EXPLORESPACE TECH
TECHNOLOGY DRIVES EXPLORATION

Space Mining is Coming:
Implications for Space Exploration and Terrestrial Mining

Keynote to World Mining Congress
New Mining Frontiers

June 27, 2023

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Why We Explore Space

- Why Explore: It's What Humans Do!
- National Pride, International Prestige
- Scientific Advancement, New Insights
- Encourage International Cooperation, Global Partnerships
- Security, Long-term Survival of the Human Species
- Stimulate Economic Development & Expansion
- Make Life Better on Earth

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These drive technology and science and human mission decisions within NASA

These are now extra drivers for NASA technology and mission decisions

These drive national strategy and public interest

ARTEMIS: Humanity's Next Giant Leap

Moon to Mars

- Returning Americans to the Moon: 1st Woman & 1st Person of Color **By 2025**
- Learning to live and work on the Moon
- Translating lessons learned so that the United States has capabilities and operational experience for a mission to Mars
- Inspires the next generation of explorers, researchers, scientists, and engineers worldwide

> "The United States will lead an innovative and sustainable program of exploration with commercial and international partners to enable human expansion across the solar system and to bring back to Earth new knowledge and opportunities. Beginning with missions beyond low-Earth orbit, the **United States will lead the return of humans to the Moon** for long-term exploration and utilization, **followed by human missions to Mars** and other destinations."

Space Policy Directive One

Artemis Architecture Segments

HUMAN LUNAR RETURN

Initial capabilities, systems, and operations necessary to reestablish human presence and initial utilization (e.g., science) on and around the Moon.

FOUNDATIONAL EXPLORATION

Expansion of lunar capabilities, systems, and operations supporting complex orbital and surface missions to conduct utilization (e.g., science) and Mars-forward precursor missions.

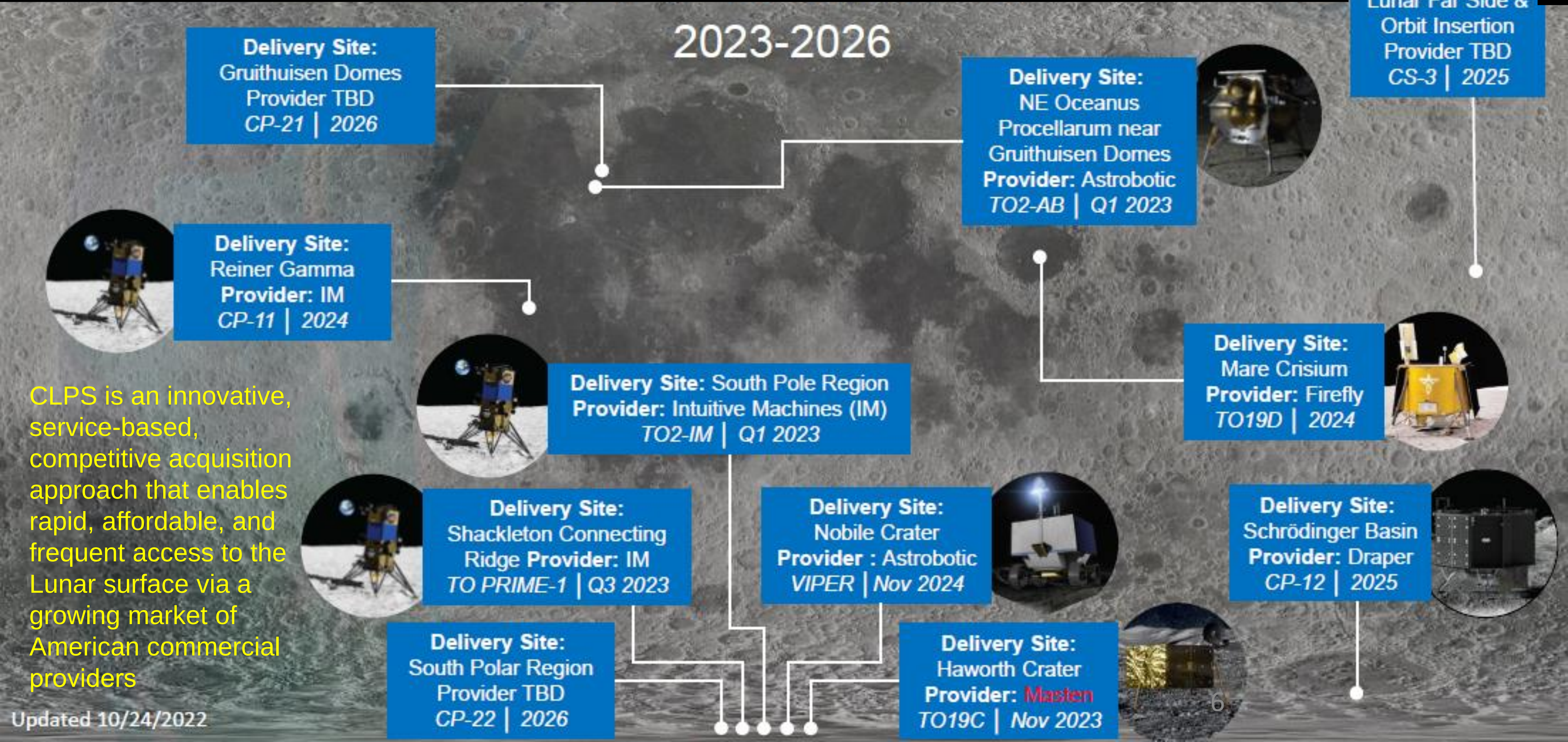
SUSTAINED LUNAR EVOLUTION

Enabling capabilities, systems, and operations to support regional and global utilization (e.g., science), economic opportunity, and a steady cadence of human presence on and around the Moon.

HUMANS TO MARS

Initial capabilities, systems, and operations necessary to establish human presence and initial utilization (e.g., science) on Mars and continued exploration.

NASA Lunar Robotic Program:
Commercial Lunar Payload Services (CLPS)



2023-2026

Delivery Site:
Gruithuisen Domes
Provider TBD
CP-21 | 2026

Delivery Site:
NE Oceanus
Procellarum near
Gruithuisen Domes
Provider: Astrobotic
TO2-AB | Q1 2023

Delivery Site:
Lunar Far Side &
Orbit Insertion
Provider TBD
CS-3 | 2025

Delivery Site:
Reiner Gamma
Provider: IM
CP-11 | 2024

Delivery Site:
Mare Crisium
Provider: Firefly
TO19D | 2024

Delivery Site: South Pole Region
Provider: Intuitive Machines (IM)
TO2-IM | Q1 2023

CLPS is an innovative, service-based, competitive acquisition approach that enables rapid, affordable, and frequent access to the Lunar surface via a growing market of American commercial providers

Delivery Site:
Shackleton Connecting
Ridge **Provider:** IM
TO PRIME-1 | Q3 2023

Delivery Site:
Nobile Crater
Provider : Astrobotic
VIPER | Nov 2024

Delivery Site:
Schrödinger Basin
Provider: Draper
CP-12 | 2025

Delivery Site:
South Polar Region
Provider TBD
CP-22 | 2026

Delivery Site:
Haworth Crater
Provider: Masten
TO19C | Nov 2023

Updated 10/24/2022

NASA INFRASTRUCTURE GOAL: Develop exploration technologies and enable a vibrant space economy with supporting utilities and commodities

Scalable Space Mining production/utilization capabilities including <u>sustainable commodities</u> on the lunar & Mars surface*

COMMERCIAL SCALE WATER, OXYGEN, METALS & COMMODITY PRODUCTION

- Lunar resources mapped at meter scale for commercial mining
- 10's of metric tons of commodities per year for initial goal commercial usage
- Scalable to 100's to 1000's metric tons per year

COMMODITIES FOR HABITATS & FOOD PRODUCTION

- Water, fertilizers, carbon dioxide, and other crop growth support
- Crop production habitats and processing systems
- Consumables for life support , EVAs, and crew rovers/habitats for growing human space activities

IN SITU DERIVED FEEDSTOCK FOR CONSTRUCTION, MANUFACTURING, & ENERGY

- Initial goal of simple landing pads and protective structures
- 100's to 1000's metric tons of regolith-based feedstock for construction projects
- 10's to 100's metric tons of metals, plastics, and binders
- Elements and materials for multi-megawatts of energy generation and storage
- Recycle, repurpose, and reuse manufacturing and construction materials & waste

COMMODITIES FOR COMMERCIAL REUSABLE IN-SPACE AND SURFACE TRANSPORTATION AND DEPOTS

- 30 to 60 metric tons per lander mission
- 100's to 1000's metric tons per year of for Cis-lunar Space
- 100's metric tons per year for human Mars transportation

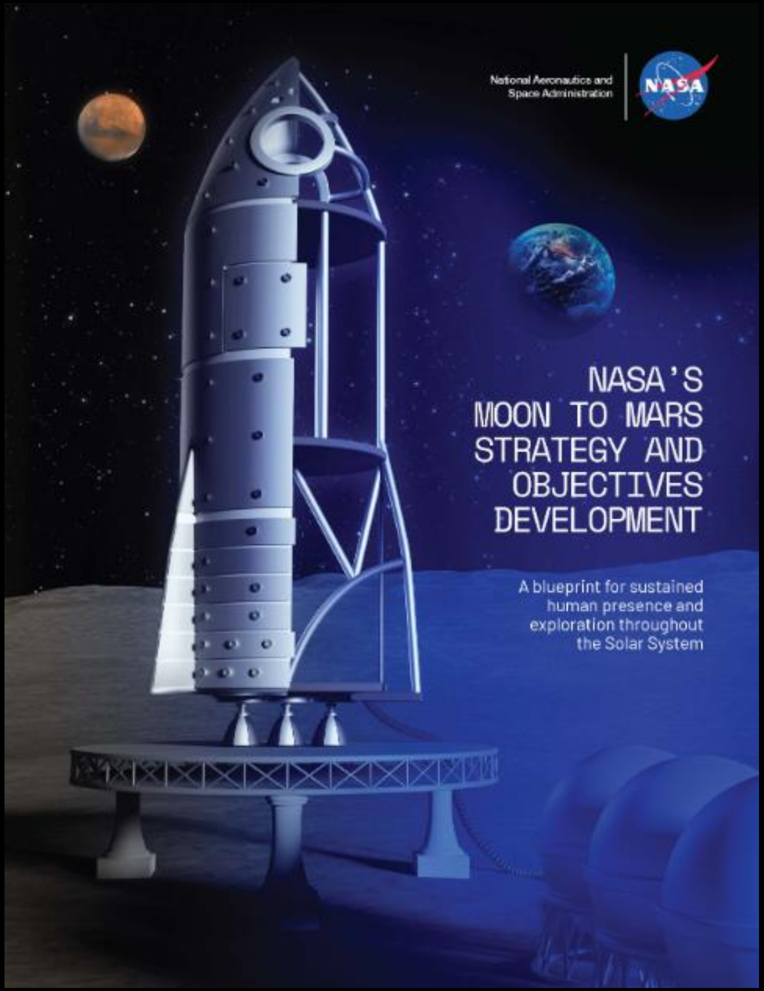
<u>All activities depicted not currently funded or approved. Depicts "notional future" to guide technology vision.</u>

*Commodities are items and consumables that can be eventually sold

NASA Moon To Mars Objectives and Space Mining

Resource Assessment

Characterize accessible Lunar and Martian resources, gather scientific research data, and analyze **potential reserves** to satisfy science and technology objectives and enable In-Situ Resource Utilization (ISRU) on successive missions.



National Aeronautics and Space Administration

NASA'S MOON TO MARS STRATEGY AND OBJECTIVES DEVELOPMENT

A blueprint for sustained human presence and exploration throughout the Solar System

Infrastructure, Space Mining, and Usage

Demonstrate **industrial scale ISRU** capabilities in support of continuous human lunar presence and a robust lunar economy.

Demonstrate technologies supporting cislunar orbital/surface depots, construction and manufacturing **maximizing the use of in-situ resources**, and support systems needed for continuous human/robotic presence.

Responsible Space Mining

Establish procedures and systems that will **minimize the disturbance to the local environment**, maximize the resources available to future explorers, and **allow for reuse/recycling of material** transported from Earth (and from the lunar surface in the case of Mars) to be used during exploration

Space Mining and Processing – *'Prospect to Product'*

Space Mining and Processing involves any hardware or operation that harnesses and utilizes 'in-situ' resources to create commodities* for robotic and human exploration and space commercialization

Destination Reconnaissance & Resource Assessment

Assessment and mapping of physical, mineral, chemical, and water/volatile resources, terrain, geology, and environment

Resource Acquisition, Isolation, & Preparation

Atmosphere constituent collection, and soil/material collection via drilling, excavation, transfer, and/or manipulation before Processing

Resource Processing

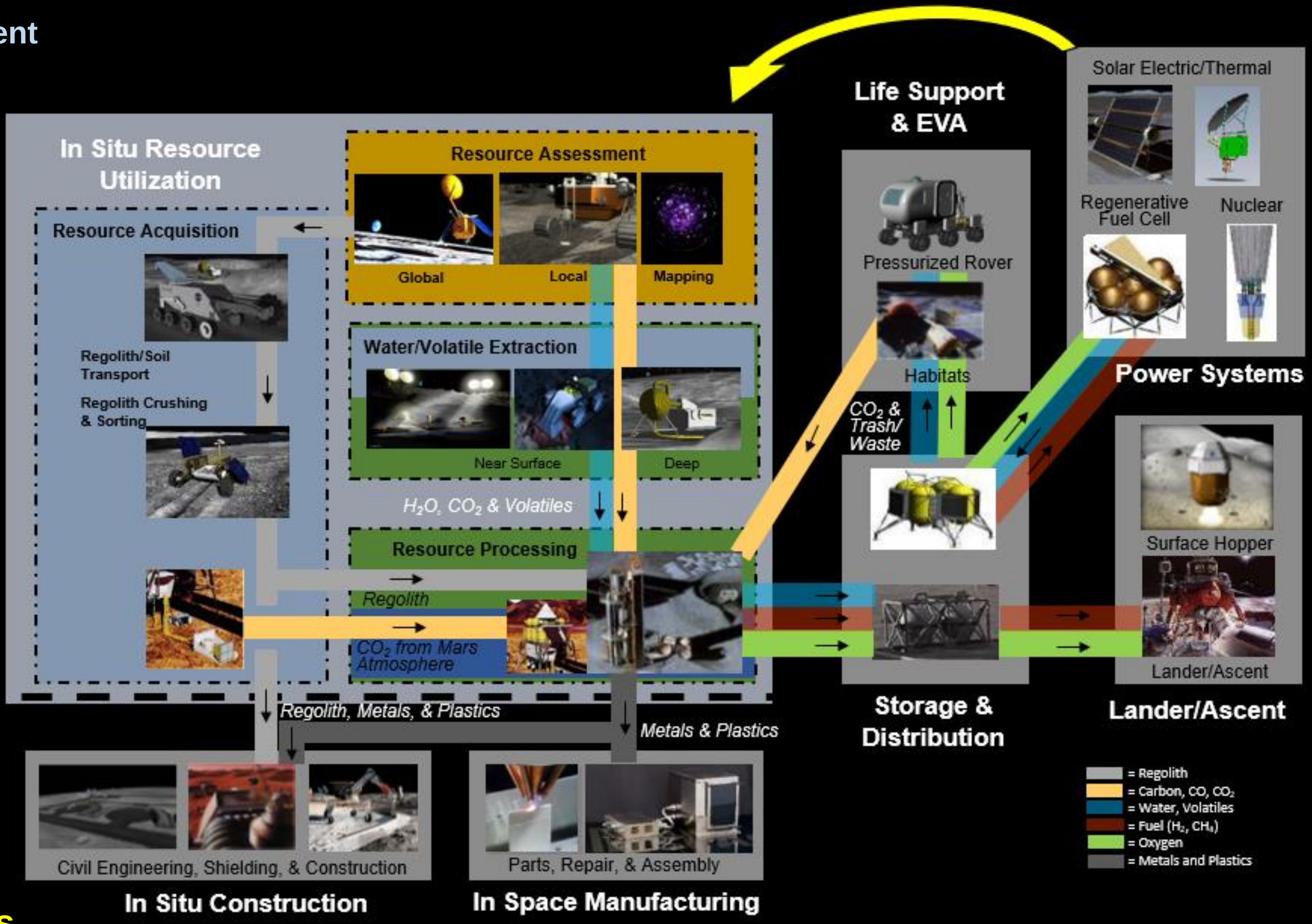
Chemical, thermal, electrical, and or biological conversion of acquired resources and intermediate products into

- Mission Consumables
- Feedstock for Construction & Manufacturing

Water/Volatile Extraction

A subset of both Resource Acquisition and Processing focused on water and other volatiles that exist in extraterrestrial soils

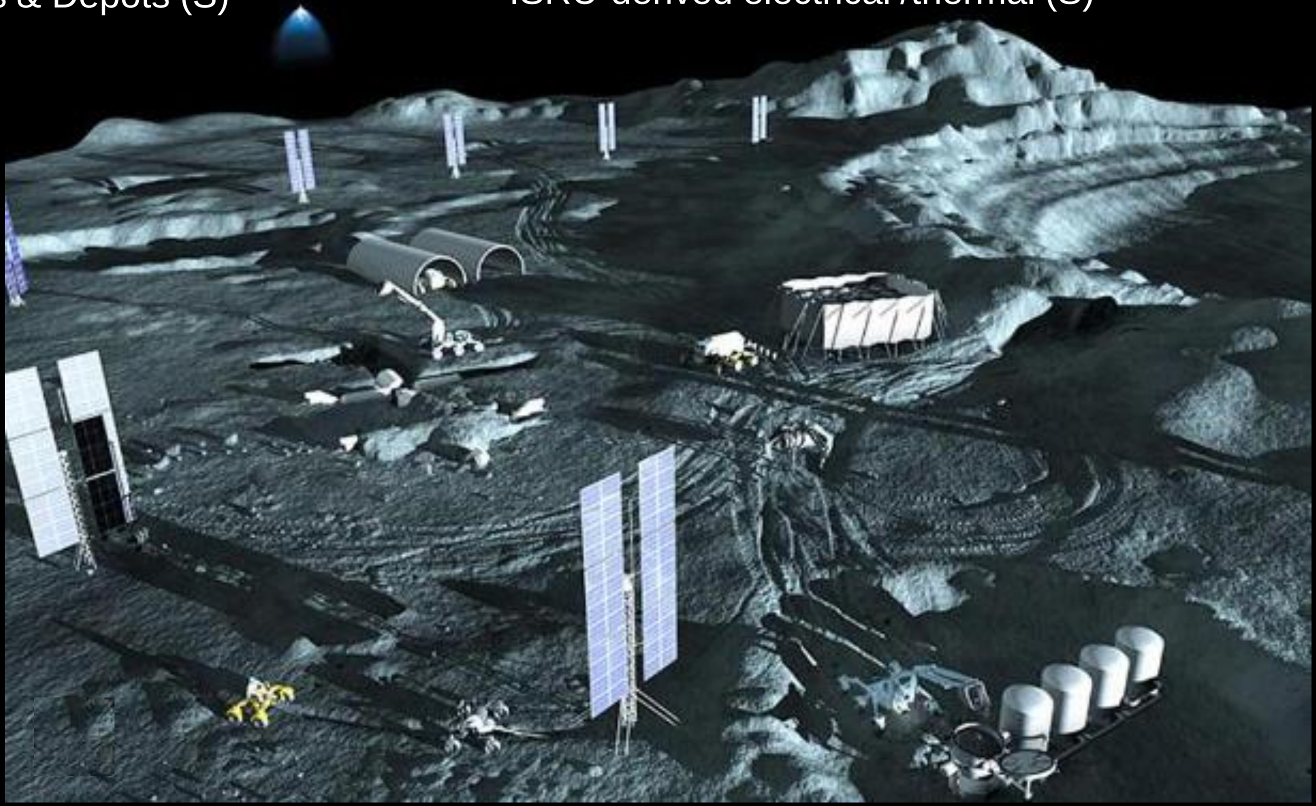
- **Space Mining does not exist on its own. It must link to users/customers of its products**



*Commodities are items and consumables that can be eventually sold

Space Mining Must Operate as Part of A Larger Architecture

- Elements and interdependencies must be designed with Space Mining product usage in mind from the start to maximize benefits
  - Transition from Earth-supplied to ISRU-supplied
  - Guided by overarching Site Master Plan



Transportation to/from Site:
- Delivery (P)
- Propellants & Depots (S)

Power:
- Generation, Storage, & Distribution (P)
- ISRU-derived electrical /thermal (S)

Communications & Navigation (P)
- To/From Site
- Local

Space Mining

Coordinated Mining Ops:
Areas for:
i) Excavation
ii) Processing
iii) Tailings
iv) Product Storage

Maintenance & Repair
Logistics Management
- Replacement parts (P)
- Feedstock (S)

Living Quarters & Crew Support Services
- Water, O_2, H_2, Gases (S)
- Trash/waste (P)
- Nutrients(S)

Commodity Storage and Distribution:
- Water & Cryogenic Fluids (CFM)
- Manufacturing & Construction Feedstock

Construction and Outfitting
- Feedstock for roads and structures (S)

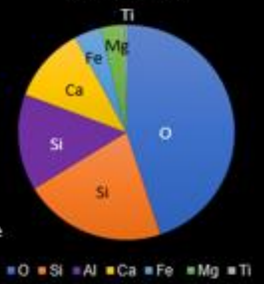
P = Provided to ISRU
S = Supplied by ISRU
***Italic* = Other Disciplines**

Time and Spatial Evolution of Lunar Resources and Commodities for Commercial and Strategic Interests

- ISRU starts with the easiest resources to mine, requiring the minimum infrastructure, and providing immediate local usage
- The initial focus is on the lunar South Pole region (highland regolith and water/volatiles in shadowed regions)
  - ISRU will evolve to other locations, more specific minerals, more refined products, and delivery to other destinations

1. Polar Highland Regolith
(Oxygen, Aluminum, Silicon)

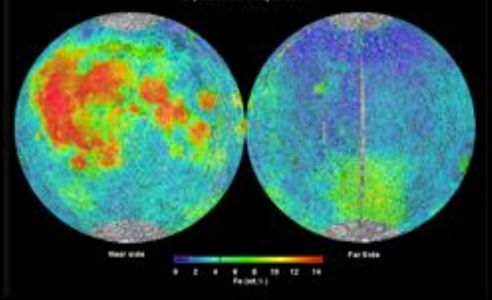
Highland Regolith
(Apollo 16)

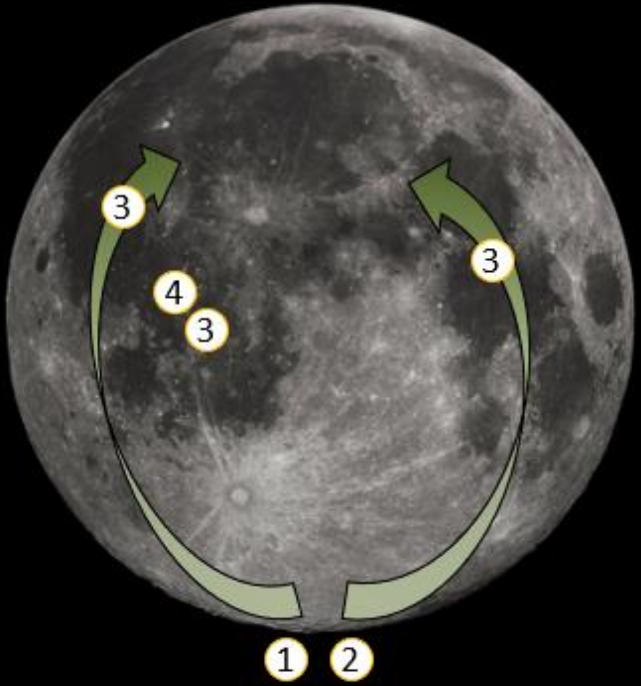


from Planetary and Space Science, Vol. 74.

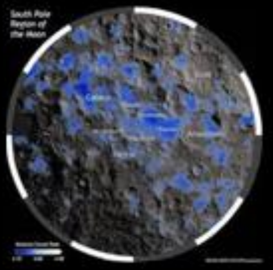
3. Ilmenite and Pyroclastic Glass
(Iron, Titanium, Solar Wind Volatiles)

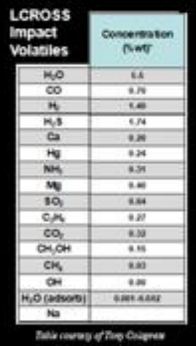
Clementine Iron Map of the Moon
Equal Area Projection





2. Polar Water/Volatiles

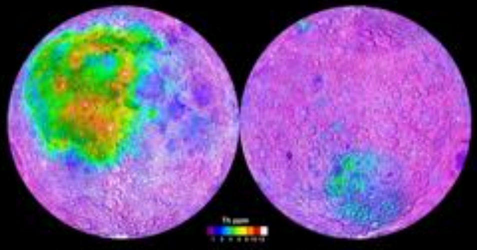




LCROSS Impact Volatiles	Concentration (%wt)*
H_2O	5.5
CO	5.70
H_2	1.40
H_2S	1.74
Ca	0.20
Hg	0.24
NH_3	0.31
Mg	0.40
SO_2	0.64
C_2H_4	0.27
CO_2	0.32
CH_3OH	0.15
CH_4	0.03
OH	0.00
H_2O (adsorb)	0.001-0.002
Na	

Table courtesy of Tony Colaprete

4. Rare Earth Elements & Thorium



Indication of where KREEP is
(Procellerum KREEP Terrane)

Commodities

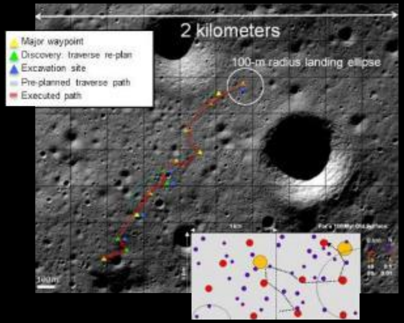
- **Oxygen**
- **Water**
- **Bulk & Refined Regolith**
- **Raw & Refined Metals (Al, Fe, Ti)**
- **Silicon and Ceramics**
- **Construction Feedstock**
- **Manufacturing Feedstock**
- **Fuels, Plastics, Hydrocarbons**
- **Food/Nutrient Feedstock**

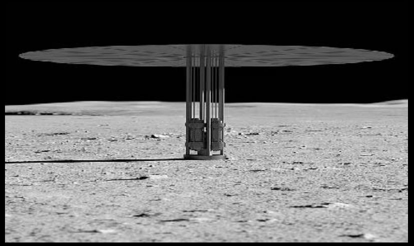
Major Areas of Common of Interest for Terrestrial and Space Mining and Processing

- Promote innovation and apply new/disruptive technologies in operations; AI/ML, robotics, automation, big data, etc.
- Increasing resource exploration assessment/mapping orbital and ground capabilities to reduce timeline
- Mining in extreme climates/environments
- Small footprint, minimal material movement, sustainable (and decarbonized) operations
- Stable, predictable, and agreed upon regulatory regime
- Government support and incentives to attract investment and maintain competitiveness
- Skilled, diverse, and inclusive workforce and personnel safety

Common Space and Terrestrial Driving Attributes

Technologies, Design, and Operations





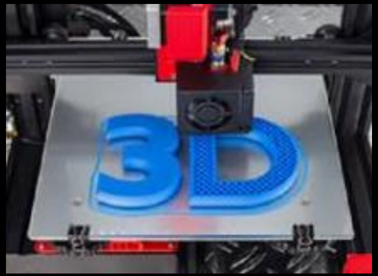


Photo: NIOSH Additive Manufacturing/3D Printing

Photo: The Canadian Minerals and Metals Plan

Photo: What is Edge Computing? Definition and Cases Explained – GIGABYTE Global

Resource Assessment – Mapping – Valuation

1. High confidence in resource reserves

Infrastructure for Mining and Processing

2. Continuous renewable power at multiple and remote locations
3. High accuracy positioning, navigation, and timing (PNT) in non-GPS environment
4. Secure, distributed, high bandwidth communication network
5. Edge compute to optimize communications network.

Operations for Mining and Processing

6. High level of autonomy for all operations
7. Minimize on-site human/crew involvement, esp. high risk operations
8. On-site part manufacturing
9. Minimize logistics and ease maintenance
10. Electrification of all mechanisms and platforms
11. Data rich environment with real-time measurements

Common Space and Terrestrial Driving Attributes

Safety and Environmental Impact


Photo: 7 Safety Tips to Reduce Mining Accidents

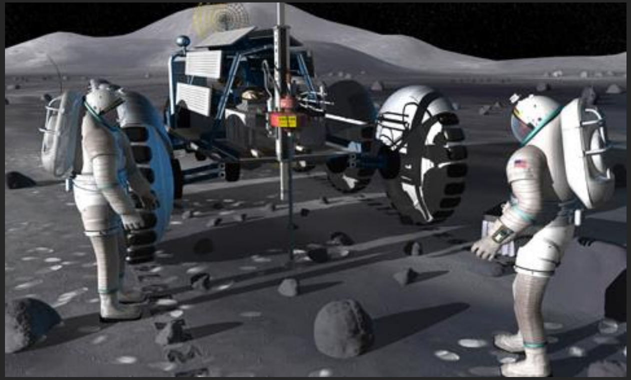



Photo: DIGI – What is Environmental Monitoring

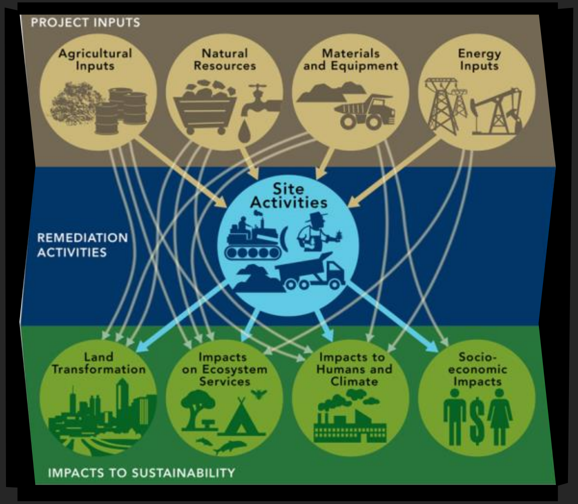


Photo: CH2M HILL Better Environmental Remediation Outcomes, by Paul Favara and Jonathon Weier, CH2M HIL

Safety

12. Minimize time critical safety operations
13. Apply wearables to personnel in the operating environment

Environmental Impact

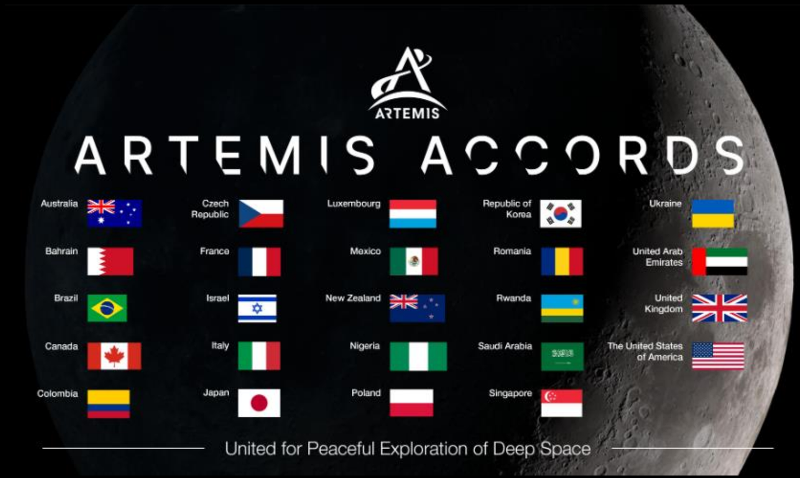
13. Minimize release/exposure of corrosive/hazardous reagents and fluids to crew/space suits and environment
14. Mitigate environment impacts on hardware/operations and vice versa
15. Continuously and distributed environmental monitoring
16. Remediate sites at completion of operations

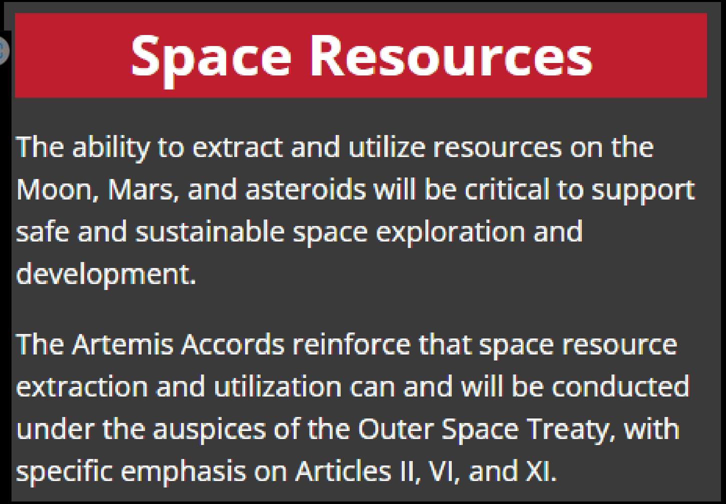
Space Mining Law and Legal Aspects to Consider

Overarching Legal Framework for Space Resources

- Art. I: "Outer space, including the Moon and other celestial bodies, shall be free for exploration and use by all States "
- Art. II: "Outer space, including the moon and other celestial bodies, is not subject to national appropriation
- Art. IX: State parties "shall conduct all their activities in outer space . . . with due regard to the corresponding interests of all other States Parties to the Treaty."

Non-Binding Agreement on Conduct for Space Resources





Space Resources

The ability to extract and utilize resources on the Moon, Mars, and asteroids will be critical to support safe and sustainable space exploration and development.

The Artemis Accords reinforce that space resource extraction and utilization can and will be conducted under the auspices of the Outer Space Treaty, with specific emphasis on Articles II, VI, and XI.

UN Framework on Space Resources

THE HAGUE
INTERNATIONAL
SPACERESOURCES
GOVERNANCE WORKING GROUP

BUILDING BLOCKS FOR THE DEVELOPMENT OF AN INTERNATIONAL FRAMEWORK ON SPACE RESOURCE ACTIVITIES
November 2019

National Laws for Space Resources

114TH CONGRESS
1st Session
HOUSE OF REPRESENTATIVES
REPORT
114–153

SPACE RESOURCE EXPLORATION AND UTILIZATION ACT OF 2015

Luxembourg: Law on Use of Resources in Space Adopted

(Aug. 22, 2017) The Luxembourg Chamber of Deputies adopted a law on the exploration of space and the use of space resources on July 13, 2017.

Japan passes space resources law

by Jeff Foust — June 17, 2021

The bill, formally known as the Law Concerning the Promotion of Business Activities Related to the Exploration and Development of Space Resources, grants Japanese companies permission to prospect for, extract and use various space resources. Companies that wish to do so must first obtain permission from the Japanese government.

UAE SPACE LAW DETAILS ANNOUNCED TO FACILITATE SPACE SECTOR DEVELOPMENT

US

Luxembourg

Japan

UAE

Emphasize Industry Involvement

Mining Economics and Mining Phases*

- Define Initial and Long-term Customer Needs and ISRU-derived Products
- Advance ISRU Technologies/Systems (thru solicitations, Public - Private Partnerships, Challenges)
- Focus NASA Work to Reduce Risk and Promote Investment (fundamental research, technology development, facilities, etc.)
- Promote Industry-led development thru End-to-End Production of Commodities

Exploration Phase

- Reserve Definition
- Mining and Recovering Technology Readiness

Development Phase: Feasibility study, contractual and legal aspects, and financing

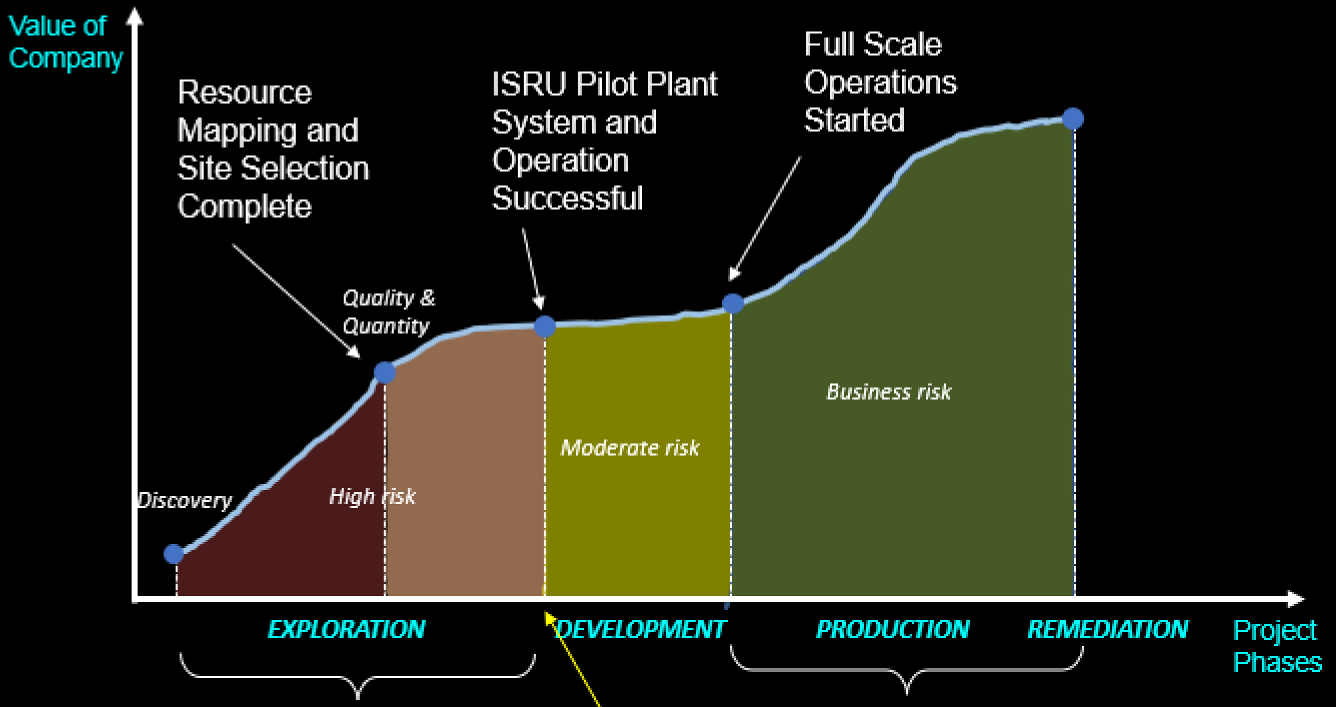
Production

- Build-up Phase: Startup and initial production
- Plateau Phase: Production rate remains steady
- Decline Phase: Reserves begin to dwindle

Remediation

- Shutdown/removal of mining equipment
- Mine site reclamation

Government support in Exploration Phase may be key to lunar commercial success



Negative cash flow due to resource assessment and technology development and testing

Positive cash flow due to production and selling of product

Investment risk significantly reduced after successful Pilot Plant demonstration

*Sommariva, A. et al, "The Economics of Moon Mining', International Academy of Astronautics, Torino, Italy, June 17-19, 2019

Transition to Lunar Mining and Processing Circular Economies*

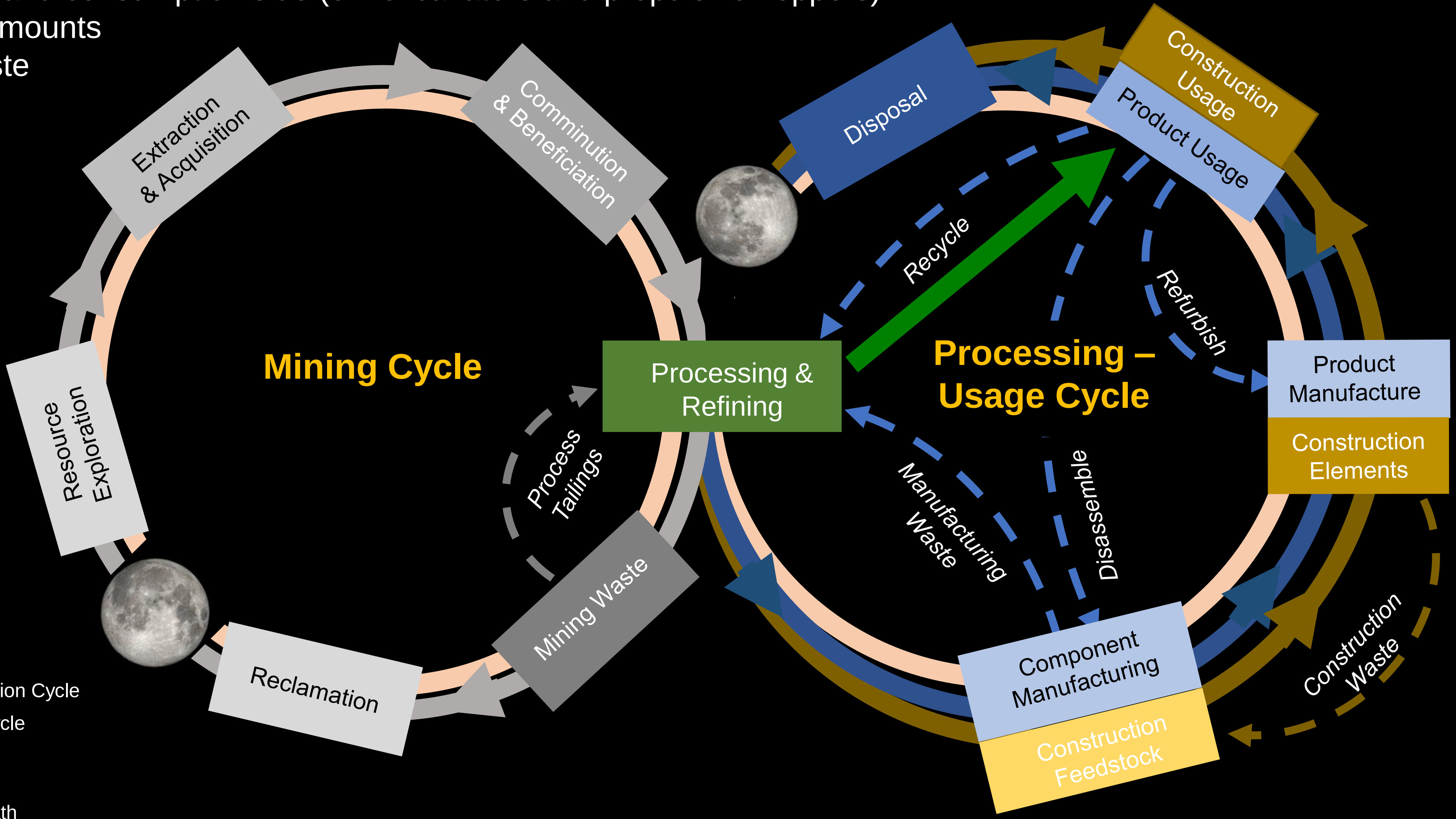
The Circular Economies needs to:

- Take into consideration not just the flow of the mining-processing products but the hardware and infrastructure associated with both the production and consumption side (ex. excavators and propulsive hoppers)
- Minimize disposal amounts
- Manage mining waste

*Circular Economy graphic inspired by fusing two graphics

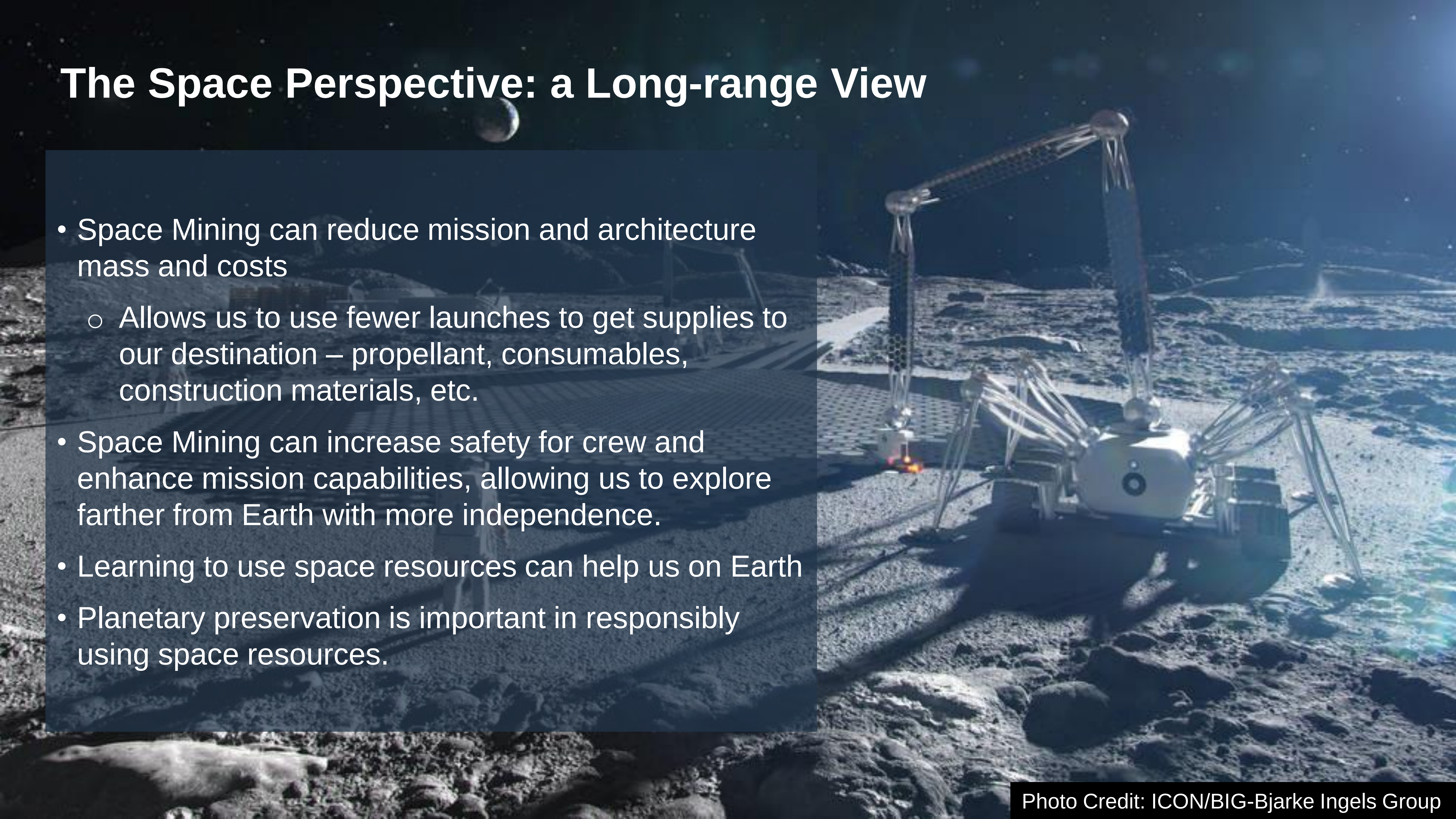
- The CANADIAN MINERALS and METALS PLAN, THE CANADIAN MINERALS AND METALS PLAN, PDF: M4-175/2019E-PDF, MinesCanada.ca, #YourCMMP, March 2019

- Afreen Siddiqi, Ph.D., "From Sustainable Development to Exploration: Concepts from Living on Earth for Forging Futures on Moon and Mars", Artemis and Ethics Workshop, NASA HQ, Washington D.C., April 12-14, 2023



⬜ = Mining & Resource Extraction Cycle
🟦 = Metals & Manufacturing Cycle
🟫 = Construction Cycle
🟩 = Consumables Path
🟧 = Hardware/Infrastructure Path

The Space Perspective: a Long-range View



- Space Mining can reduce mission and architecture mass and costs
  - Allows us to use fewer launches to get supplies to our destination – propellant, consumables, construction materials, etc.
- Space Mining can increase safety for crew and enhance mission capabilities, allowing us to explore farther from Earth with more independence.
- Learning to use space resources can help us on Earth
- Planetary preservation is important in responsibly using space resources.

Photo Credit: ICON/BIG-Bjarke Ingels Group

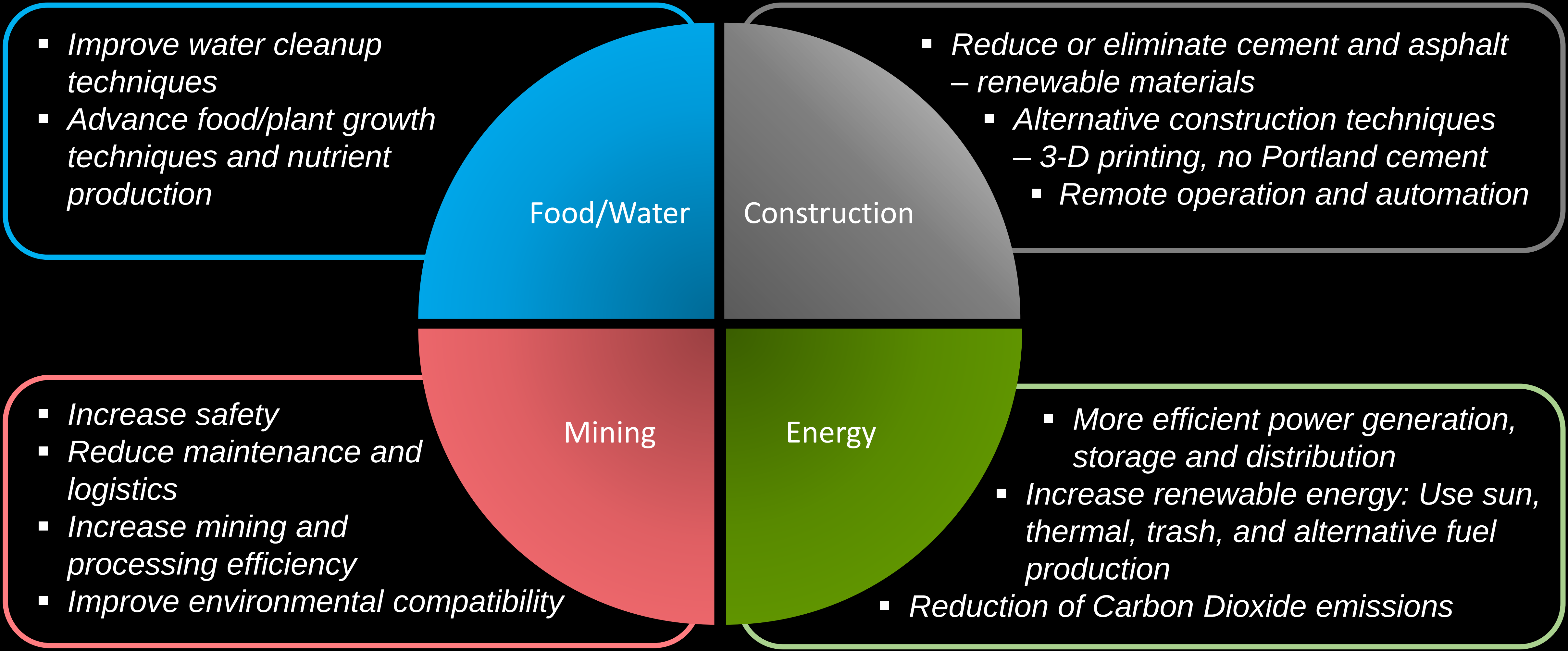
Thank You. Questions?

New **ISRU Envisioned Future Priorities at:**

https://techport.nasa.gov/framework

Backup

Space Resource Utilization Is Synergistic with Terrestrial Needs



Food/Water

- *Improve water cleanup techniques*
- *Advance food/plant growth techniques and nutrient production*

Construction

- *Reduce or eliminate cement and asphalt – renewable materials*
- *Alternative construction techniques – 3-D printing, no Portland cement*
- *Remote operation and automation*

Mining

- *Increase safety*
- *Reduce maintenance and logistics*
- *Increase mining and processing efficiency*
- *Improve environmental compatibility*

Energy

- *More efficient power generation, storage and distribution*
- *Increase renewable energy: Use sun, thermal, trash, and alternative fuel production*
- *Reduction of Carbon Dioxide emissions*

Promote *Reduction, Reuse, Recycle, Repair, Reclamation*

…for benefit of Earth, and living in Space.

What are the Barriers to Commercial ISRU?

Today: There is Neither a Production Capability or Market

Barriers

Resource Uncertainty

- Resource Exploration
- Reserve Estimation

Mining Technology Readiness

- Demonstrated Scale
- Demonstrated Operations

Customers

- Known users/market
- Market growth potential

Sustainable Operations

- Reliable/Cheap Transportation
- Logistics and Maintenance
- Infrastructure

Regulatory

- Legal Framework
- Product/Property Rights
- Standards
- Taxes

What Can/Should Be Done?

- Increase global resolution of resource information
- Campaign of resource exploration missions (Gov. & Industry)
- Agreement/standards for reserve estimation (ex JORC/NI43-101)

- Government/industry partnerships & space mining institute
- Spin-in/Spin-off Technologies into Terrestrial Applications
  - Incentives for insertion; greener/safer innovations
- Demonstrate technologies, production rate, and product quality

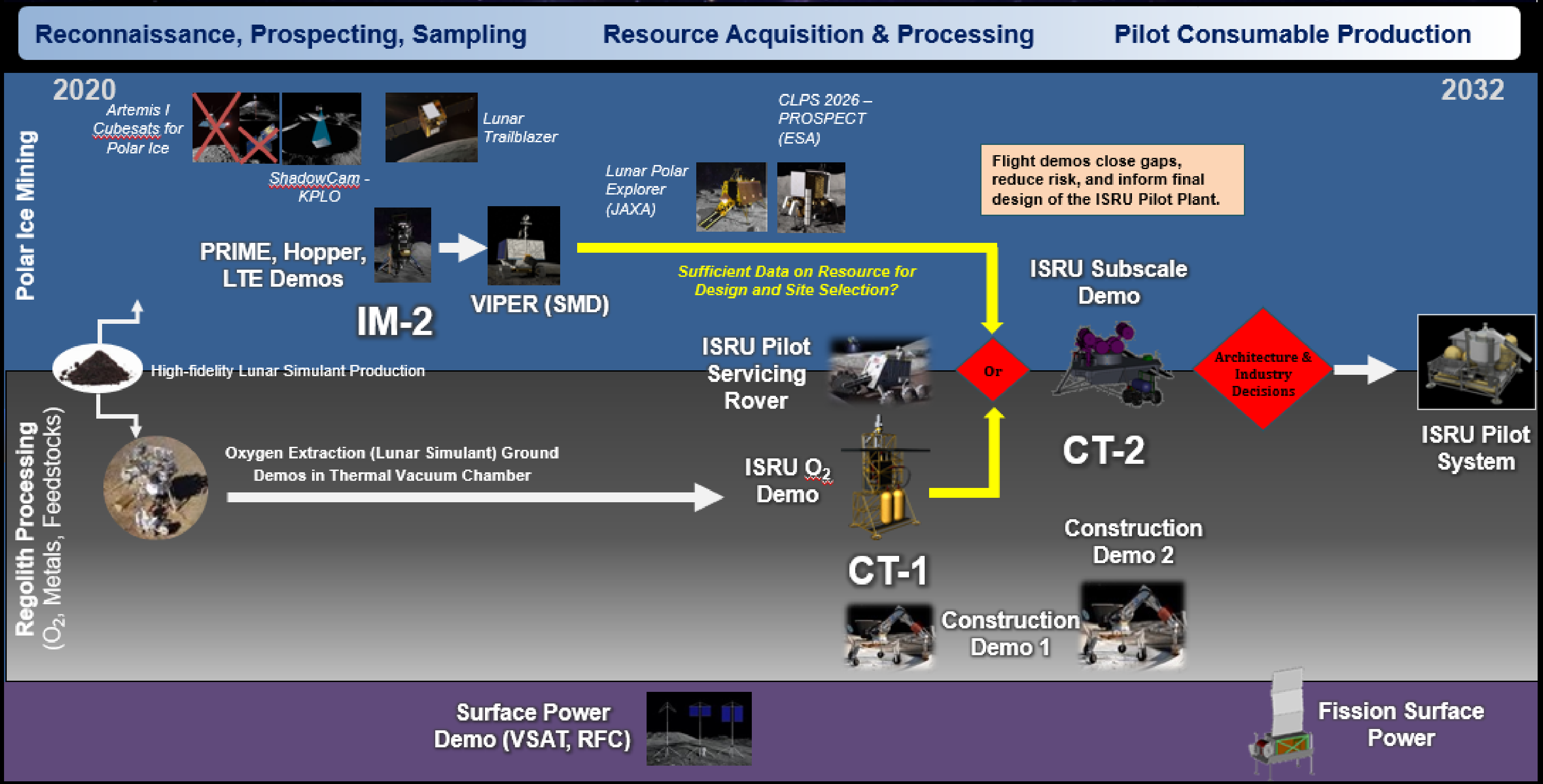
- Terrestrial market use of technology/capability
- Demonstrate product usage
- Develop space transportation & infrastructure growth around ISRU
- Gov. as anchor tenant once demand has been established
- Enable bootstrapping through stepwise incentives

- Utilize additive manufacturing for high wear parts
- Governments help establish initial transportation, power, communication, and surface infrastructure
- Establish common interfacing standards

- Establish international agreements **(Artemis Accords)**
- Establish stable legal and regulatory framework
- Establish tax incentives/flow-through shares
- Enable ownership enforcement

ISRU Path to Full Implementation & Commercialization*

**Proposed missions and timeline are contingent on NASA appropriations, technology advancement, and industry participation, partnerships, and objectives*



Full-scale implementation & Commercial Operations

LI-7^{L}	Demonstrate industrial scale ISRU capabilities in support of continuous human lunar presence and a robust lunar economy.
OP-11^{LM}	Demonstrate the capability to use commodities produced from planetary surface or in-space resources to reduce the mass required to be transported from Earth.
TH-3^{L}	Develop system(s) to allow crew to explore, operate, and live on the lunar surface and in lunar orbit with scalability to continuous presence; conducting scientific and industrial utilization as well as Mars analog activities.
RT-6	Responsible Use: Conduct all activities for the exploration and use of outer space for peaceful purposes consistent with international obligations, and principles for responsible behavior in space

Requires transition and 'Pull' from STMD to ESDMD and Industry

- Dual Path that includes both Water Mining and Oxygen/Metal from Regolith
  - Regolith Processing and O$_2$/Metal Path supports Surface Construction activities
- Ground development of multiple critical technologies in both pathways underway to maximize success and industry involvement
- Resource assessment missions to obtain critical data on mineral and water/volatile resources have started
  - Significant uncertainty if existing missions are sufficient to define resources for design and site selection

What are the Challenges? - ISRU Development & Implementation

Space Resource Challenges

R1 What resources exist at the site of exploration that can be used?

R2 What are the uncertainties associated with these resources?
Form, amount, distribution, contaminants, terrain

R3 How to address planetary protection requirements?
Forward contamination/sterilization, operating in a special region, creating a special region

ISRU Operation Challenges

O1 How to operate in extreme environments?
Temperature, pressure/vacuum, dust, radiation, grounding/plasma charging

O2 How to operate in low gravity or micro-gravity environments?
Drill/excavation force vs mass, soil/liquid motion, thermal convection/radiation

O3 How to achieve long duration, autonomous operation and failure recovery?
No crew, non-continuous monitoring, time delay

O4 How to survive and operate after long duration dormancy or repeated start/stop cycles with lunar sun/shadow cycles?
'Stall' water, lubricants, thermal cycles

O5 How to operate responsibly with minimal impact to science and the environment

ISRU Technical Challenges

T1 Is it technically and economically feasible to collect, extract, and process the resource?
Energy, Life, Performance

T2 How to achieve high reliability and minimal maintenance requirements?
Thermal cycles, mechanisms/pumps, sensors/ calibration, wear

ISRU Integration Challenges

I1 How are other systems designed to incorporate ISRU products?

I2 How to optimize at the architectural level rather than the system level?

I3 How to manage the physical interfaces and interactions between ISRU and other systems (esp. with International Partners and multiple companies)?

I4. How to ensure critical exploration and infrastructure capabilities are delivered in the correct sequence and in a timely manner?

I5. How to grow a commercial ecosystem of supply-demand?

Scale up, Long-duration, & Environmental testing with Realistic simulants Required