HABITATION-DRIVEN DEMAND AS A CATALYST FOR LUNAR ISRU DEPLOYMENT.

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Introduction: A sustained human presence on the Moon and the emergence of a cislunar economy both depend on the development of lunar habitation architectures. As human activity on the lunar surface expands, demand will grow for life support consumables, construction materials, power, and propellants—many of which could ultimately be supplied through in-situ resource utilization (ISRU). Most ISRU economic analyses focus on large-scale production scenarios that assume mature infrastructure and high demand for favorable economies of scale while neglecting to analyze near-term, small-scale opportunities such as initial lunar habitation.

Early habitation elements being developed for NASA's Artemis campaign, including the Japan Aerospace Exploration Agency Pressurized Rover (PR) and the Agenzia Spaziale Italiana Multi-Purpose Habitation module (MPH), represent potential near-term lunar resources customers. These habitation elements are currently expected to rely on open-loop environmental control and life support systems (ECLSS), requiring periodic resupply of oxygen and water from Earth [1, 2]. This study evaluates whether this demand could provide a catalytic early market for lunar ISRU.

Our approach quantifies habitation demand, translates that demand into logistical impacts associated with Earth-based resupply, and uses those impacts to estimate lifecycle costs including design, development, test and evaluation (DDT&E), transportation, and operations. The cost of Earth-based consumable resupply is then used to estimate the intrinsic value of lunar-derived water and oxygen. Results suggest even modest levels of habitation demand may exhibit high intrinsic value due to the substantial overhead of transporting consumables from Earth, potentially creating a bridge market supporting early ISRU deployment.

Early Habitation Demand: Using bounding assumptions representing minimum, baseline, and maximum habitation architectures, including variations in crew size, mission duration, extravehicular activity frequency, airlock design, and atmospheric operating conditions [1-3], lifetime demand for oxygen and water can be calculated. For representative Artemis mission architectures with a PR and MPH, an expected 4.4 metric tons of water and oxygen is needed over a 10-year lifetime. Considering an Earth-based resupply architecture leveraging an International Space Station (ISS)-based delivery paradigm [4], this demand results in an expected delivered mass of 8.3 metric tons due to containment systems and packaging support.

Although the raw consumable demand is modest relative to potential ISRU propellant markets, proposed pilot-scale ISRU systems could more than adequately meet most demand scenarios. This alignment suggests that early habitation demand could represent an intermediate or "bridge" customer capable of supporting the first operational ISRU deployments while larger resource markets materialize.

ISRU Pilot-Scale Opportunities: Conceptual pilot-scale ISRU systems have been proposed that target production rates on the order of 1 metric ton of oxygen per year, equivalent to roughly 1.1 metric tons of water per year when produced through hydrogen reduction or electrolysis pathways. Regolith-based oxygen production approaches include carbothermal reduction, molten salt electrolysis, and molten regolith electrolysis, while water production architectures focus on the extraction and processing of possible ice deposits in permanently shadowed regions.

Most of these concepts were originally developed with propulsion markets in mind. Tailoring these concepts to support habitation demand may require different subsystems, such as water purification assemblies or high-pressure oxygen compression systems capable of delivering 3,000–6,000 psia oxygen for habitat repressurization and spacesuit recharge. To complete a rough order of magnitude comparison with Earth-based resupply architectures, representative minimum, baseline, and maximum ISRU system masses were assessed for water, oxygen, and combined production architectures. The tailored conceptual system masses ranged from approximately 1.0 to 1.6 metric tons, which supported DDT&E, transportation, and operations lifecycle cost estimates.

Estimating Habitation Consumable Value: To catalyze lunar economic development, three elements are required: the presence of a resource, technology capable of recovering and processing that resource, and a customer with clearly defined needs. If lunar water and oxygen resources and supporting ISRU technologies are assumed to exist, the remaining question is whether an economically meaningful customer is present.

In this work, the intrinsic value of lunar-derived consumables is defined as the avoided lifecycle cost of supplying those consumables from Earth, expressed per kilogram delivered to the lunar surface. Estimating this value integrates demand, logistics, and cost models. Demand modeling captures the raw quantities of water and oxygen required to support the range of expected early habitation mission architectures and designs. This raw consumable demand can then be converted into delivered mass impacts and quantities of tanks, bags, and associated packaging. Resulting masses and unit quantities then inform lifecycle cost modeling, inclusive of DDT&E for logistical support hardware, transportation to the lunar surface, and associated operations costs.

Three parametric cost estimating methods were leveraged to assess the variability in DDT&E cost estimation: the Advanced Missions Cost Model (AMCM), NASA's Project Cost Estimating Capability (PCEC), and simplified industry cost factors. Median DDT&E cost estimates, typically aligning with the PCEC model results, were combined with an assumed $100k/kg lunar surface delivery cost [5] and operational wrap factors to approximate total lifecycle costs.

Dividing lifecycle costs by the underlying consumable demands yielded intrinsic value representing the effective economic value of locally produced water, oxygen, or both to an early habitation customer. This intrinsic value represents deferred logistics cost rather than profitability, providing a first-order metric that can inform more detailed economic analyses of potential ISRU business cases. Similarly, estimated lifecycle production costs for the range of pilot-scale ISRU systems were calculated for comparison.

Results: Analysis of early habitation architectures suggests an expected demand averaging 2.9 metric tons of water and 1.4 metric tons of oxygen over a 10-year lifetime. Despite the relatively modest quantity of consumables required, the logistics of transporting these materials from Earth approximately doubles the effective mass delivered to the lunar surface.

When full lifecycle resupply costs are normalized by consumable demand, intrinsic values can be estimated for water, oxygen, and a combined water and oxygen architecture. Water holds an intrinsic value of approximately $121k/kg while oxygen holds a value of approximately $297k/kg. Oxygen exhibits substantially higher intrinsic value than water due to the additional containment and packaging masses associated with the transport of compressed gas. A combined architecture holds a value of approximately $189k/kg. This combined architecture value is lower than average due to assumed differences in packaging water and oxygen and the increased learning curve effects from manufacturing larger quantities of similar packaging materials.

These intrinsic values exceed many previous ISRU economic assumptions by one to two orders of magnitude, reflecting the full logistical overhead associated with Earth-based consumable delivery based upon a low-risk adoption of ISS-derived logistical resupply norms. Normalized production costs for pilot-scale ISRU concepts average approximately $86k/kg for water-only architectures, $73k/kg for oxygen-only, and $103k/kg for a combined water and oxygen architecture, suggesting the possibility of profitable business cases at pilot-scale demand and production.

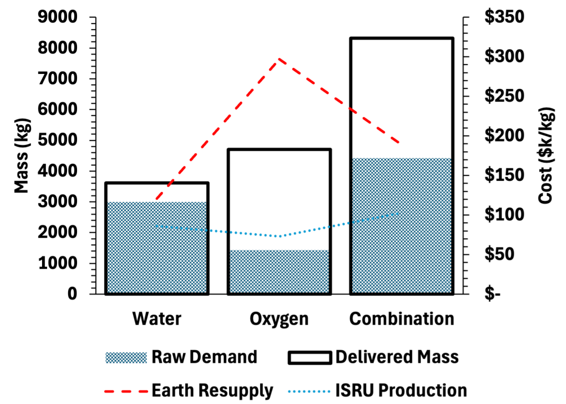

Figure 1. Comparison of early habitation demand, delivered mass (left axis), and estimated cost of Earth-based resupply vs. ISRU production (right axis).

Conclusion: The high intrinsic value of habitation consumables suggests that relatively small ISRU systems could provide meaningful economic benefit if production costs can be minimized. Estimated production costs for several pilot-scale ISRU concepts fall below the intrinsic value range identified in this analysis, with oxygen production possibly being the most lucrative.

It is expected that habitation demand emerges earlier in the Artemis exploration timeline than large-scale propellant markets. This creates a potential development pathway in which ISRU technologies may be deployed to support early habitation before expanding toward larger industrial applications.

However, this opportunity may be time limited. As lunar infrastructure matures, the economic incentive to reduce logistical overhead may also be addressed through the adoption of regenerative ECLSS architectures that reduce consumable demand. In addition, continued reductions in launch and lunar delivery costs could further shift the breakeven point between Earth-based resupply and ISRU production given the driving effects of delivery cost.

Nevertheless, consideration should be given to early habitation demand as a critical bridge market capable of accelerating ISRU technology maturation while supporting sustained human presence on the Moon and eventually beyond.

References: [1] Parodi P. et al. (2025) Overview of ASI Multi-Purpose Habitation Module Development. ICES. [2] Yamazaki C. et al. (2024) Overview of JAXA Pressurized Rover Development and ECLSS Design. ICES. [3] NASA (2025) Moon to Mars Architecture Definition Document. [4] Lynch C. et al. (2023) Logistics Rates and Assumptions for Future Human Spaceflight Missions Beyond LEO. ASCEND. [5] SpaceX. (2025) Starship. www.spacex.com/vehicles/starship