TOWARDS A LUNAR COMMODITIES DEVELOPMENT STRATEGY

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Executive Summary: The establishment of a permanent, sustainable human presence on the Moon depends on the successful development and scaling of In-Situ Resource Utilization (ISRU). With delivery costs to the lunar surface up to $1 million per kilogram in early 2026, Earth-supply dependency renders permanent settlement economically fragile and politically vulnerable. We claim that the principal barriers to expanded human activities on the Moon are decisional, not technical, and that the most important barrier is a collective-action problem (supply awaits demand, demand awaits supply) that neither government nor industry can resolve alone. Here, we propose: a reframing of the overall ISRU challenge from a "utilization" to a "development" mindset; a strategic public-private partnership for lunar development by drawing on the historical parallel of the US Transcontinental Railroads; a Test-as-We-Build development strategy [1]; and five early, actionable steps for policymakers [2].

Motivation: Permanent lunar settlement requires breaking the logistical tether to Earth. For every kilogram delivered to the lunar surface, 7X to 20X of propellant is expended, a dependency that is starkly at odds with permanence. Lunar ISRU, especially the production of propellant, commodities and manufactured products, can potentially decouple capability and endurance from mass launched from Earth. In addition, ISRU technologies refined on the Moon are direct precursors to those required for Mars, where crews will be self-reliant for longer periods [3].

From Utilization to Development: Lunar ISRU has too often been viewed through a narrow lens: the mechanical processes of transforming lunar natural resources into useful products and services. We advocate for a broader framework, Lunar Commodities Development [2], that reframes the issue from experimental capability development to the economic grounding essential for long-term viability [1, 2]. Given the logistical cost and risk of Earth dependence, waste is a luxury the future lunar economy cannot afford. Scope would encompass four distinct commodity streams: (1) **material commodities from natural resources** (e.g., bulk regolith; oxygen, water, and metals from regolith and volatiles); (2) **material commodities from recycled and upcycled sources** (e.g., water recovery from biological waste, reprocessing of scrap plastics, scavenging metals from defunct hardware); (3) **non-material commodities from natural sources** (e.g., heat, cold, shadow, and shielding managed as environmental services; for example, the naturally-occurring cold inside a PSR can store cryogenic liquids at near-zero electrical energy cost); and (4) **non-material commodities from recycled sources** (e.g., excess heat, unused electrical power, and data bandwidth treated as tradeable commodities within the settlement ecosystem). This four-stream taxonomy supports system designers to consider the entire lifecycle of every lunar surface system, and to identify synergies across streams and their intersection with lunar commodities early in the design process, when there is still design freedom at both the system level and the system-of-systems level.

The Railroad Analogy and the "First Customer": The transition from exploration to economics is stalled by multiple market failures related mainly to incomplete / imperfect information and the underprovision of public goods. Commercial companies cannot raise capital for lunar commodity plays because there are no customers on the Moon, while system architects are not motivated to design systems which would depend on lunar commodities and other infrastructure because none is available or planned [4, 5]. Without demand, there is no supply; without supply, there is no demand. Historical precedent offers a solution. The construction of the U.S. Transcontinental Railroads in the 19th century faced an almost-identical paradox: technically feasible, but economically impossible for private capital alone. The Federal Government intervened not by building the railroad itself, but by structuring a market in which private companies could succeed: right-of-way land grants, bond guarantees, and baseline demand through postal contracts and military transport. The lunar parallels are direct. NASA and its partners should act as the "First Customer" by publishing credible demand intent and committing to binding agreements for lunar-derived commodities, whether through pre-purchase contracts or service commitments [6]. Such a contract becomes a bankable asset: it allows a lunar commodities company to raise debt financing. This is a strategic procurement lever that converts latent demand into the economic signal private capital requires.

Test-as-We-Build Development Strategy: On the Moon, the environment is the primary unknown – we do not know exactly how regolith will flow, how lunar dust will degrade seals or connectors, or how ice behaves when drilled. Designing a "perfect" industrial plant on Earth for an unknown lunar environment is a recipe for elevated technical and schedule risk. Test-as-We-Build is a philosophy of iterative development where the deployment of infrastructure *is* the test [1]; it is distinct from a "Technology Demonstration", which merely proves that a technology works. Leveraging the accelerated cadence for both CLPS and Artemis, Test-as-We-Build prioritizes putting hardware on the surface earlier so as to generate operational data, rather than taking more time to perfect the system on Earth. Data informs both the current and the next generation, in a continuous loop of "deploy, operate, measure, iterate." The implementation steps scale progressively: (1) Micro-Pilots to validate physical processes in partial gravity; (2) Integrated Pilots at sub-scale to test the interfaces and resource flows between subsystems; and (3) Industrial Precursors at full economic scale, producing usable quantities for the first customers [2, 3]. Test-as-We-Build enables two distinct feedback loops: "Knob-Turning" (real-time adjustment of operational parameters) and "System-Iterating" (data from Pilot A feeds directly into the design of Pilot B). A key byproduct is data itself: for example, the geotechnical properties of lunar highlands regolith, etc. Test-as-We-Build missions can be instrumented to measure these properties, and private companies can be incentivized to share non-proprietary data, resulting in a practical "handbook" of lunar engineering data that reduces risk for everyone. Early infrastructure must also be conceived as persistent, reusable, and positioned for growth rather than treated as disposable demonstrations, with each element contributing to the accumulation of infrastructure beyond its first mission.

Five actionable steps for policymakers: We propose the following five actionable steps. (1) *Operationalize "First Customer" Contracts:* pursue binding agreements for lunar commodities, including pre-purchase contracts, off-take agreements, or service commitments, with specific delivery dates and locations, converting latent demand into bankable assets for private financing [6]. (2) *Incentivize Test-as-We-Build in Contracts:* motivate all surface infrastructure providers to collect detailed performance and environmental data, to share non-proprietary data where appropriate, and to follow an iterative deployment schedule, so that every mission contributes to the private and/or collective engineering knowledge base; early assets should be designed to persist and remain useful across multiple missions [1]. (3) *Harmonize Safety Zones:* work within the Artemis Accords and with non-signatories via open dialogue to establish clear, practical protocols for Safety Zones that prevent interference and conflict [1]. (4) *Fund Prospecting and Close Site-Selection Gaps:* immediately fund a coordinated international campaign of robotic prospectors to define the reserve potential of critical lunar resources [1, 4]; in parallel, conduct a minimum-viability site screen assessing repeatable access, persistent power, expandable area, and room for additional actors, and then select an initial site that can support long-term growth [1]. (5) *Promote Open Interfaces with Proprietary Protection:* where possible, pursue the coordinated award of contracts for interdependent infrastructure systems and require open, documented common interfaces where sharing is necessary to enable interoperability, while protecting proprietary internal design and performance details; and, in addition, support industry consortia to develop *voluntary* consensus standards for all interfaces [1].

Discussion and Conclusion: The findings in this work reinforce each other: ISRU is critical for sustainability; the development mindset and the four-streams taxonomy are a more appropriate framing for system-of-systems lunar surface architects; the historical lesson of the Railroads confirms the need for and presents a model of successful public-private collaboration; Test-as-We-Build is an appropriate development strategy given increasing flight cadence and many environmental unknowns; and emergent interoperability is the glue that will hold a future multi-vendor ecosystem together. Overall, in our view, the principal barriers are decisional rather than technical [1]. Near-term institutional commitments will largely determine whether early lunar activities will enable the accumulation of lunar surface infrastructure, which can then start to deliver long-term value, or whether they will lock in short-duration outcomes. Taken together, these findings point toward a lunar economy that evolves from government as the first and only customer to one of many customers, much as it now buys launch services instead of building rockets. Longer-term, the development of lunar commodity supply chains will lower barriers to lunar entry for large and small, space and non-space companies, as well as for Artemis Accords partners.

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