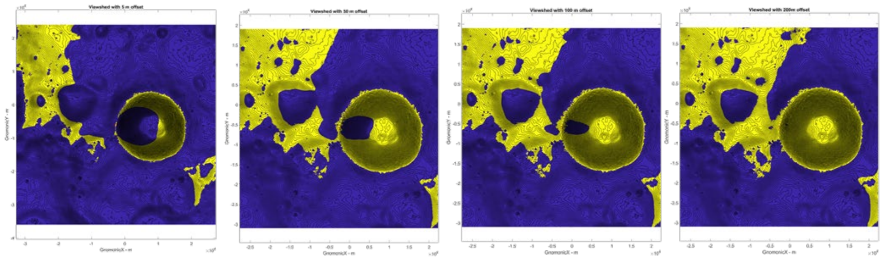




Honeybee Robotics: a networked tower for power, comms, and PNT

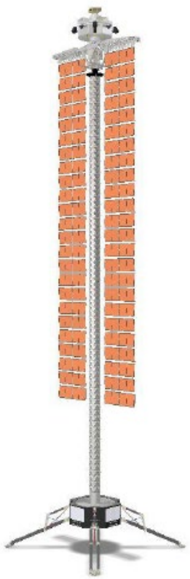
LUNARSABER is a utility tower for services including navigation, sensing, and power distribution

- Lightweight, deployable tower capable of hosting elevated payloads
- Increased line-of-sight for comms, power beaming, and PNT while simultaneously collecting solar power



% Viewable of Local Area (15 km radius)			
19.37%	32.14%	35.50%	40.05%

Services on Masthead:



Comms/PNT Terminals

Wireless Power Transmission (1+kWe)

Honeybee Mast Services

- Lights for Lunar Nights
- Cameras for Asset Monitoring
- Localized PNT
- Instruments

Services at Base:

Honeybee Dust Tolerant Connector — Wired Power Transmission — Honeybee Dust Tolerant Connector

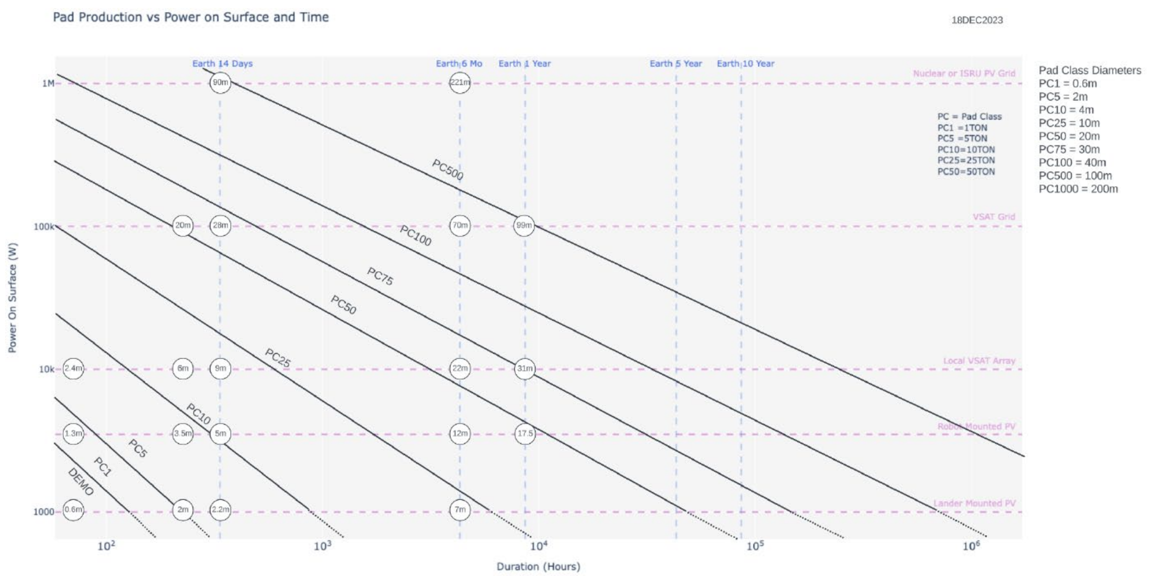
crescent, GITAI, SIERRA SPACE, NOKIA BELL LABS, ICON, HELIOS, FIBERTEK, INC., CISLUNAR INDUSTRIES, NORTHROP GRUMMAN, SPACEX

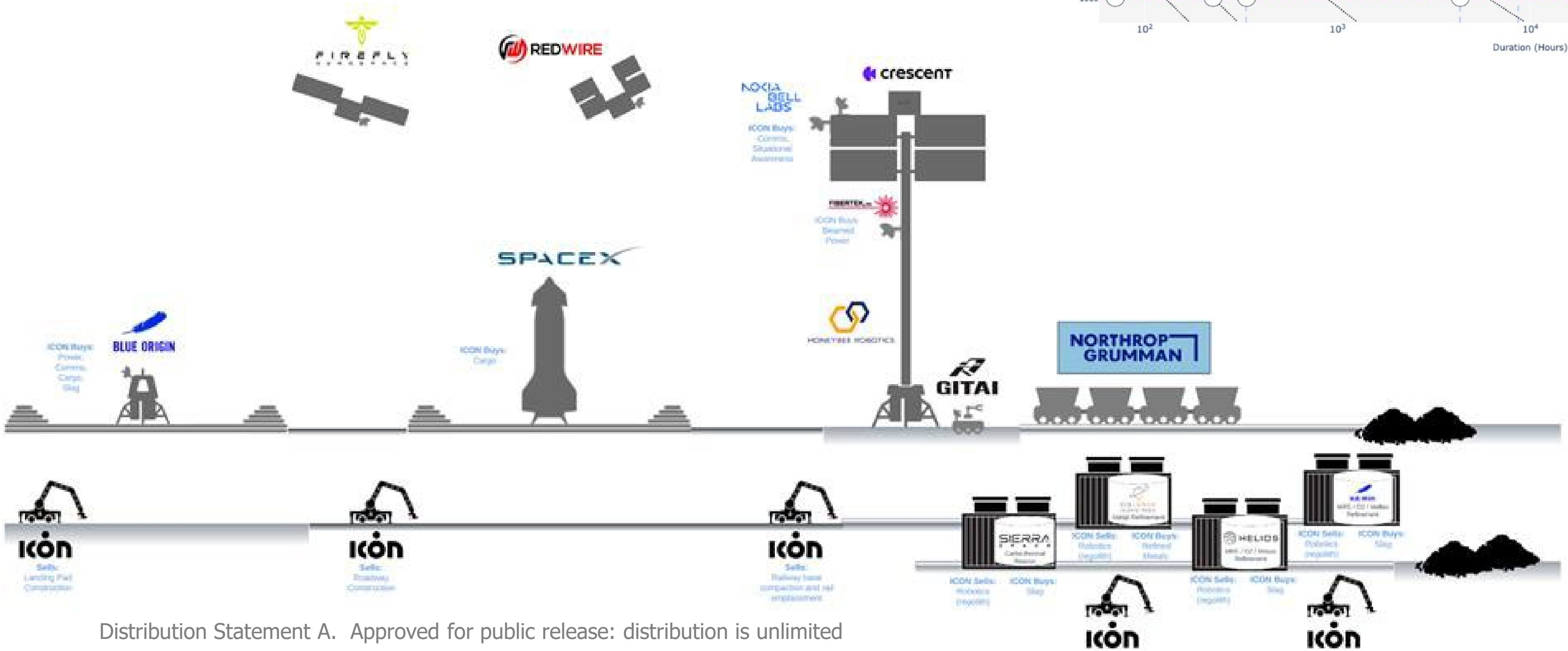
Users

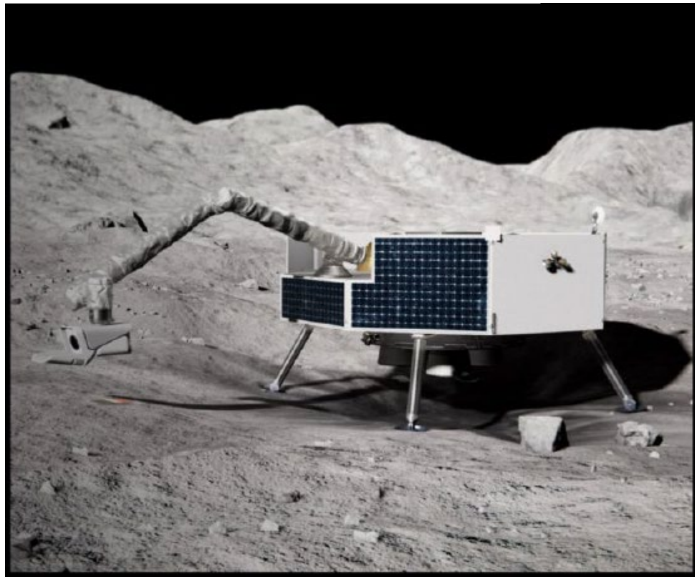
ICON: Sintering regolith for foundational transportation infrastructure

Laser VMX to pave roads and landing pads

- Resource-efficient inputs of raw regolith requires minimal materials launched to surface
- Current production time estimate is ~1 month for a 10m diameter landing pad with 10 kW surface power supplied





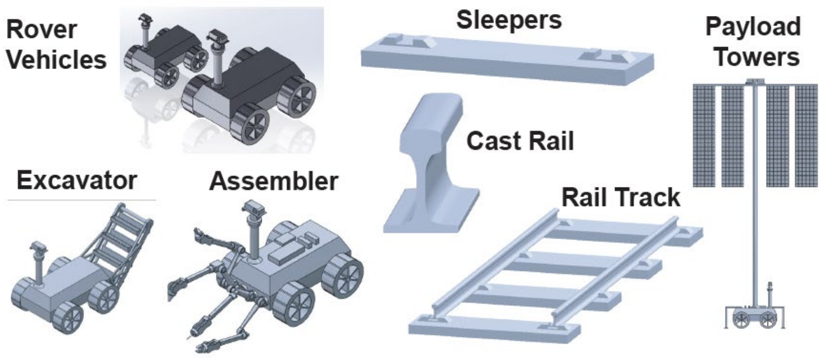

ICON's Project Olympus for NASA and commercial lunar projects

Northrop Grumman: a lunar railway network for efficient crossmass

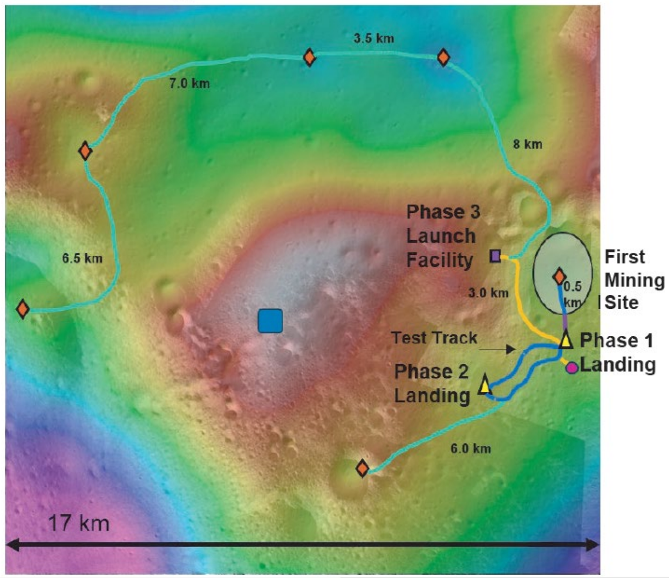
Multi-purpose railway for lunar mobility

Concept designs of rail equipment to include:

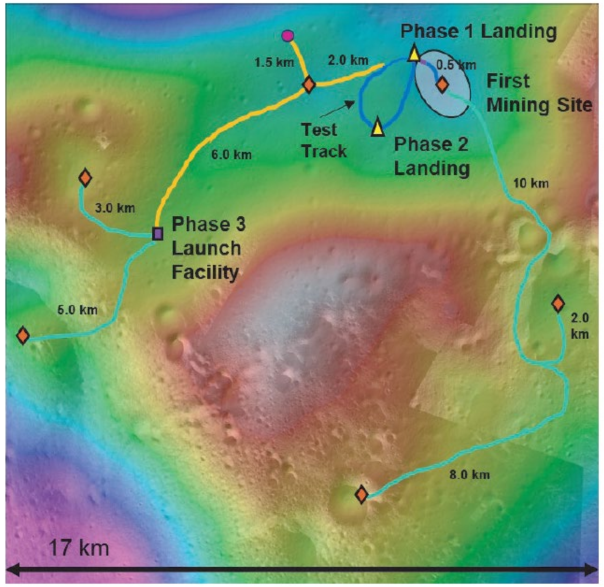
- Construction materials and track foundation design
- Railcars for cargo transportation
- Vehicles for construction and maintenance operations

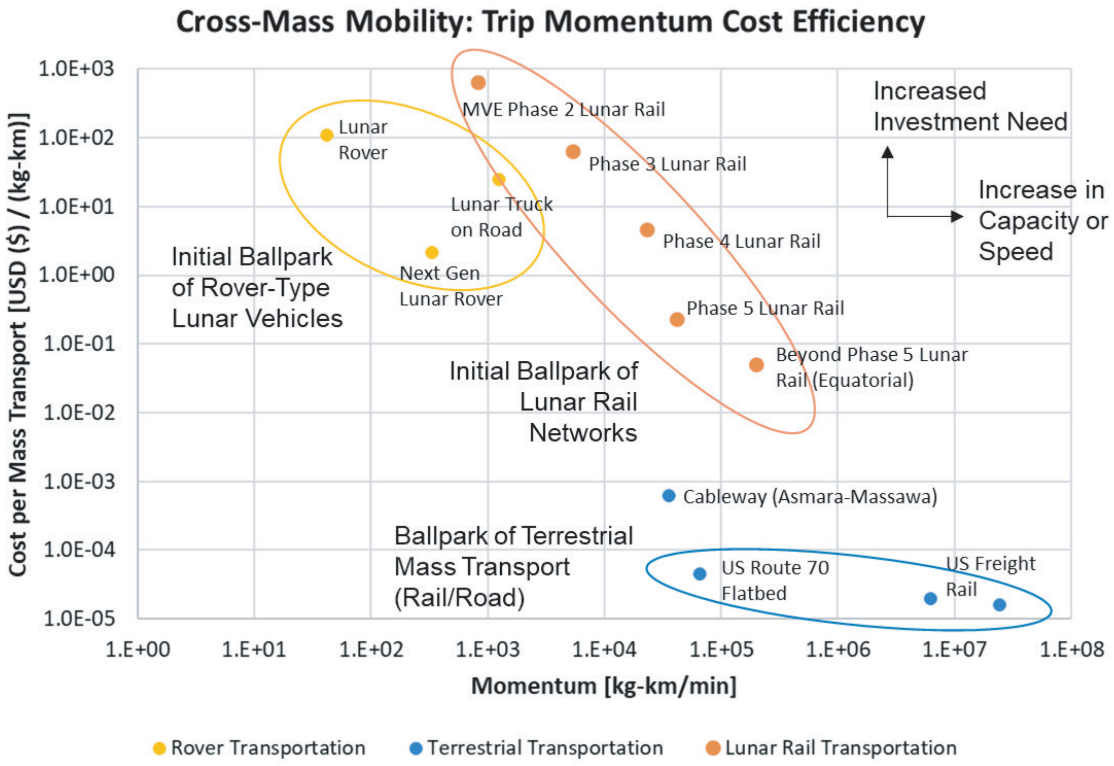


Lunar Rail Network Study: Design Reference Plan 1



Lunar Rail Network Study: Design Reference Plan 2

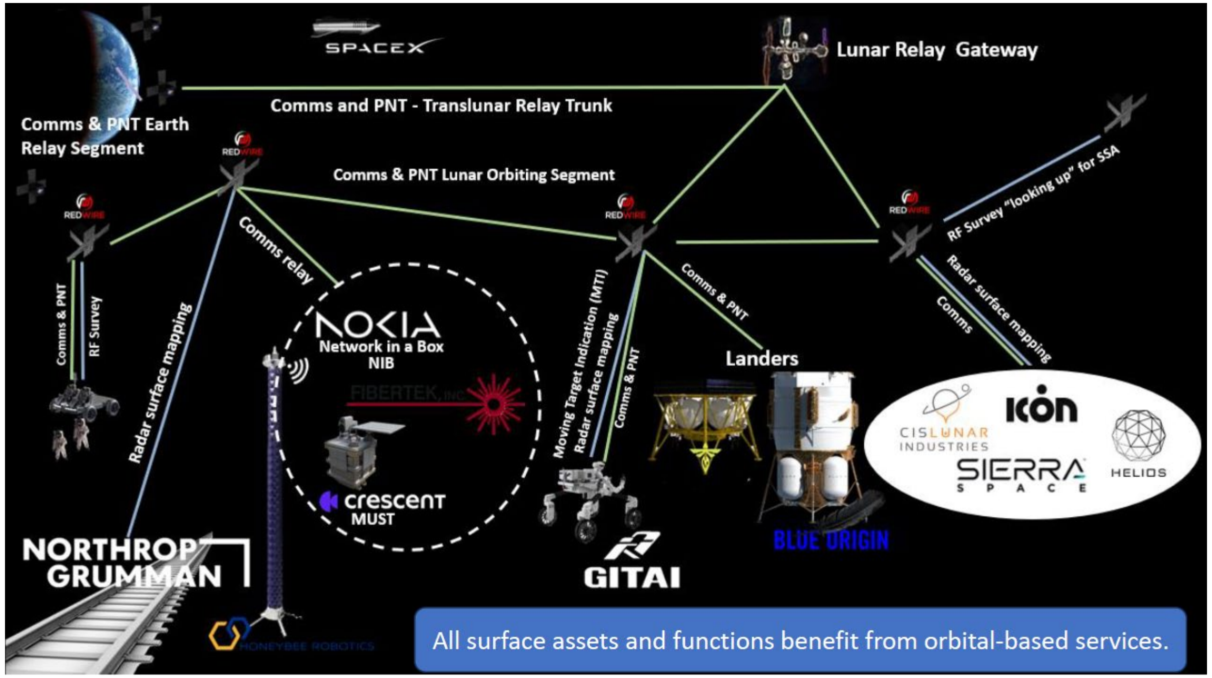


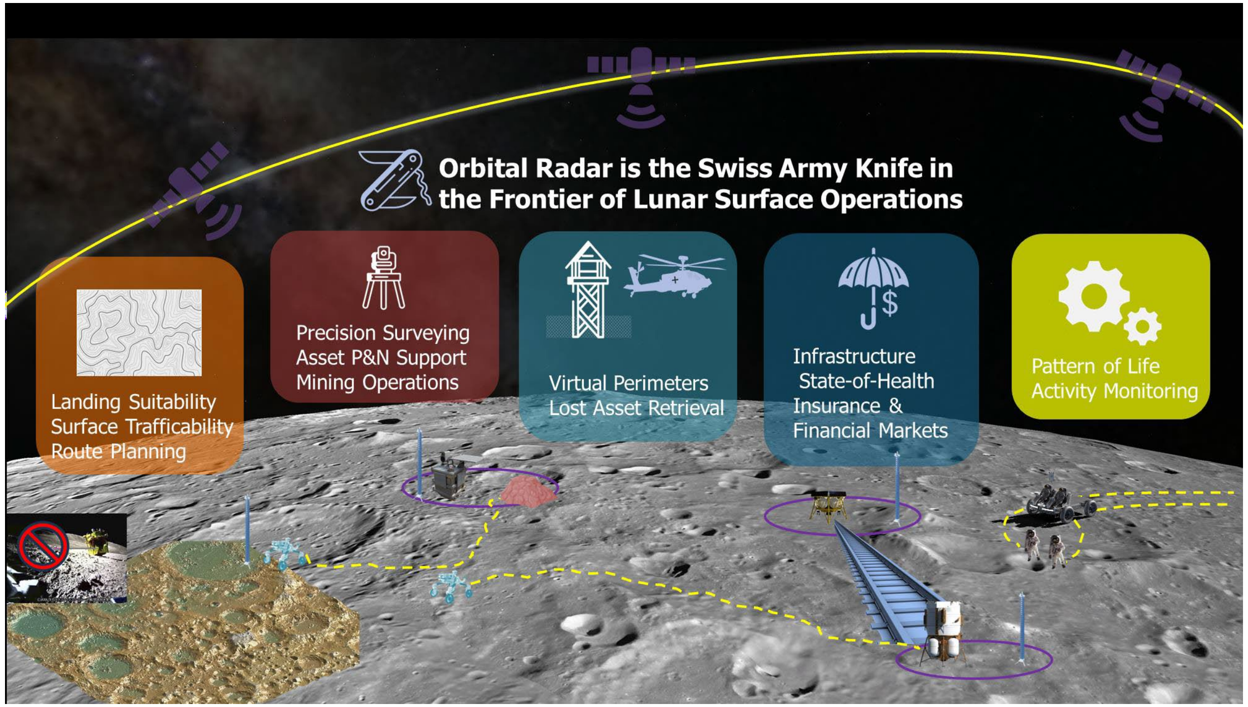


Redwire: orbital constellation for RF services

Constellation of cislunar orbiters to provide:

- Communications
- PNT
- RF Survey
- SAR/MTI
- Microwave space-based solar power beaming

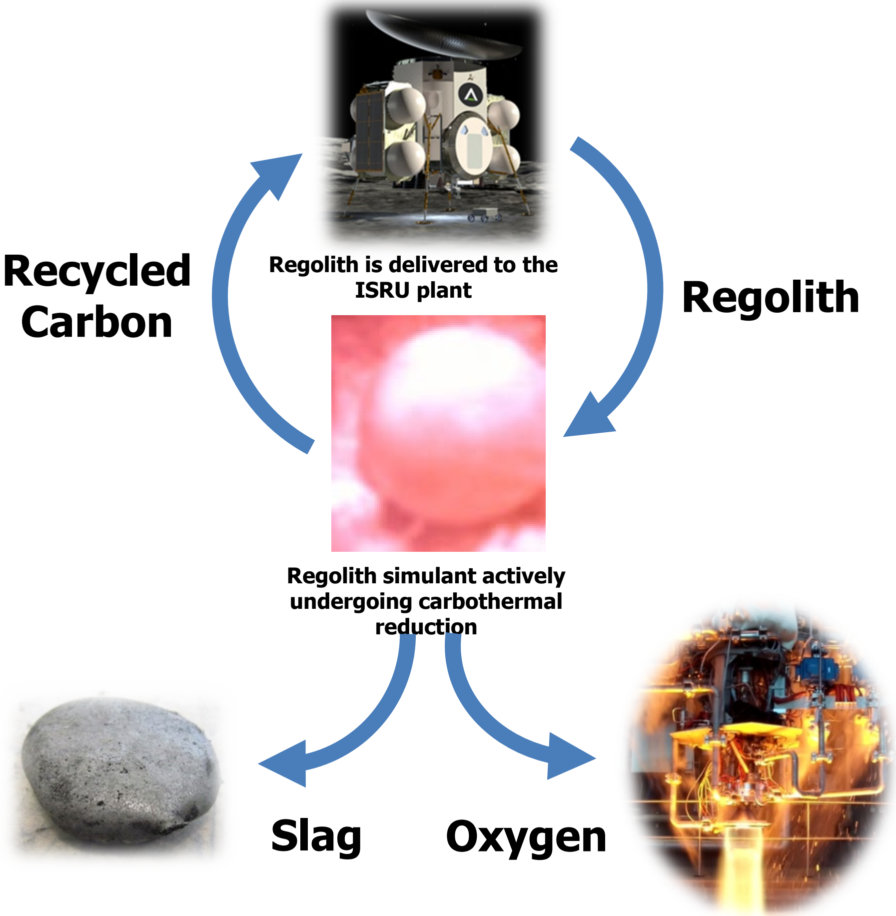


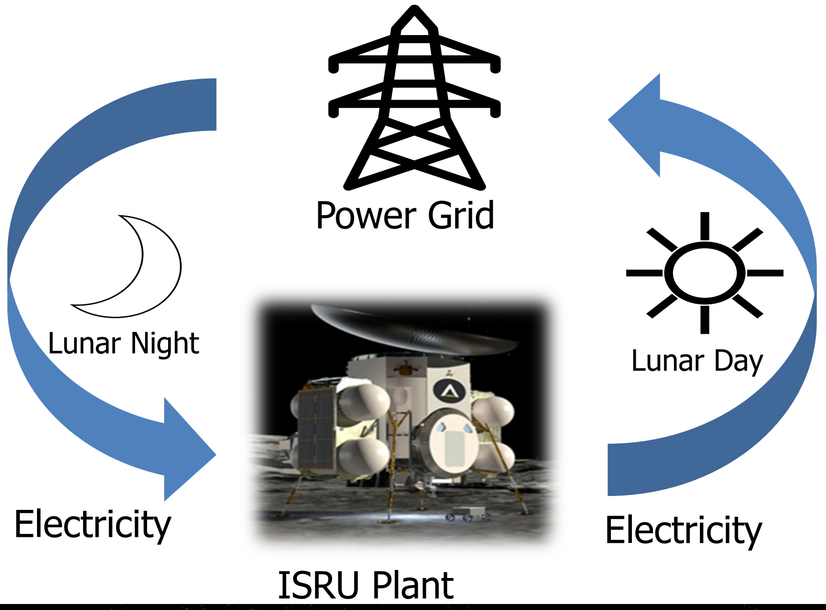


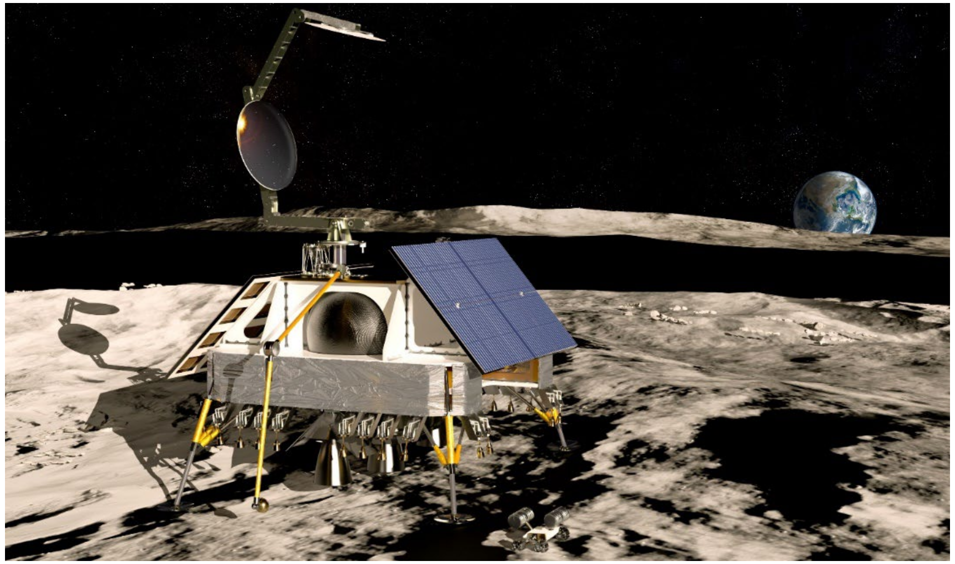
Sierra Space: a night-survivable oxygen plant with integrated fuel cell

Oxygen ISRU plant with three main functions:

1. Oxygen Extraction from Regolith
2. Fuel Cell Energy Storage for STN
3. Chemical Conversion for Recycling and Storage







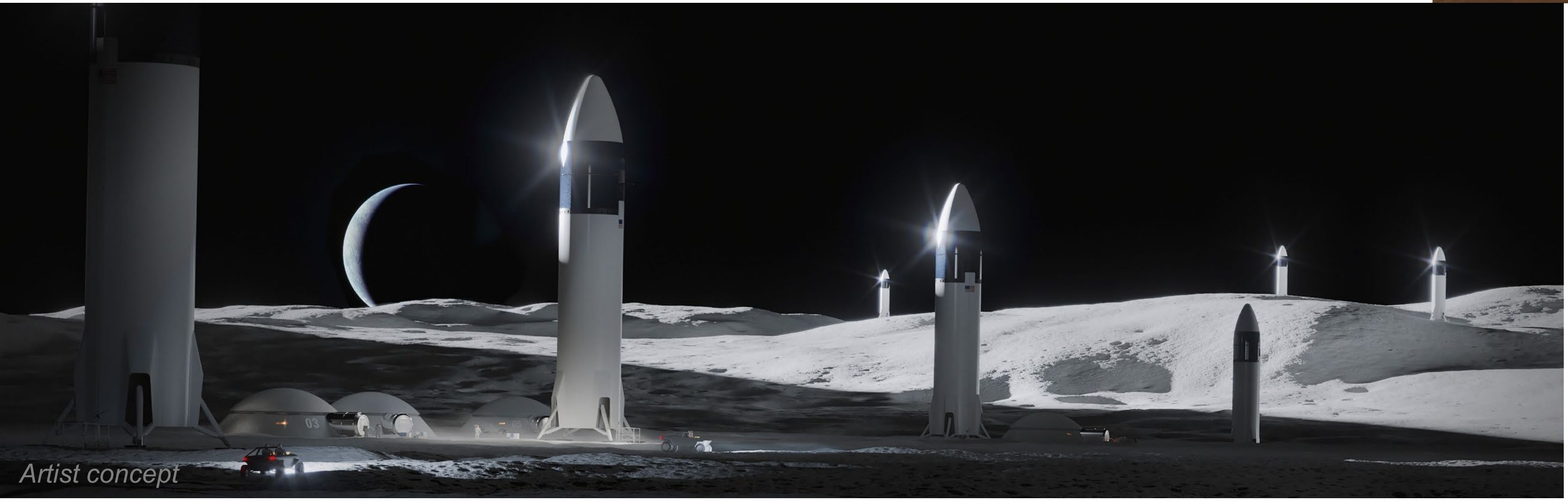
Artist concept of a carbothermal oxygen production plant

SpaceX: a streamlined service for transit and mobility

Starship as both an earth-to-moon launch vehicle and a lunar surface hub

- Super-heavy, reusable transportation vehicle with integrated comms, power, and nighttime battery services
- 3rd party payloads deployable from height of Starship
- Surface hub can provide propellant and fluid transfer services

Image Credit: SpaceX



Artist concept

Designed for reuse and re-launch from lunar surface

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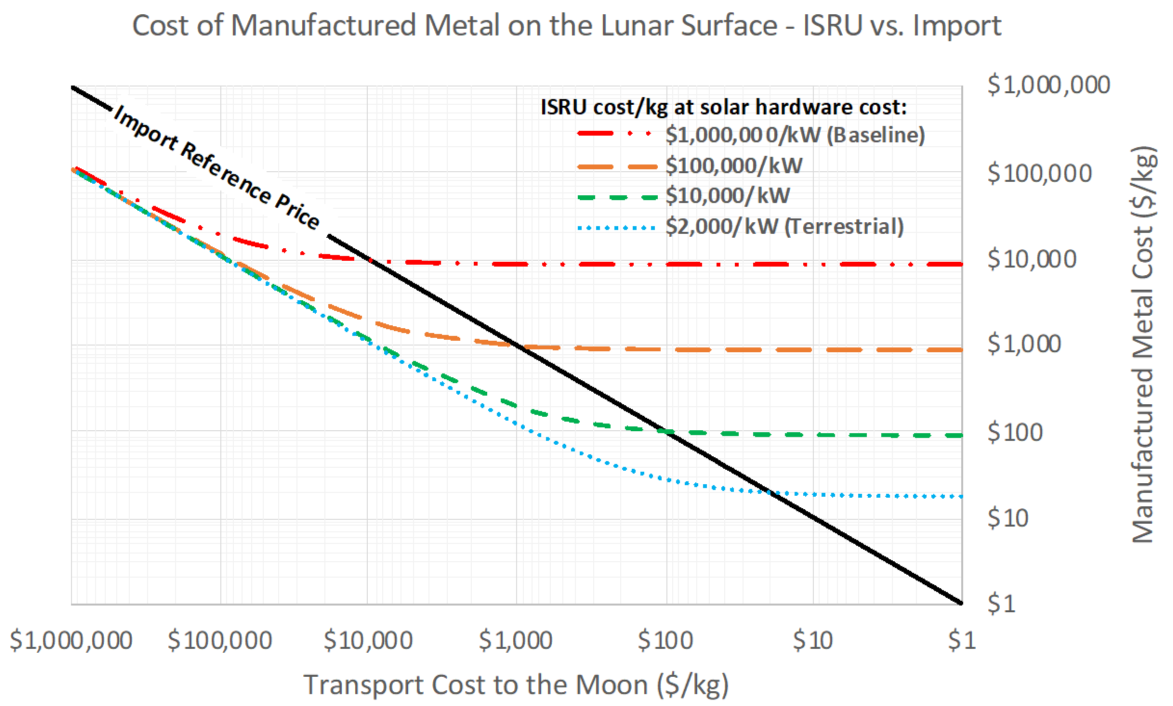
Emerging topics that require further technical development

New concept of Re-ISRU: Recyclable ISRU

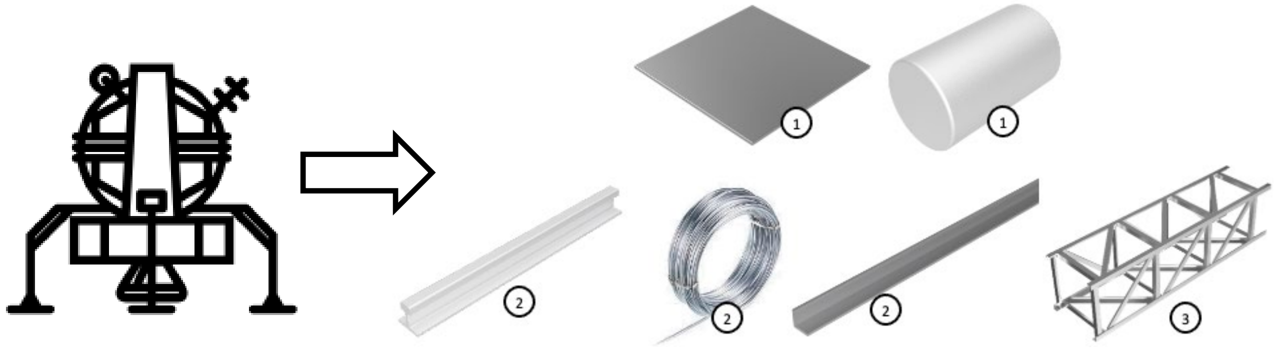
Man-made equipment on the Moon may grow by an order of magnitude in next 10 years

The definition of “in-situ” resources also includes defunct manmade equipment

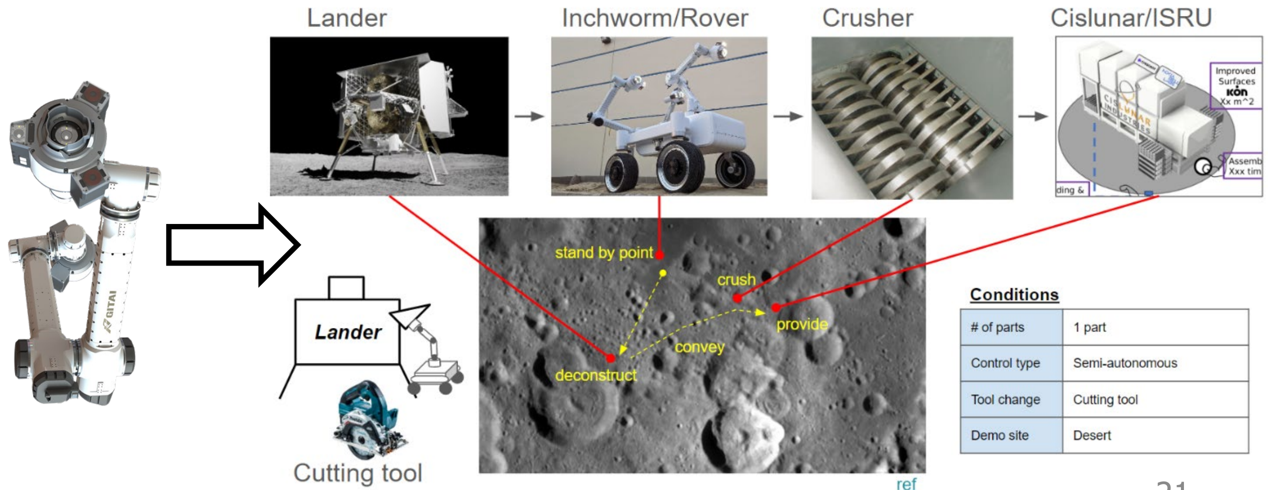
How do we use that to reduce mass required from Earth?



Enabled by metal recycling and robotic disassembly and foundry ingest



[1] Casting (radiators, billets); [2] Extrusion (Lunar rail, wire, L-channel); [3] Fabricated products (tower truss)



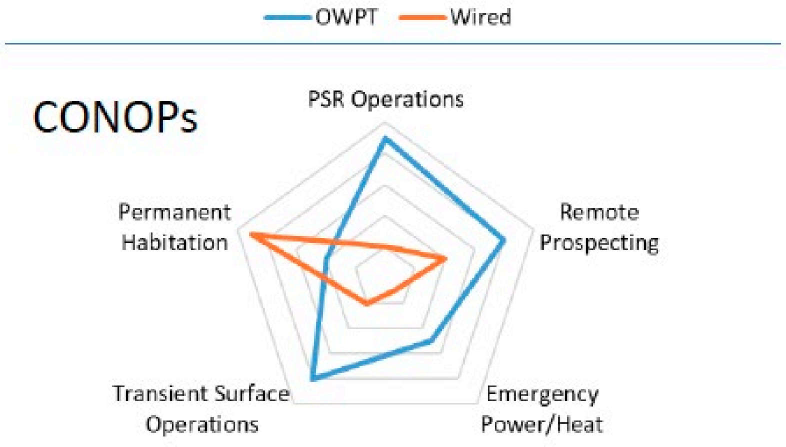
Conditions

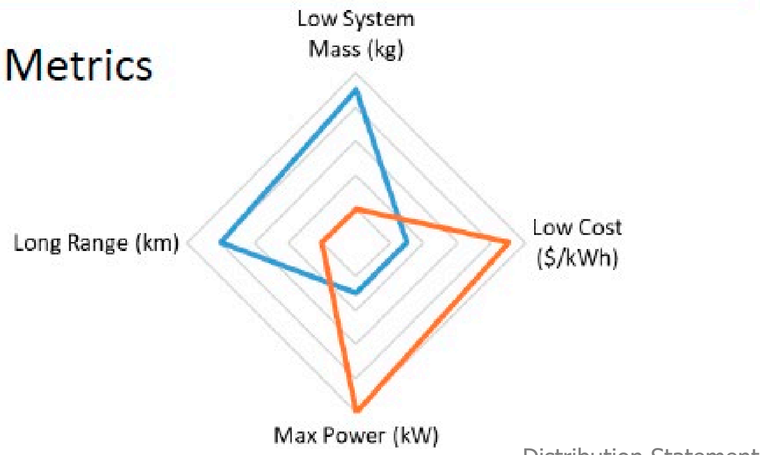
# of parts	1 part
Control type	Semi-autonomous
Tool change	Cutting tool
Demo site	Desert

Mobile lunar systems demand wireless power Tx/Rx: technically feasible

PSR exploration: Cabled power solutions are limited.

Wireless power ($/kWh) a viable near-term commercial solution





Regulated Power to User (kW)

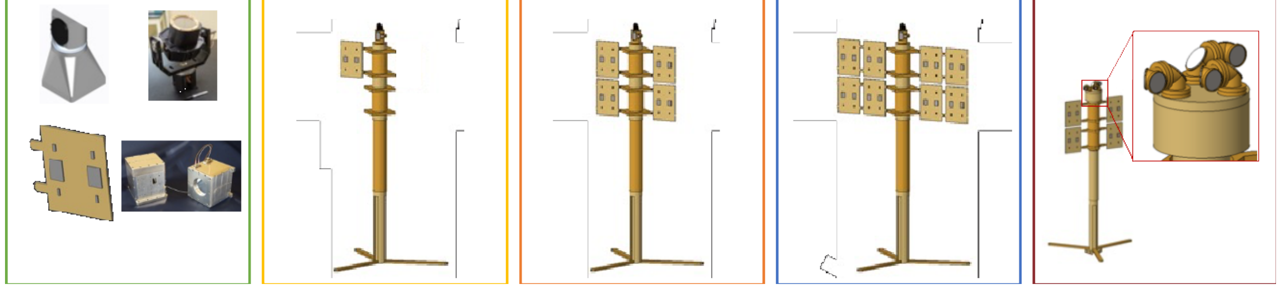
LION Nano
- **0.35 kW regulated power**
- 0.97 kW radiated heat
- Mass: <80 kg, *no tower*

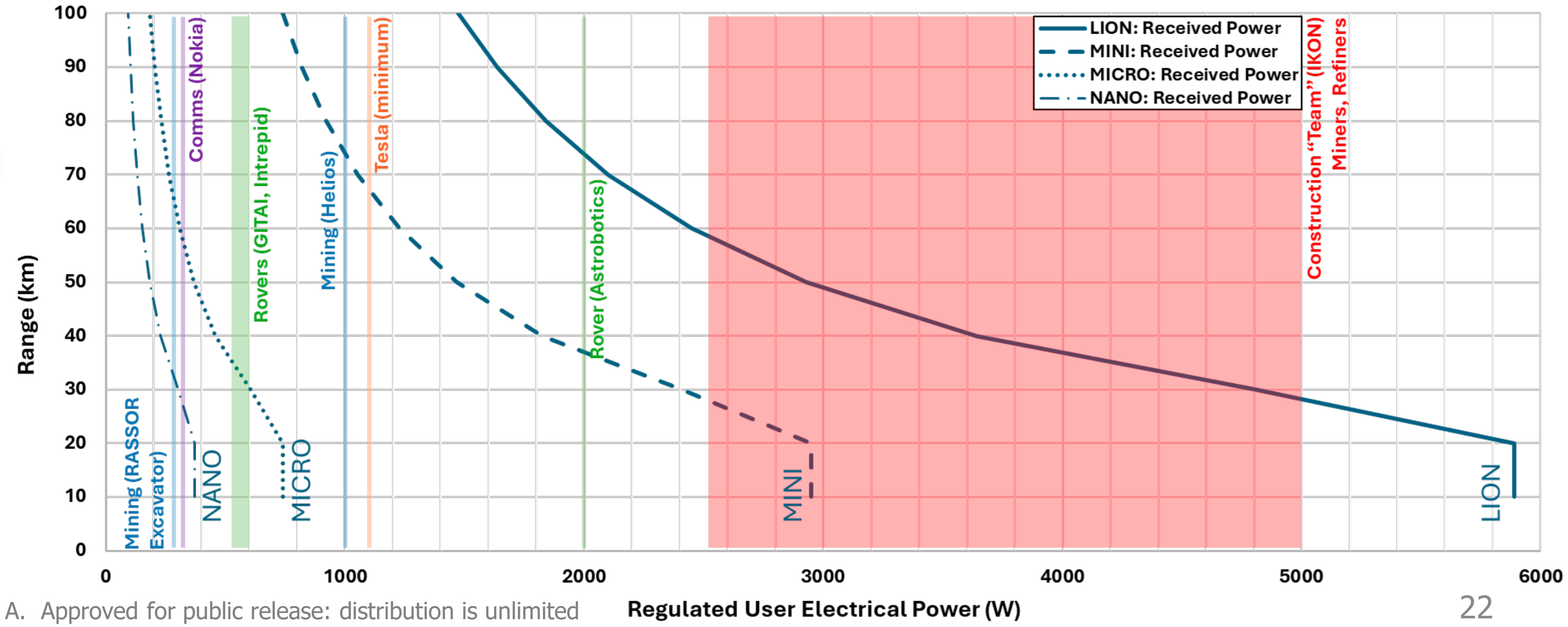
LION Micro
- **0.74 kW regulated power**
- 1.9 kW radiated heat
- Mass: 223 kg, including tower
- Tower height per application

LION Mini
- **3.0 kW regulated power**
- 7.8 kW radiated heat
- Mass: 285 kg, including tower
- Tower height per application

LION
- **5.9 kW regulated power**
- 15.5 kW radiated heat
- Mass: 360 kg, including tower
- Tower height per application

LION Multi
- **Individual beam directors per laser**
- **Power scalable**
- SWaP: Scalable, up to full LION
- Tower height per application

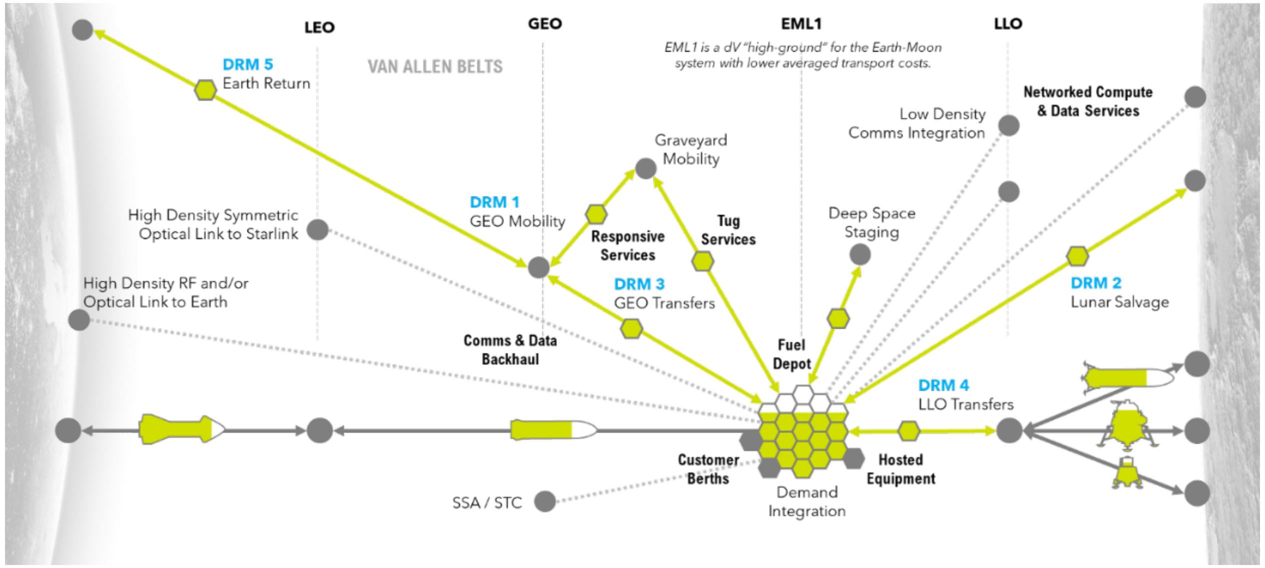


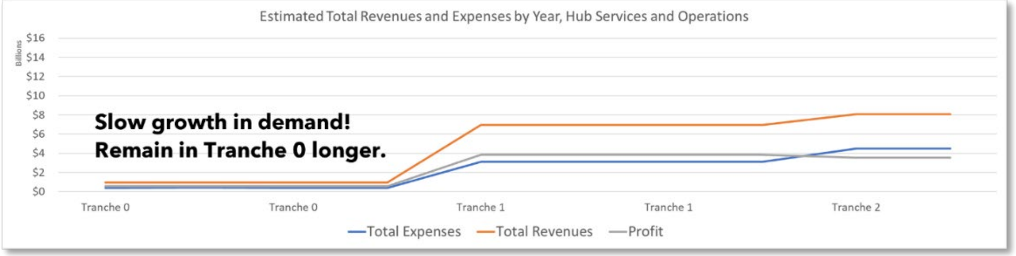


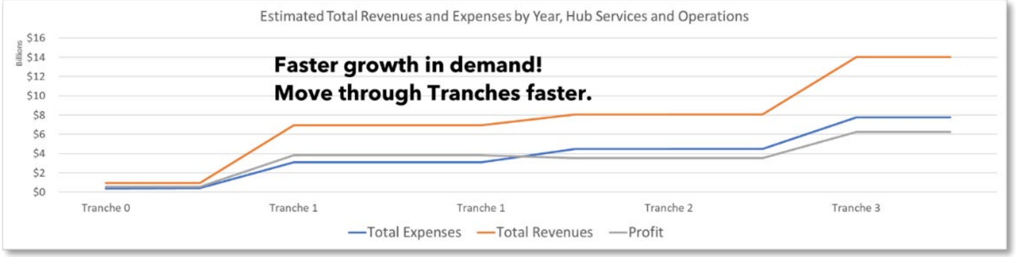
A commercial cislunar harbor: E-M logistics and spacecraft retirement

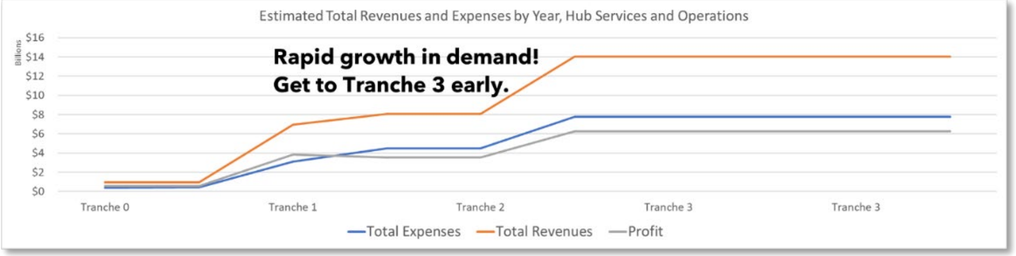
Lunar spacecraft retirement at a cislunar hub

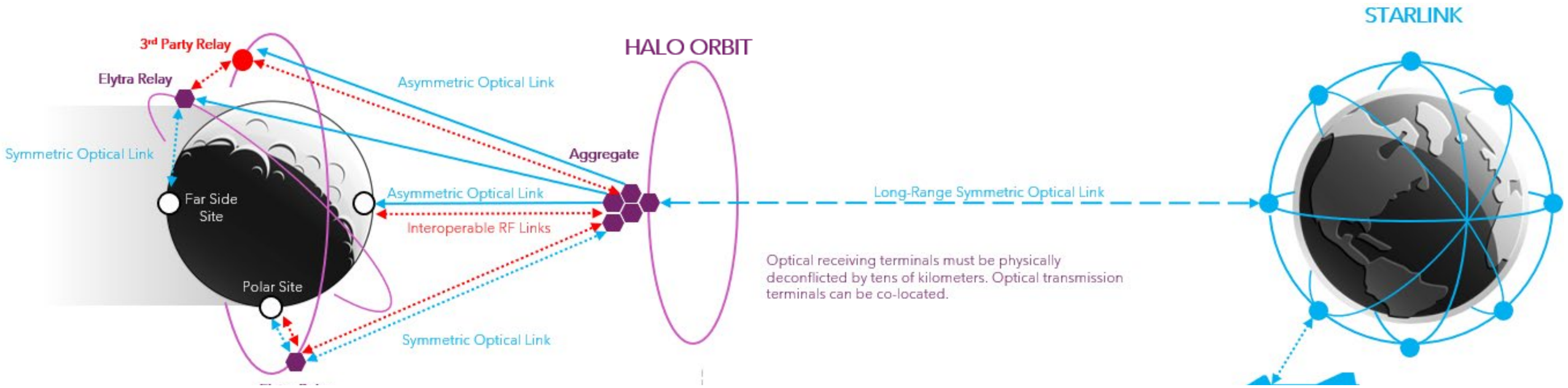
Aggregation of shared resources, including propellant, communications, & solar power











Robotics as a Service (RaaS) to bootstrap lunar infrastructure

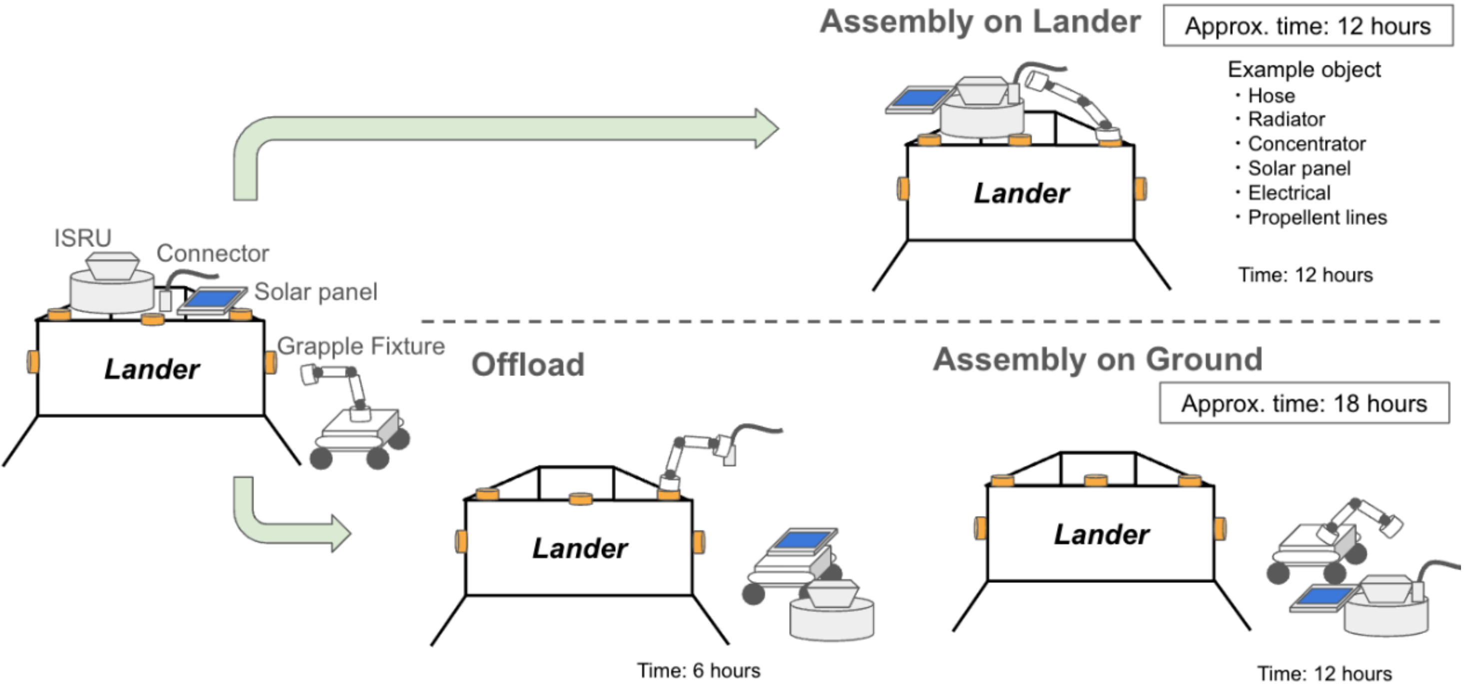
Inchworm robots coupled with mobile rovers will provide tele-operated robotic labor

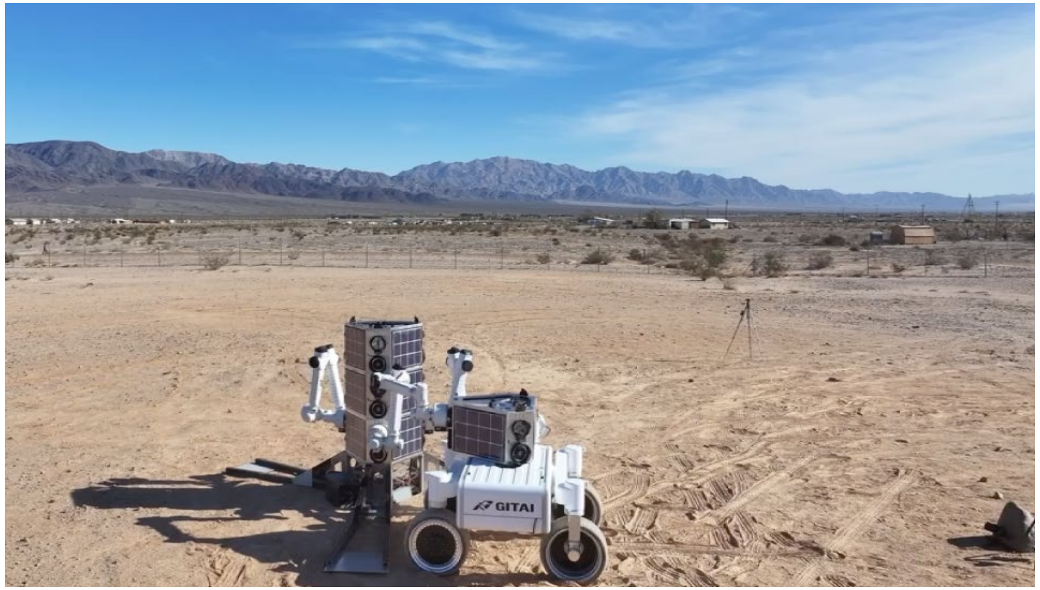
Charged based on hourly rate

Customizable to a user's construction needs

Ideal for building, maintenance, and component replacement

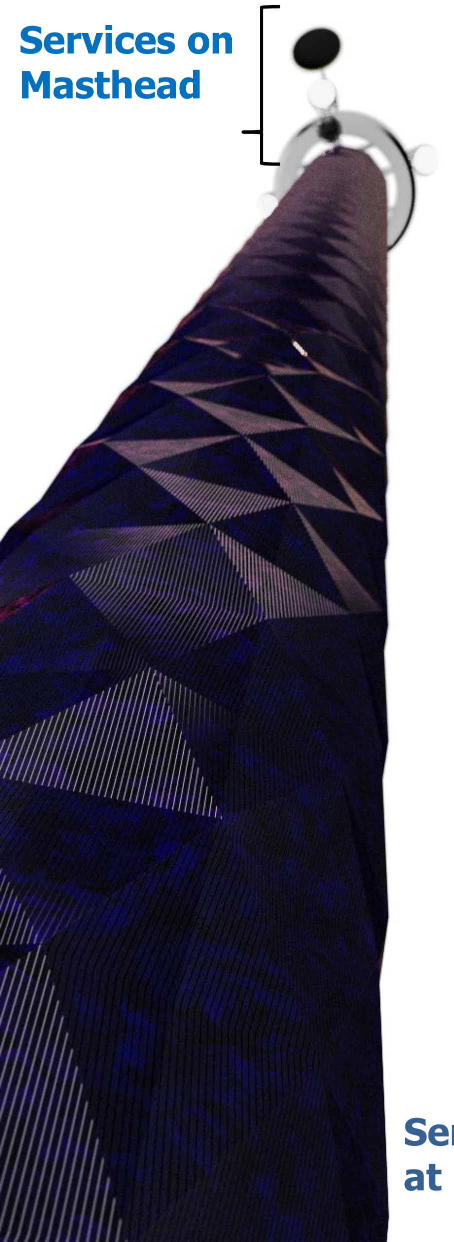
Modular and scalable to most lunar construction applications



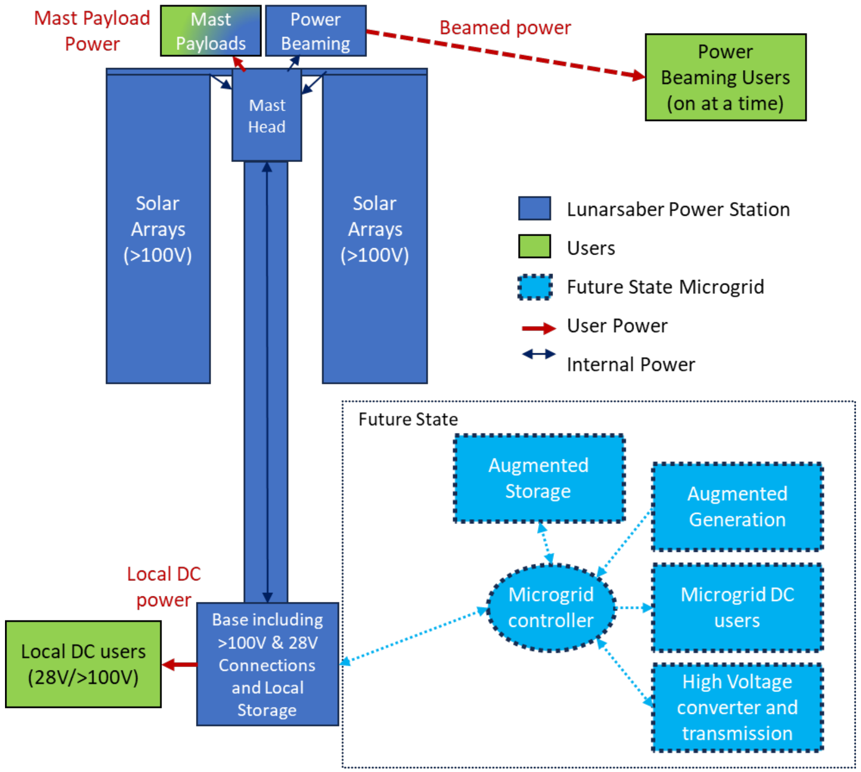


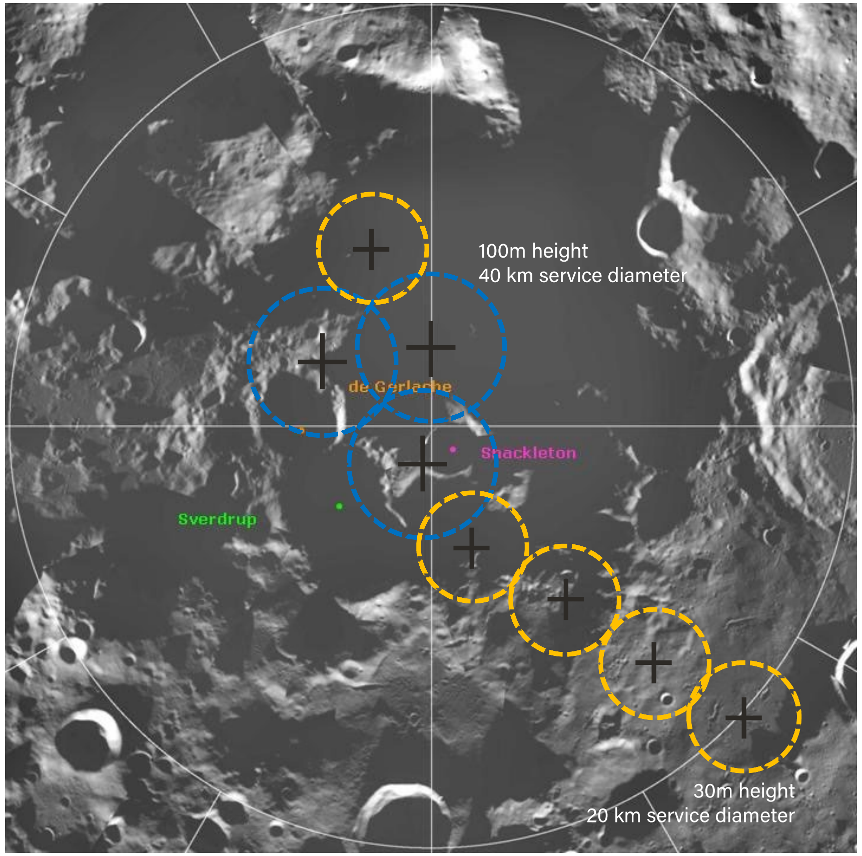
Foundational Networked towers for Multi-service consolidation

Services on Masthead



- Centralized service node with expanded line of sight across rugged lunar terrain.
- Can service or be integrated with almost any current or future lunar service: power, storage, data, comms, PNT, light, thermal, and more.
- "In one launch" setup paradigm.





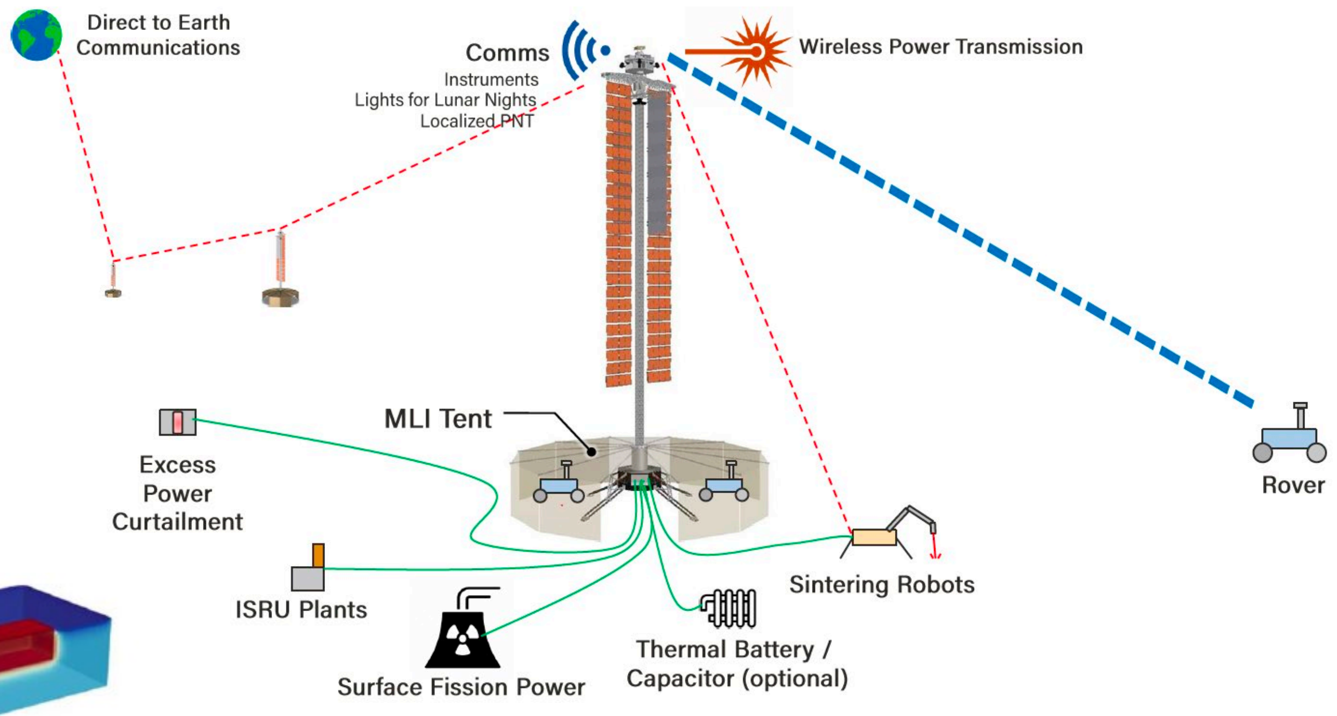
Services at Base

![DARPA]

Thermal as a Service: Provide heat rejection/generation and change future lunar design paradigms

Thermal management is a need for all users on lunar surface

- Several key ISRU processes run at high temps (>1000C)
- Lunar night challenges to maintain survivable temps (14+ earth days)
- High % of thermal mass required on-launch



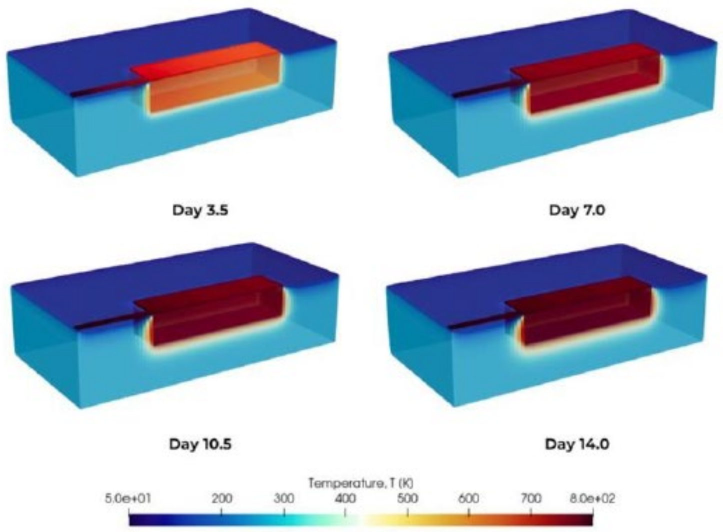
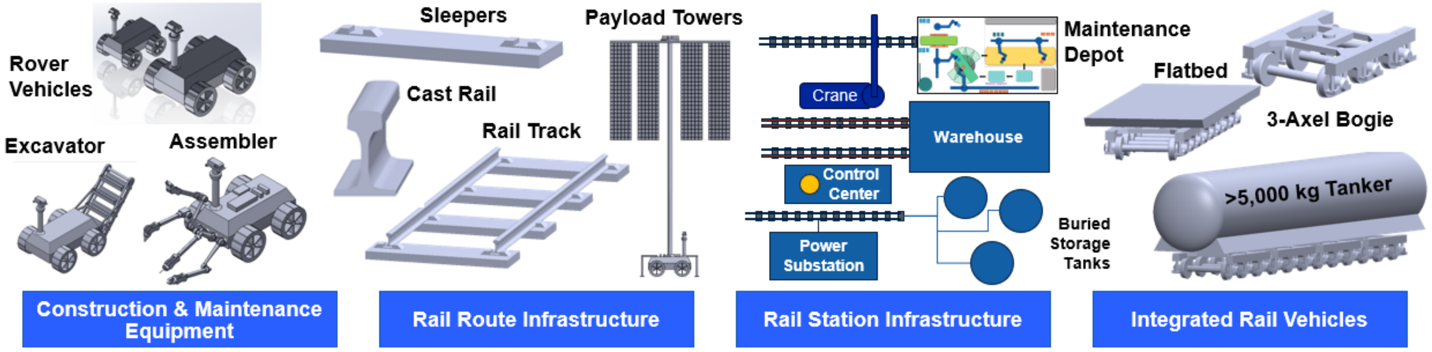


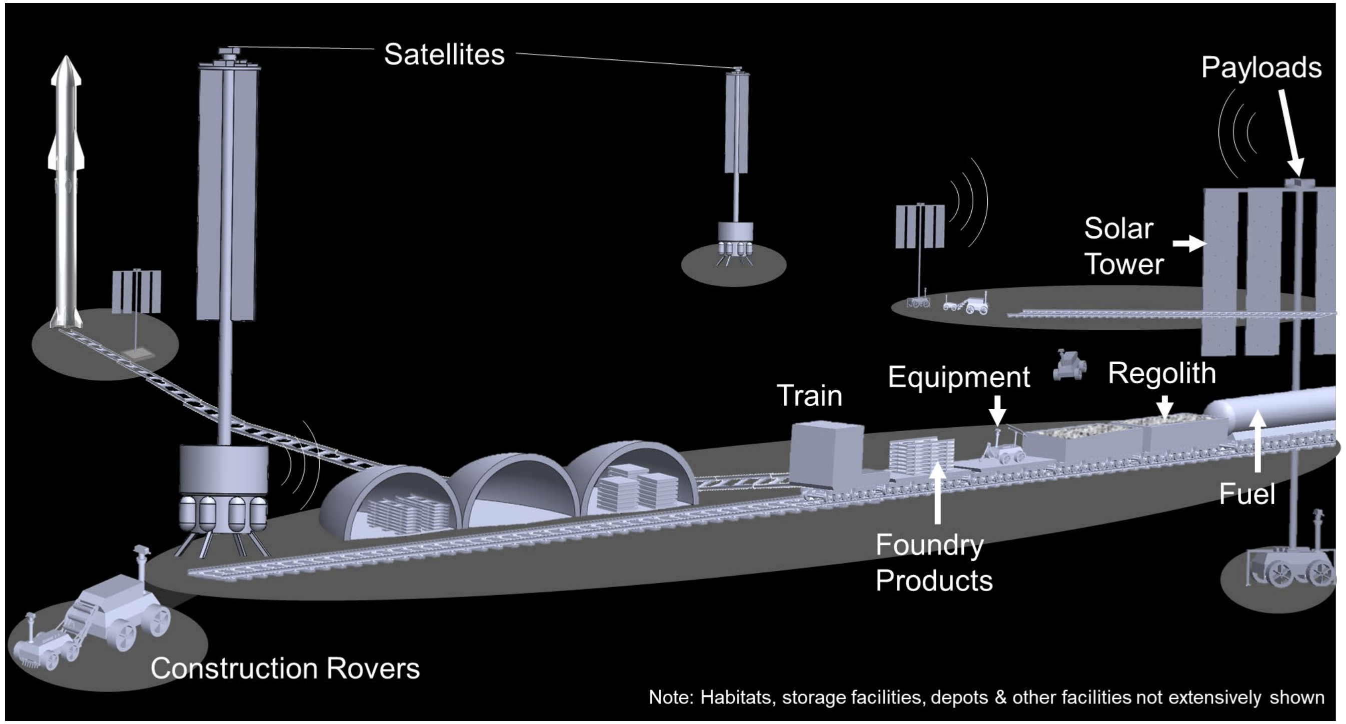
Figure: Example of a simulation-set run in CFD, 14 Earth days, 800 K Input

A thermal utility service is needed to accommodate the Moon's extreme thermal environment

Lunar Rail Network:
Provide crossmass capability for development of regional hubs

Cargo transportation to enable expansion of a lunar base
Infrastructure design based on material properties of regolith and anticipated user requirements (LunA-10 partners)

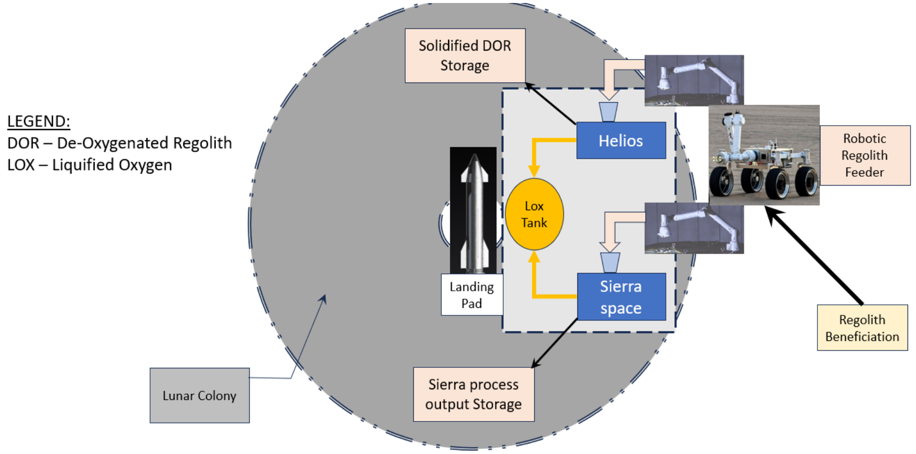




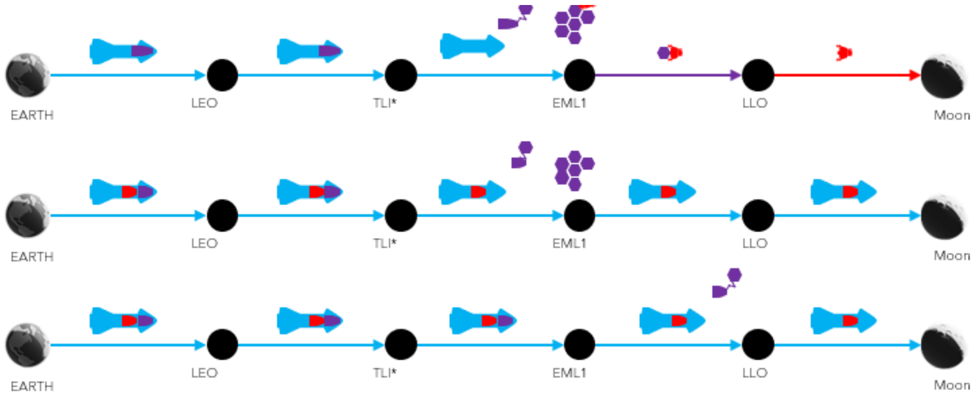
Current solution for crossmass: Rovers
- Limited heavy material-handling capabilities
- Limited infrastructure for storage of volatiles
- Limited travel distances with onboard power

One example set of teaming arrangements (changed every 2 weeks)

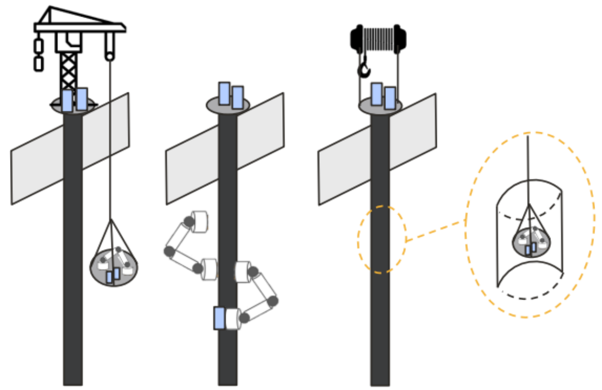
Team 1: How would *GITAI* assemble and maintain a *Sierra Space* and *Helios* oxygen plant with robotic labor?



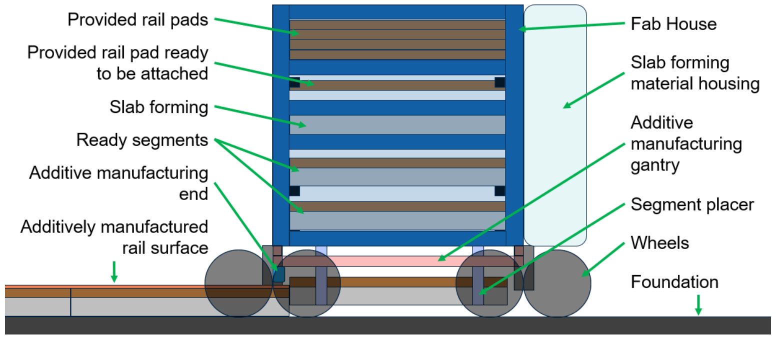
Team 2: Is there demand from a *SpaceX* spacecraft to join a *Firefly* orbital aggregation hub?



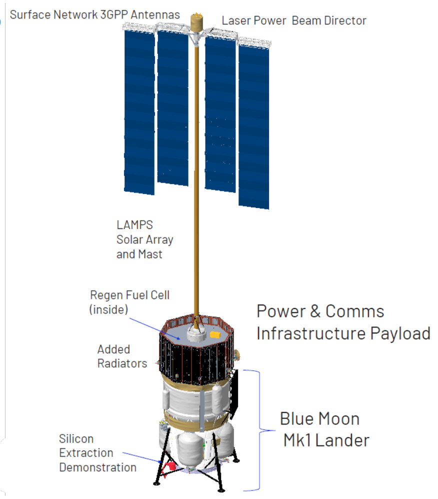
Team 3: How would a *Honeybee* solar power tower be designed and integrated with *Fibertek* power beaming and *Crescent* comms systems at the tower's height?



Team 4: Do *CisLunar*'s metal products and *ICON*'s sintered regolith have sufficient material properties to construct a *Northrop Grumman* lunar rail network?



Team 5: How can a *Blue Origin* lander be integrated with *Redwire* SSA and PNT from orbit & *Crescent* surface comms?



Not a fully inclusive list (not even close)

Please attend LunA-10 breakthrough sessions to learn more

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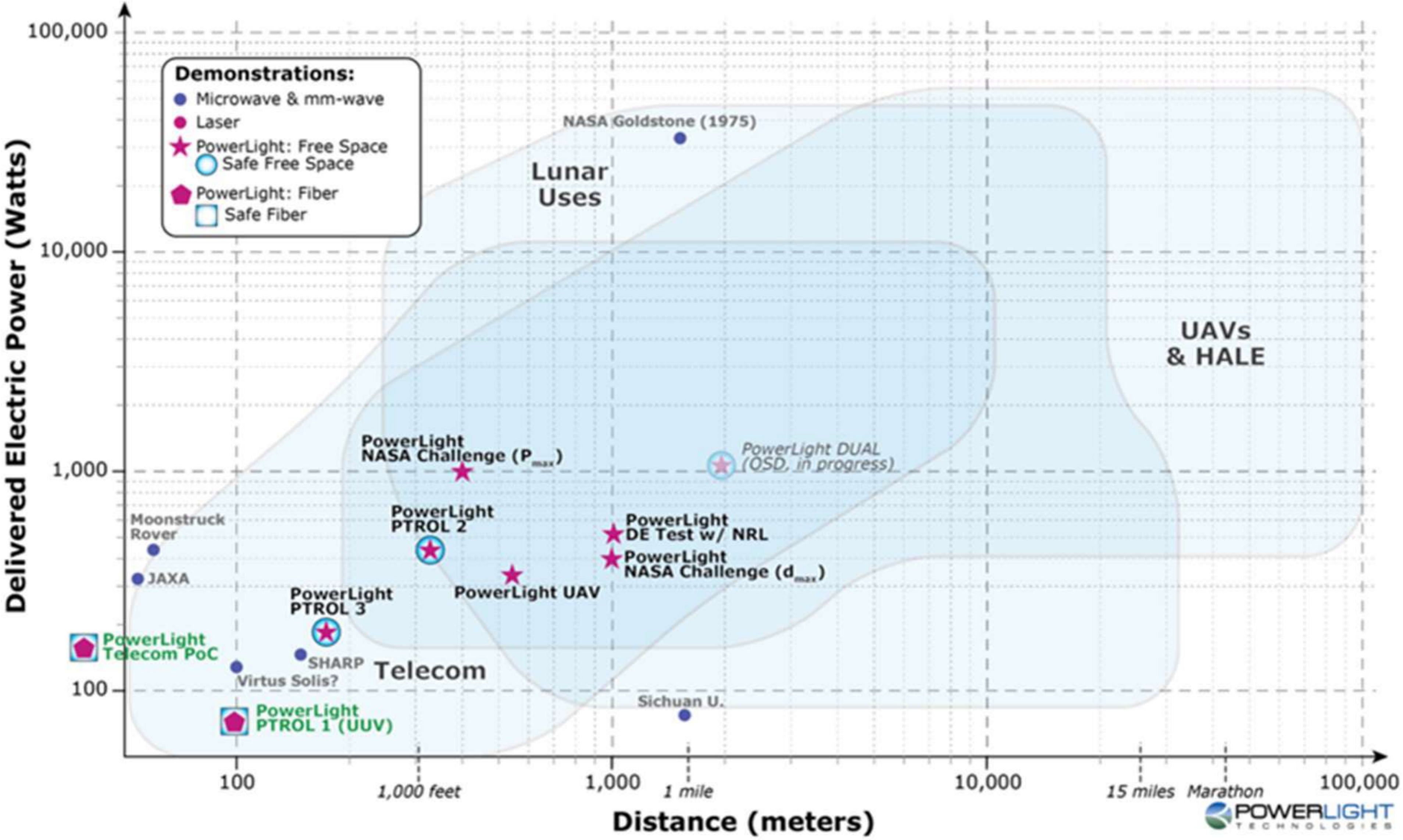
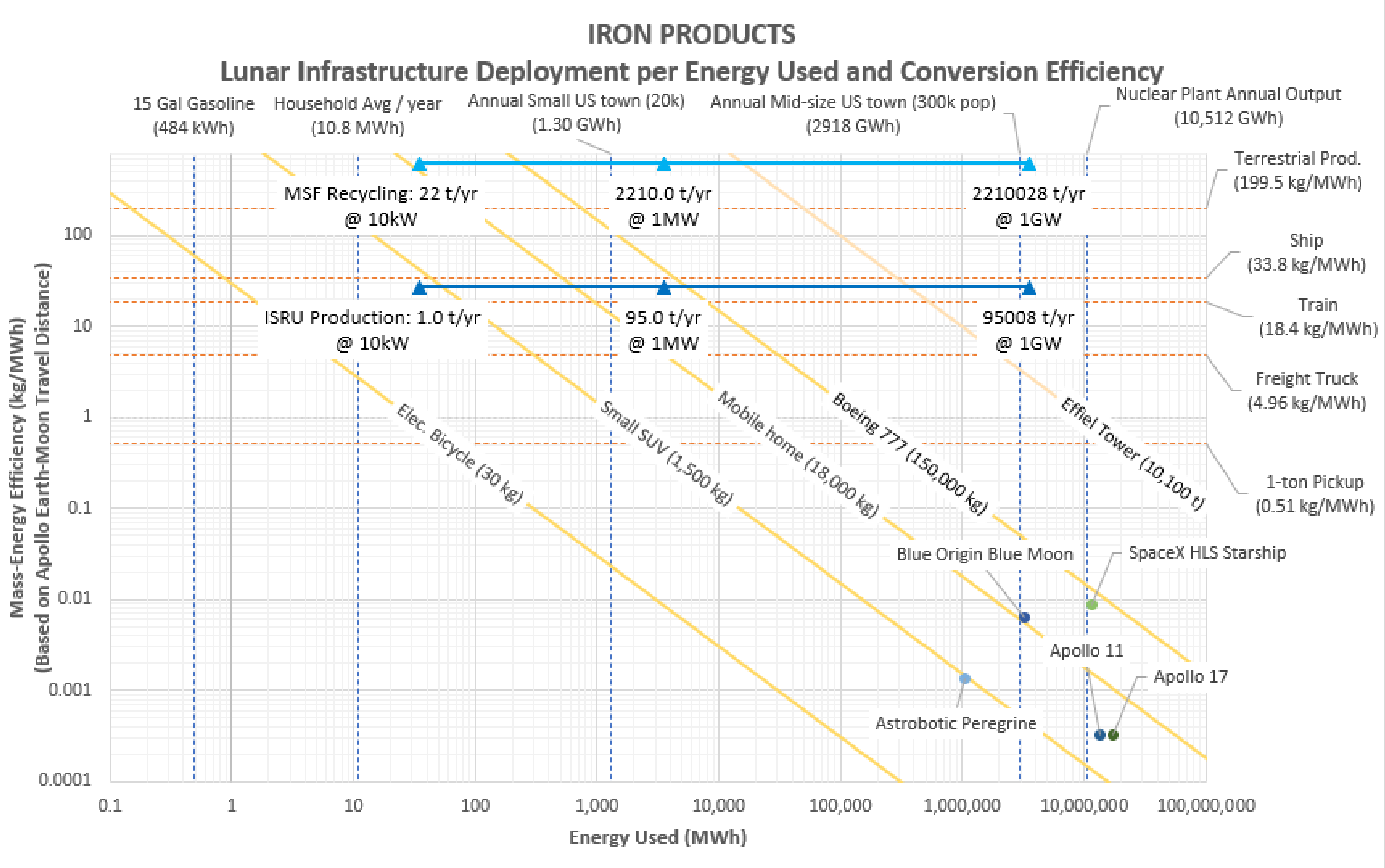
Appendix – White Space Charts

Blue Origin

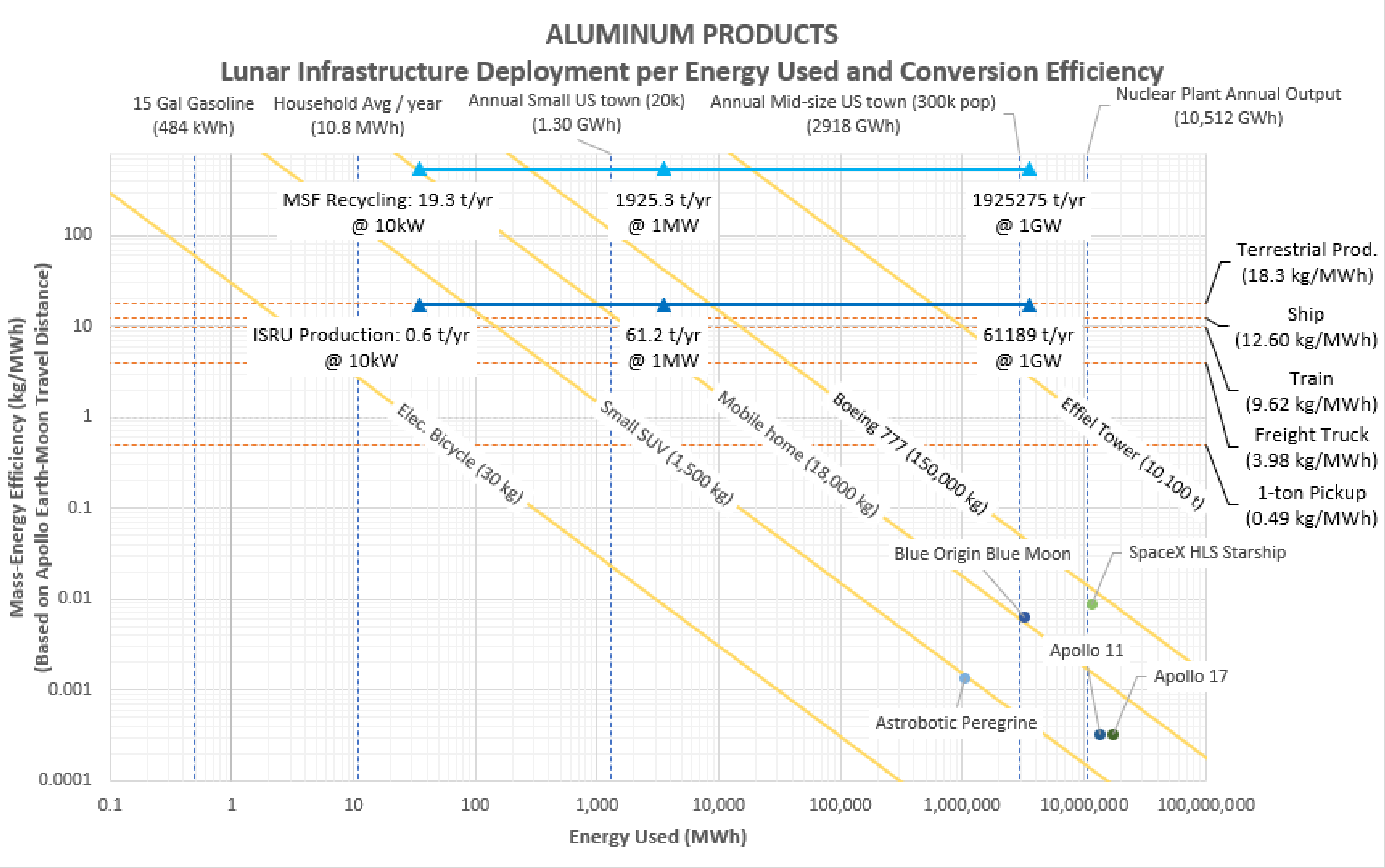


Demonstrations:
Microwave & mm-wave
Laser
PowerLight: Free Space
Safe Free Space
PowerLight: Fiber
Safe Fiber
Delivered Electric Power (Watts)
100,000
10,000
1,000
100
NASA Goldstone (1975)
Lunar Uses
UAVs & HALE
PowerLight NASA Challenge (P_{max})
PowerLight DUAL (OSD, in progress)
PowerLight PTROL 2
PowerLight DE Test w/ NRL
PowerLight NASA Challenge (d_{max})
Moonstruck Rover
JAXA
PowerLight UAV
PowerLight PTROL 3
PowerLight Telecom PoC
SHARP
Telecom
Virtus Solis?
Sichuan U.
PowerLight PTROL 1 (UUV)
100
1,000 feet
1,000
1 mile
10,000
15 miles
Marathon
100,000
Distance (meters)
POWERLIGHT TECHNOLOGIES

CisLunar Industries



CisLunar Industries



Question 4 “White space chart of financial aspect”

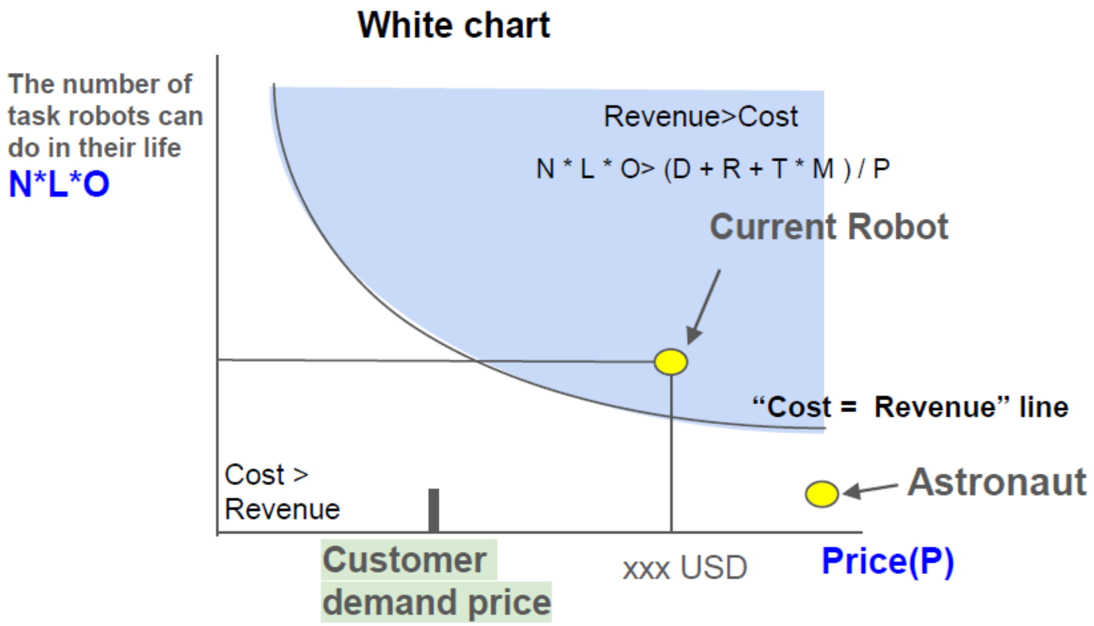
In order to keep providing RaaS, The formula “**Cost < Revenue**” should hold.
This formula can transform to the following formula.

$$D + R + T * M < N * L * O * P$$

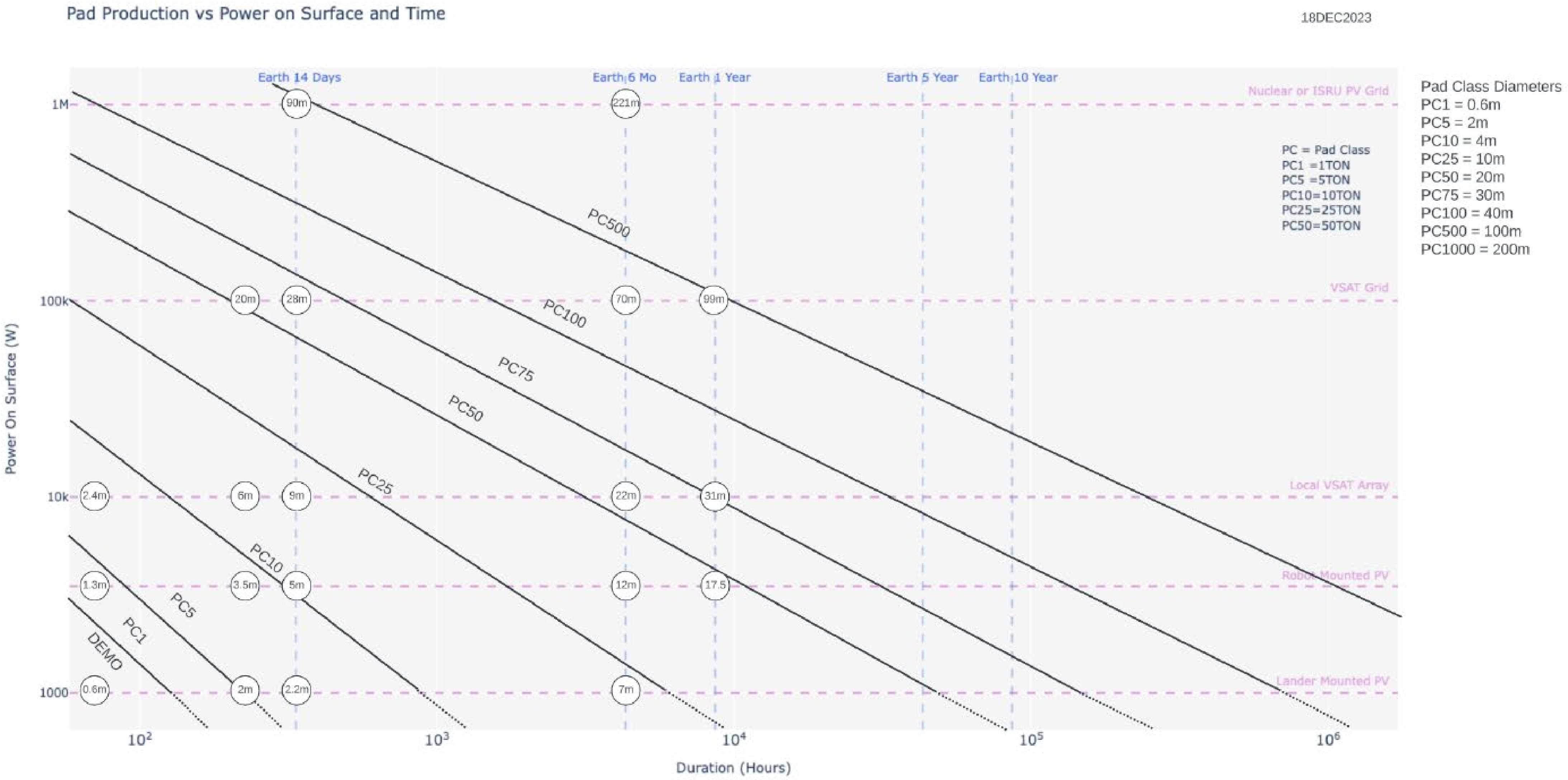
D = Development cost
R = Running cost = Maintenance cost + Energy cost
T = Transportation cost[USD/kg]
M = Total Mass

N = Number of services per year
L = Life time
O = Operating ratio
P = Price per service

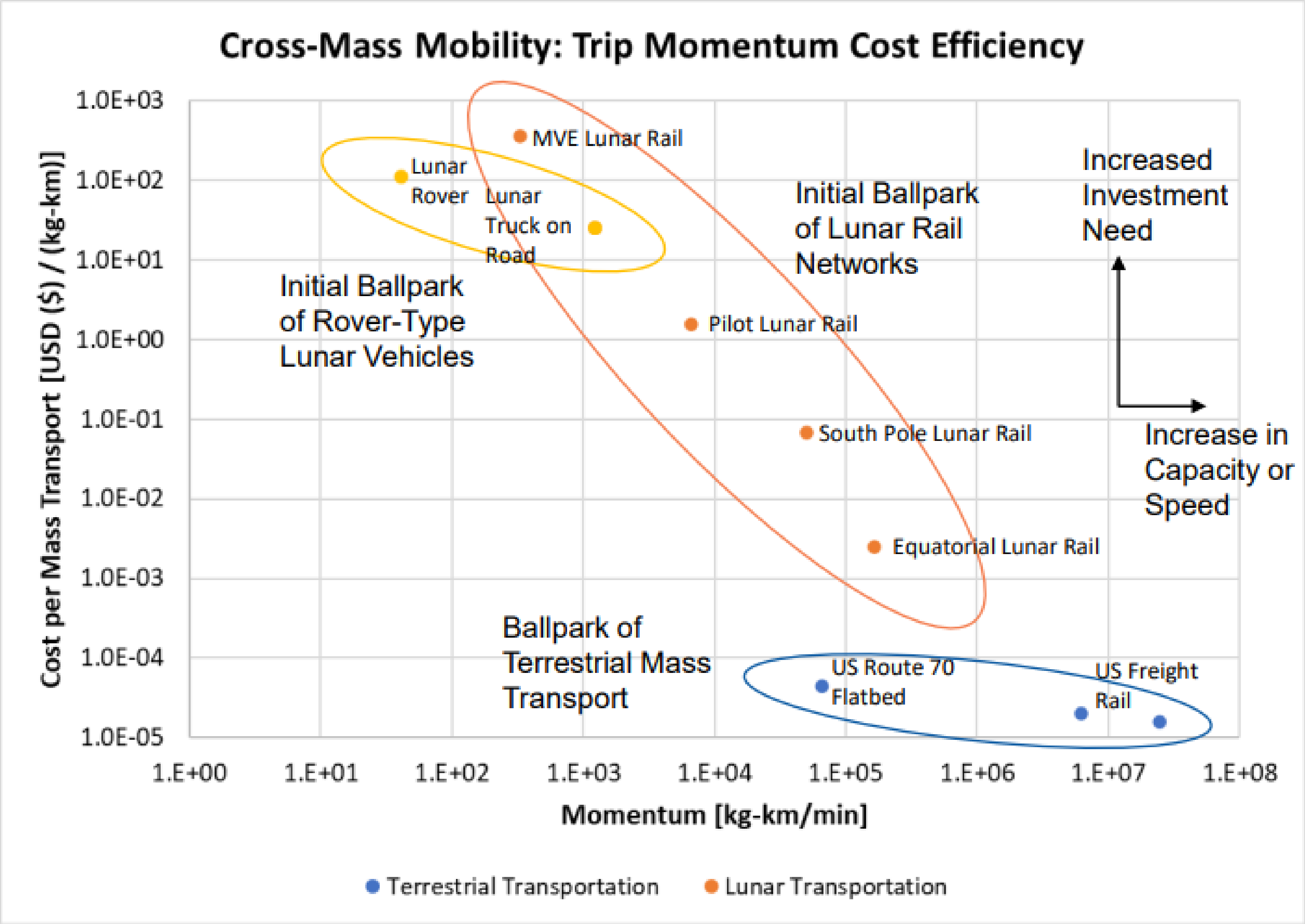
* Price is per-service payment which consists of initial fee and time charge fee



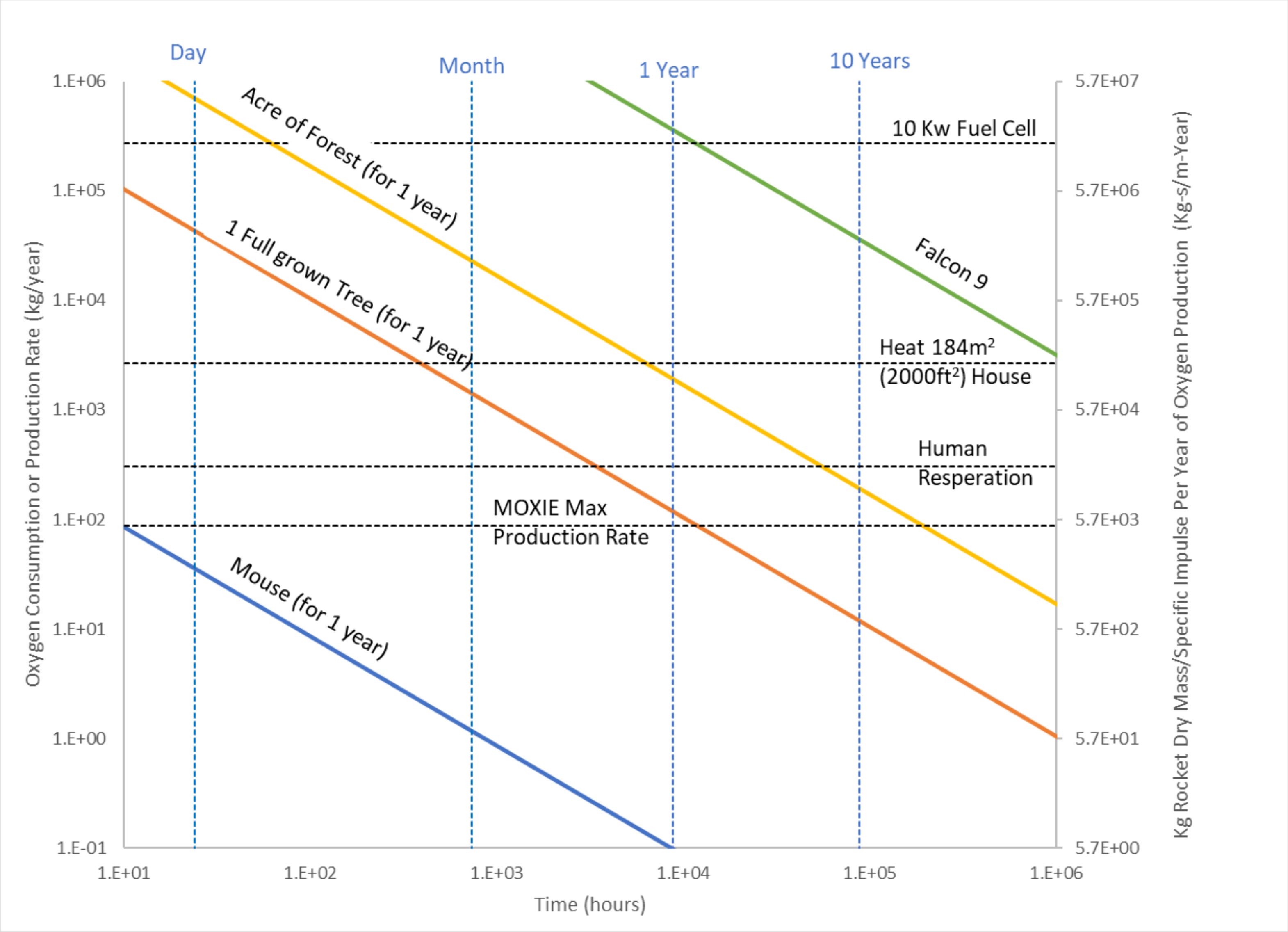
In order to keep providing RaaS in lunar commercial market, the price should fit to customer demand price. If the price doesn’t meet the customer demand price, we can take two types of strategy as shown on the next page.


Pad Production vs Power on Surface and Time
18DEC2023
Earth 14 Days
Earth 6 Mo
Earth 1 Year
Earth 5 Year
Earth 10 Year
Nuclear or ISRU PV Grid
VSAT Grid
Local VSAT Array
Robot Mounted PV
Lander Mounted PV
PC = Pad Class
PC1 =1TON
PC5 =5TON
PC10=10TON
PC25=25TON
PC50=50TON
Pad Class Diameters
PC1 = 0.6m
PC5 = 2m
PC10 = 4m
PC25 = 10m
PC50 = 20m
PC75 = 30m
PC100 = 40m
PC500 = 100m
PC1000 = 200m
PC500
PC100
PC75
PC50
PC25
PC10
PC5
PC1
DEMO
90m
221m
20m
28m
70m
99m
2.4m
6m
9m
22m
31m
1.3m
3.5m
5m
12m
17.5
0.6m
2m
2.2m
7m
1M
100k
10k
1000
Power On Surface (W)
10^2
10^3
10^4
10^5
10^6
Duration (Hours)

Northrop Grumman



Sierra Space



Assumptions:
Second Y axis is Rocket Dry Mass / Delta V-Year achievable assuming Mass ratio of 0.5248 (Same as SLS) ISP of 465