ECONOMIC MODELING OF THE COMPETITIVENESS OF LUNAR WATER OVER EARTH-LAUNCHED WATER, INCLUDING WRIGHT'S LAW, OPTIMIZATION OF RELIABILITY, AND ECONOMIES OF SCALE. P. T. Metzger[1], [1]Florida Space Institute, University of Central Florida, 12354 Research Parkway, Partnership 1 Building, Suite 214, Orlando, FL 32826, Philip.Metzger@ucf.edu.

Introduction: The question has been raised whether lunar-derived propellant can be economically competitive against Earth-launched water now that low-cost launch systems such as the SpaceX Starship are expected to come online. This discussion invariably assumes the launch systems will achieve very low cost due to economies of scale and the deep experience curve of decades of rocketry. The skepticism about lunar water's competitiveness derives from a failure to apply these same well-known economic forces to lunar industry.

It can be shown that for lunar water delivered to LEO to equal the cost of launching water from Earth,

$$L \approx \frac{\omega}{1 - G^2\phi - x}$$

where L is launch cost per kg terrestrial water, ω is operations cost per kg water extracted on the Moon, $G \approx 4$ is the gear ratio from LEO to the lunar surface, $\phi \ll 1$ is the mass ratio of lunar surface hardware per water extracted over its lifetime, and x is the routine cost of fabricating (on Earth) lunar surface hardware per kg of water it produces (over its lifetime) divided by L. For lunar water to be competitive in LEO, we expect to meet $G^2\phi \ll 1$, $x \ll 1$, and thus $\omega < L$. All three seem achievable as lunar industry matures over time.

Optimization of Reliability: NASA costing models based on prior missions have a built-in premium for high reliability, since government-led space agency missions reflect on the nation with geopolitical significance and failures cannot be tolerated. Commercial efforts can be tolerant of hardware failures since profit rather than national reputation is the primary focus. Data show that higher reliability of systems incurs exponentially larger cost. Mettas [64] provided a cost-reliability model based on real-world data,

$$c_{\mathrm{R}} = \exp\left[(1-f)\,\frac{R - R_{\min}}{R_{\max} - R}\right]$$

where c_{R} is the reliability cost factor, $R_{\min}$ is the baseline reliability, R is system reliability achievable with higher quality components and design resilience plus more testing, $R_{\max} \cong 100\%$ is the maximum achievable reliability, and f is a parameter between 0 and 1 that estimates the difficulty of improving the reliability. For example, Stancliff, et al. [2] used $f = 0.95$ for lunar rovers. When L is reduced, it is less expensive to launch a less-reliable system despite the increased cost launching a larger mass in spare hardware. Optimization drives $R =$ ~85% to ~50% as L drops, resulting in two orders of magnitude reduction in hardware fabrication cost.

Experience Curve/Wright's Law: Industry data show that industries generally increase efficiency and reduce cost by more than two orders of magnitude through production experience. This has been quantified several ways, including Wright's Law,

$$c_{\mathrm{WL}} = \left(\frac{\int_0^t P(t)\mathrm{d}t}{S(0)}\right)^{\mathrm{Log}_2(b)}$$

where $c_{\mathrm{WL}} < 1$ is the cost factor due to Wright's Law, $P(t)$ is the production rate, $S(0)$ is the total production up to the point of the baseline cost, and b is a parameter usually between 0.75 and 0.9 per industry data.

Economies of Scale: Industry data shows that a larger scale for an operation can also achieve lower cost due to geometric and other scaling efficiencies. The empirical data have been fitted by

$$c_{\mathrm{EoS}} = \left(\frac{X}{X_0}\right)^{a-1}$$

where c_{EoS} is the cost factor per unit production due to economies of scale, X is production capacity of an operation, X_0 is baseline production capacity corresponding to baseline cost, and a is a parameter with an average measured value of ~0.65 across industries [3].

Starship Expected Cost Reduction: Skeptics of lunar water say that Starship will drop costs from the current \$2000/kg to LEO to \$20/kg making lunar water non-competitive. They base this on a launch rate of perhaps 365 launches per year 30 years from now, the high rate representing the serious settlement of Mars. Using the nominal $a = 0.65$ for economies of scale, this cost reduction also implies a learning curve with $b = 0.92$. These parameters are the improvement rates that lunar industry must beat to outcompete Earth-launched water.

Modeled Futures of Lunar Water: Using these same parameters for lunar water plus the cost of reliability optimization (which does not apply to launch costs, since the launch industry is driven to high reliability), and (for now) using the intial cost estimates of the Aqua Factorem lunar water extraction system [4], the cost of lunar water and terrestrial water are plotted below. High specific impulse electric thrust H_2O propulsion is used to transport water from LLO to LEO, but high thrust chemical propulsion is used to/from either planetary surface. The heavy dashed line represents the boundary between where terrestrial water (to the left) or lunar water (to the right) is less expensive. The colors represent cost per kg for whichever source is cheaper.

This shows lunar water is perpetually cheaper no matter how low the launch cost goes, except in LEO where terrestrial water is cheaper. Thus, lowering launch costs cannot drive lunar resources out of business. While terrestrial water is cheaper in LEO, comparative advantage probably still gives that part of the business to lunar water since the cost differential is only 5%.

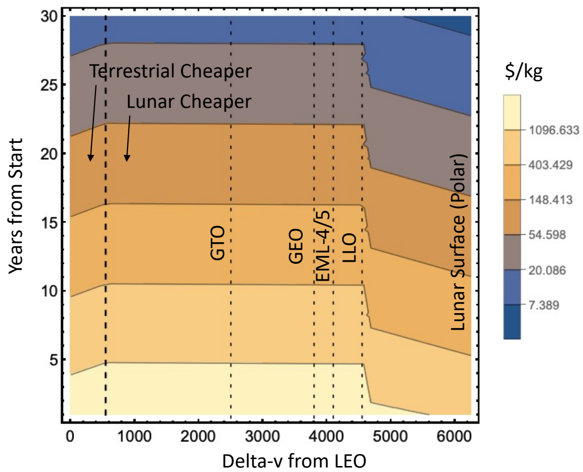

Fig. 1. Nominal Case

In the following case, the learning curve exponent for lunar water is changed to $b = 0.8$, which represents faster learning since lunar mining is less mature than rocketry and thus has more room to improve, and because 0.8 is in the mid-range measured for industry. The result is shown below. By year 2, lunar water is now less expensive even in LEO and throughout cislunar space.

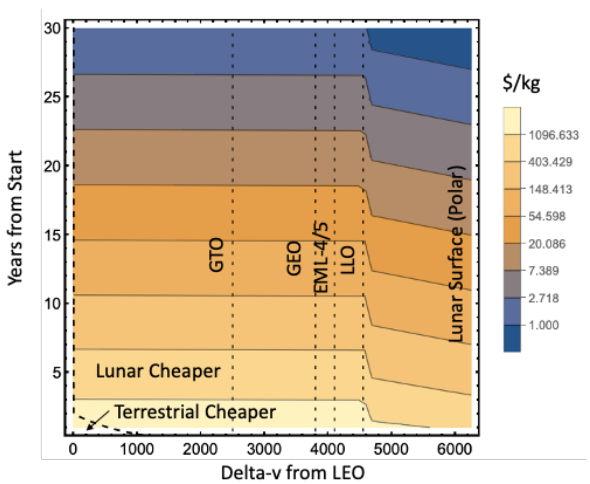

Fig. 2. Industry-Nominal Learning Curve for Lunar

The next case asks the question, what if costs were underestimated for lunar water due to bias of the space resources community? This case multiplies the mass of lunar water extraction systems by a factor of five (increasing the transportation cost of the hardware to the Moon) and the operational costs by a factor of five from what [4] estimated. Initially, terrestrial water out-competes lunar water all the way to LLO, but it takes only 8 years of experience before lunar water outcompetes terrestrial water throughout cislunar space including LEO.

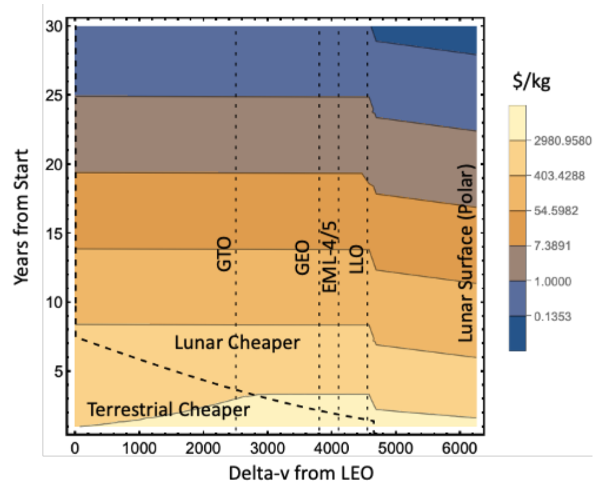

Fig. 3. Conservatively Imposing 5x Cost for Lunar

Figure 4 shows the fractional difference in cost for lunar vs. terrestrial water in this conservative case. By year 10 lunar is 11% cheaper in LEO. By year 15 it is 30% cheaper. The lunar advantage grows perpetually.

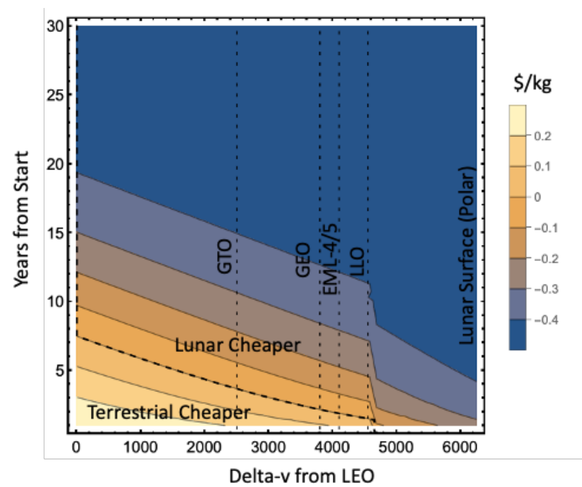

Fig. 4. Cost Differential

The presentation will discuss additional factors such as economies of scope and will use the costs derived by additional lunar water studies as inputs to this model.

References: [1] Mettas A. (2000) Int. Symp. on Product Quality and Integrity, 216–221. [2] Stancliff S., Dolan J., Trebi-Ollennu A.. (2007) Workshop on Performance Metrics for Intelligent Systems, 204–208. [3] Haldi J. and Whitcomb D. (1967) *J. Polit. Econ.* 75(1), 373–385. [4] Metzger P. et al. (2021) NASA NIAC grant 80NSSC 20K1022, final report.