ECONOMIC EVALUATION OF LUNAR MINING PROJECTS. G. Smith-Vaniz[1,2], S.C. Stähler[2], and F. Kehl[1,2], [1]University of Zurich, Winterthurerstr. 190, Zurich, Switzerland, [2]ETH Zurich, Sonneggstr. 5, Zurich, Switzerland (gaspard.smith-vaniz@uzh.ch; simon.staehler@eaps.ethz.ch; florian.kehl@uzh.ch)

Introduction:

In anticipation of a lunar resource economy, early economic assessments are essential for identifying key variables and establishing clear viability thresholds. Evaluating economic feasibility provides an objective framework for decision-making. By defining key questions — such as the data needed, the criteria for viability, and the steps required to move forward — economic evaluation helps guide progress. Ultimately, three key thresholds must be met to achieve a sustainable lunar resource economy: informational, technological, and operational.

Economic Evaluation of Mining Projects:

Discounted Cash Flow (DCF) analysis is the standard model for assessing project viability [1]. It sums future cash flows, discounted to present value, yielding the Net Present Value (NPV), where NPV > 0 indicates viability. The NPV criterion helps differentiate between resources (total identified deposits) and reserves (those portions of resources that can be profitably extracted). A positive NPV indicates economic viability, marking the boundary between a resource and a reserve. It is given by:

$$\text{NPV} = \sum_{t=1}^{N} \frac{R_t - C_t}{(1+r)^t} - C_i \qquad (1)$$

Where $R_t = Q_t \cdot P_t$ is revenue at time t, from selling quantity Q_t at price P_t. C_t is the total operational cost, including extraction, processing, and transport: $C_t = Q_{e,t}(C_{e,t} + C_{p,t}) + C_{return,t}$. Additionally, $Q_t = F \cdot Q_{e,t}$, with F, the mass concentration of the resource in the soil, relating extracted quantity $Q_{e,t}$ from resource quantity. The annual discount rate $r = r_{base} + r_{tech} + r_{market} + r_{policy}$ adjusts future cash flows to their present value, accounting for sources of risk, including technical (r_{tech}), market demand (r_{market}), and policy (r_{policy}) over N years. A higher r reflects greater uncertainty and reduces the present value of predicted returns, making only the most robust projects viable. Finally, the initial capital investment $C_i = C_{r\&d} + C_h + C_l$ includes *research and development*, *hardware*, and *launch* costs. As such, NPV becomes:

$$\sum_{t=1}^{N} \frac{Q_{e,t}(FP_t - C_e - C_p) - C_{return,t}}{(1 + r_{base} + r_{tech} + r_{market} + r_{policy})^t} - C_i \qquad (2)$$

Thresholds:

Informational Landscape: The main source of uncertainty in lunar resource economics is the lack of detailed geological knowledge about resource deposits. While resources such as water ice and metals have been inferred through remote sensing [2], direct measurements remain sparse, and little is known about deposit concentration, form, and accessibility. Whether a resource is chemically bonded within regolith, concentrated in pure aggregates, or dispersed will determine extraction methods and, therefore, the entire cost structure. On Earth, extraction costs vary drastically depending on deposit geometry and grade [3], and similar variability should be expected on the Moon. Geological uncertainty complicates estimating key variables such as extractable quantity (Q_e), concentration (F), and costs for extraction (C_e), processing (C_p), and upfront technology development ($C_{r\&d}$, C_h).

Without clear geological data, estimates of economic viability remain speculative. Existing studies often arrive at conflicting conclusions, depending on assumptions [4] [5]. Thus, geological characterization is the most critical hurdle in assessing feasibility, as it is a necessary step from inferred resources to proven reserves (Figure 1).

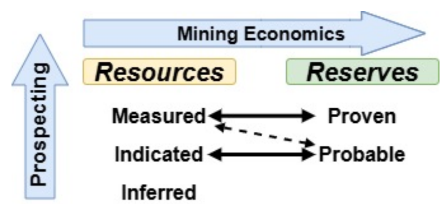

Figure 1: Resources vs Reserves.

Market demand and space policy add further layers of uncertainty. Because there is no established market for lunar materials, demand quantity (Q) and price (P) have yet to emerge beyond comparative estimates. While some demand may exist on Earth for specific lunar materials, the majority of demand — particularly for human life support and in-situ infrastructure — will be local. As primary customers and regulators, space agencies will shape the legal and economic environment, influencing perceived risks and discount rate components (r_{market}, r_{policy}).

Overall, geological uncertainty, demand, and policy shape the informational gaps which must be addressed to assess and enable a sustained lunar resource economy.

Technology and Architecture: As geological and market uncertainties fade, extraction technologies become the next critical barrier. For each target resource and its geology, systems must be engineered to achieve required quality and refinement standards. These must meet stringent capability and cost thresholds. Capability metrics — final product quality, throughput, concentration tolerance, energy efficiency, and scalability—directly impact Q_e, Q, and P. Equally vital are cost factors — C_e, C_p, and C_h — as profitability depends on generating positive resource rent, defined as $R_r = R - C$.

Operational Phase: As the technology matures, aligning with market demand and geologic certainty, mining operations can begin. This stage must meet strict thresholds to sustain a resource economy: reliability, maintainability, output matching demand, and logistics. These factors must be optimized to transition from technological achievement to a stable supply of critical resources and revenue, stabilizing Ce and C_p at sustainable levels.

Next Steps and Priorities:

Prospecting: To transition from inferred to measured resources (moving upward in Figure 1), large-scale prospecting is essential. Orbital imaging and prospecting missions have laid a basis for this, starting with Lunar Prospector in 1998 [6], which produced global maps of surface compositions. A next step needs to be large-scale geophysical prospecting of the subsurface (seismic, GPR, EM) in combination with more detailed compositional surface mapping at a resolution matching the length scale of typical resource formations. This could be done by a combination of multi-robot missions [7], long endurance rovers [8] , and very low orbit remote sensing. However, such initial prospecting would require governmental funding, akin to the effort of the USGS and other national surveys.

Policy and Transparency: A sustainable lunar resource economy requires strong and reliable government leadership to reduce uncertainty and enable private investment. Space agencies must maintain long-term procurement strategies that persist across political cycles, directly lowering r_{policy} and derisking early ventures. Equally critical is early transparency around demand: explicit disclosure of expected resource types, quantities, and price ranges will direct technological efforts and clarify market potential. Reducing ambiguity around demand lowers r_{market}, enabling mining ventures to align capabilities with needs and attract capital.

Costs: Early mining technologies will be costly due to their novelty and limited deployment. Lunar mining firms must adopt rapid, iterative development, as seen in the launch sector [9], to accelerate learning. Learning curves describe cost reduction of a process per iteration: $C_n = C_0 \cdot n^{-b}$, where C_n is the cost of the n-th iteration, C_0 the initial cost, and b the learning rate. As processes mature, extraction costs will decline until resource rent turns positive, marking the onset of profitable operations (Figure 2). In turn, increasing resource rents move the cursor from resource to reserve in Figure 1.

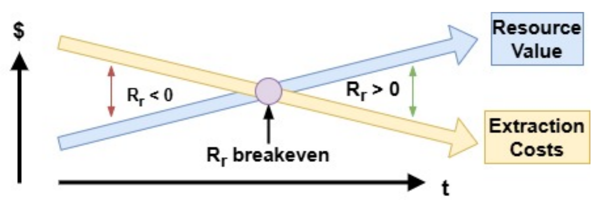

Figure 2: Resource Rent Evolution over time.

To cover initial losses, companies will continue requiring government backing and should explore auxiliary revenue avenues, such as licensing technologies and selling science or data to institutions.

Operations: Achieving a reliable operational state will require the field to engage with experienced mining engineers from the terrestrial industry early and often. Many lessons already learned on Earth's mining projects and operations can be applied to the Moon, avoiding easy pitfalls. For instance, Terry McNulty identified various mine output evolutions in the start-up phases depending on process maturity — having a large impact on economic outcomes [10]. Further, accrued knowledge provides guiding principles on optimizing systems in the stable production period, supporting consistent positive returns. Leveraging this experience and bridging the gap between space technology and longstanding mining practices will enable the industry to stabilize in conditions where positive feedback loops can be initiated. As demand increases, mining lunar resources will become viable, leading to technological developments and learning, which will decrease costs — sustaining higher demand. This will enable further prospecting — for lower investment and higher return prospects, as shown in Figure 3.

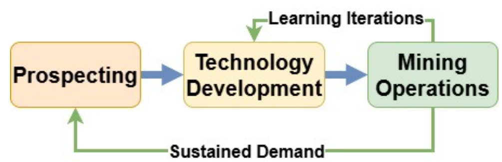

Figure 3: Key steps and feedback loops.

Conclusion:

Due to the challenging nature of lunar mining, it is reasonable to expect that early iterations will not meet the necessary thresholds. Yet, the path forward is clear. With persistence, frequent iteration, and strong leadership, profitable lunar mining can become a reality. A global effort for large-scale prospecting missions will largely improve the information landscape by shifting from inferred to measured resources. Continual improvement in lunar mining technologies is likely to decrease costs, while long-anticipated human activity on the Moon will generate demand. Together, these factors will increase resource rent, moving from resource to reserve. Reliable government policy and proactive, transparent communication can focus efforts and unlock private funding opportunities by decreasing risk. These efforts will, over time, combine to trigger virtuous cycles, leading to a self-sustaining and profitable lunar resource economy.

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