A Comparison of Previously Published Papers on the Economics of Lunar *In Situ* Resource Utilization (ISRU)

Robert Shishko, Ph.D.

Jet Propulsion Laboratory, California Institute of Technology

Introduction

Space Policy Directive-1, issued in December 2017, refocused NASA's immediate attention on returning humans to the lunar surface, and on furthering a cislunar space economy. Moreover, federal R&D budget guidance for FY21, issued in August 2019, states that NASA "should prioritize *in situ* resource utilization on the Moon and Mars." Lunar water to be processed into propellant is widely recognized as the most significant lunar resource for expanding human presence and building a sustainable space economy. Its extraction is regarded as a key ISRU technology. Nevertheless, does mining water on the Moon make sense from an economics point-of-view? While there have been studies of lunar water ISRU economics over the past dozen years, there is little consistency in assumptions[1] regarding technical, operational, financial, and cost parameters to be used, and as a result, these studies reach different, often contradictory, conclusions. It seems worthwhile, then, to examine several recent studies, and identify what their results were, and what assumptions and parameter values lead to those results.

Basis of Comparison

Table 1 shows attributes one might expect to find in a study of the commercial potential of mining lunar water. These attributes form the basis of analyses of supply and demand. Basic questions to be address in an analysis might include (a) where is the demand for propellant and in what quantity, and (b) at what price. On the supply side, key questions might include (a) what is the cost to produce propellant on the Moon, and (b) is it competitive with delivery from Earth.

For each study considered in this white paper, I attempted to find the value (or narrative) imparted to each attribute. Unfortunately, many studies did not provide any discussion of some of these attributes, much less specify a quantitative value. This, of course, does not reflect on the completeness of these studies, but reflects only what I was able to determine from them.[2] Some of the quantitative attributes in Table 1 can have a significant effect on the conclusions put forth in a particular study. Recognizing this, I indicate which attributes in each study, if any, were subjected to a sensitivity analysis.

I selected the studies to be compared in this white paper because they quantitatively dealt with the economics of lunar water/ice mining. As such, studies that just described a particular ISRU technology, or just made a market forecast were not selected. A secondary consideration in selecting studies was how recently they were published. Studies published before 2007 were not

[1] Common to all the studies considered in this paper was the general location of mining activities—the Permanently Shadowed Regions (PSRs) at the Lunar South Pole (LSP).

[2] Any errors in my interpretations of the attributes or in my summaries are entirely my own.

selected. To maintain comparability when presenting costs from studies published in different years, I adjusted them from the stated FY dollars to FY19 dollars using the NASA New Start Index.

Table 1: Attributes for Comparison

Attribute Group	Attribute
Financial/Cost	
	Measure of Economic Performance
	Discount Rate (percent/year)
	Time Horizon (years)
	Equipment Development Cost ($)
	Equipment Production Cost ($)
	ISRU Equipment Transport Cost to Lunar Surface ($/kg)
	Other Equipment Delivery Cost ($/flight)
	Propellant Transport Cost to Propellant Delivery Location ($/kg)
	Propellant Price at Delivery Location ($/kg)
	Management/Operational Supervision Costs ($/year)
	Spares Cost ($/year)
Operational/Technical	
	Mining Location
	Regolith Density (kg/m^3)
	Regolith Percent Water by Weight
	Mining Technology
	Processing Location Following Extraction
	Propellant Delivery Location(s)
	Propellant Delivery Ops Concept
	Nominal Propellant Transporter Capacity (kg)
	Δv to Propellant Delivery Location (m/s)
	Inert Mass Fraction for Propellant Transporters
	I_{sp} for Propellant Transporters (s)
	Mine Aggregate Equipment Mass (kg)
	Mine Water Output (kg/year)
	Propellant / Water Ratio
	Propellant Demand (kg/year)
	Water Demand (kg/year)
	O_2 Demand (kg/year)
	Maintenance and Repair Concept
	Spares Demand (kg/year)
	Transfer Losses/Boiloff (%)
	Launch Vehicle Payload From Earth (kg)
	Power Source for ISRU Processing
	Power System Size (kW)

Because different measures of economic performance may have been used in the various studies, I needed to distinguish what was an input to the analysis and what was an output. For example, propellant sales prices at various cislunar locations were outputs in the first study below, but in other studies, propellant sales prices may have been an assumed input in calculating revenues and Net Present Value (NPV). Thus in the tables below, outputs are shaded to emphasize the distinction.

Synopsis of Charania and DePasquale (2007)

This study analyzed three delivery locations (lunar surface, LLO, and GEO), with some scenario variations within each. The analysis developed sizing relationships for ISRU equipment and reusable propellant transporters. The output of the analysis was a set of prices for propellant (LOX/LH_2) at each delivery location that would enable a commercial firm to breakeven, taking into account all capital and operations costs and their respective timing.

Figure 1: A Lunar ISRU Plant Concept

Customers included government and commercial buyers, with demand largely determined by the tempo of human lunar missions, and by the reboost needs of commercial satellite operators in GEO. Development and acquisition costs, a source of major uncertainty in the analysis, were based on the sizing analysis results, combined with cost estimating relationships (CERs) and analogy techniques. The study further assumed the purchase of delivery services to LLO from the government using Constellation-era launch vehicles, just the reverse of the current trend of the government purchasing delivery services from commercial providers.

The effect of uncertainty in the costs on the breakeven prices was systematically investigated using Monte Carlo simulation. The resulting probability distributions were skewed as expected, with means higher than the deterministic results reported below.

Table 2: Attributes for Charania and DePasquale (2007)

Study: Charania, A.C., DePasquale, D., "Economic Analysis of a Lunar ISRU Propellant Services Market," IAC Paper 07-A5.1.03, 2007		
Attribute	**Attribute Value**	**Basis for Value**
Measure of Economic Performance	Propellant prices, $\vec{p}$, that resulted in a breakeven Net Present Value = 0—that is, find $\vec{p}$ such that NPV(ρ, T, $\vec{p}$) = 0.	The resulting propellant prices, i.e., prices for propellant delivery at various cislunar nodes, can then be compared to alternatives such as delivery from Earth.
Discount Rate (percent/year)	21.7%	Cash flows were discounted at a baseline rate, ρ, representing a Weighted Average Cost of Capital (WACC). The baseline WACC (21.7%) was based on a debt-to-

		equity ratio of 3, an equity beta of comparable industries, a tax rate of 30%, a nominal interest rate of 7.5%, inflation of 2.1% and a risk-free interest rate of 4%. A sensitivity analysis was run with WACC from 10% to 30%
Time Horizon (years)	18	Eight years from start of development to Initial Operational Capability (IOC), then 10 years of revenue-generating operations
Equipment Development Cost ($)	*ISRU Equipment:* $957 ($FY06M) $1,258 ($FY19M) *Reusable Lunar Tanker Vehicle (LTV):* $1,200 ($FY06M) $1,578 ($FY19M) *Reusable Orbiter Tanker Vehicle (OTV):* $400 ($FY06M) $526 ($FY19M)	Cost uncertainty was applied -25% to +75%. At lowest estimate for ISRU equipment: $45K/kg ($FY19) At baseline estimate for ISRU equipment: $60K/kg ($FY19) At highest estimate for ISRU equipment: $105K/kg ($FY19) Cost uncertainty was applied -25% to +75%. Cost uncertainty was applied -25% to +75%.
Equipment Production Cost ($)	*ISRU Equipment:* $319 ($FY06M) $419 ($FY19M) *Reusable Lunar Tanker Vehicle (LTV):* $700 ($FY06M) $920 ($FY19M) *Reusable Orbiter Tanker Vehicle (OTV):* $25 ($FY06M)	Cost uncertainty was applied -25% to +75%. At lowest estimate for ISRU equipment: $15K/kg ($FY19) At baseline estimate for ISRU equipment: $20K/kg ($FY19) At highest estimate for ISRU equipment: $35K/kg ($FY19) Cost uncertainty was applied -25% to +75%. Cost uncertainty was applied -25% to +75%.

	$33 ($FY19M)	
ISRU Equipment Transport Cost to Lunar Surface ($/kg)	$68.8 ($FY06K) $90.5 ($FY19K)	Costs estimated for the *Constellation Program's* Heavy Lift Launch Vehicle (HLLV), Earth Departure Stage (EDS), and Lunar Surface Access Module (LSAM). Each cargo-variant LSAM is assumed capable of delivering 21mt of cargo to the lunar surface. Cost uncertainty was applied -10% to +25%. At lowest estimate for ISRU equipment: $81.4K/kg ($FY19) At highest estimate for ISRU equipment: $113K/kg ($FY19)
Other Equipment Delivery Cost ($/flight)	*Reusable Lunar Tanker Vehicle (LTV) to the Lunar Surface:* $775 ($FY06M) $1,019 ($FY19M)	Costs estimated for the *Constellation Program's* Heavy Lift Launch Vehicle (HLLV) and Earth Departure Stage (EDS). Cost uncertainty was applied -10% to +25%. At lowest estimate: $917 ($FY19M) At highest estimate: $1,274 ($FY19M)
Propellant Transport Cost to Propellant Delivery Location ($/kg)	-	
Propellant Price at Delivery Location ($/kg)	*Lunar Surface:* $26.8 ($FY06K) $35.3 ($FY19K) *Low Lunar Orbit (LLO):* $133.9 ($FY06K) $176.1 ($FY19K) *GEO:* $7,053.3 ($FY06K) $9,273.7 ($FY19K)	Propellant prices are for scenarios in which the excess O_2 is not sold. When the excess O_2 can be sold on the lunar surface, propellant prices fall by about 5%. These propellant prices include the full cost of financing and the financial return on company equity.
Management/Operational Supervision Costs ($/year)	$35 ($FY06M) $46 ($FY19M)	Cost uncertainty was applied -10% to +50%. At lowest estimate: $41.4 ($FY19M) At highest estimate: $57.5 ($FY19M)
Spares Cost ($/year)	-	
Mining Location	Lunar South Pole PSR	

Regolith Density (kg/m^3)	-	
Regolith Percent Water by Weight (%)	1.0	
Mining Technology	Bucket wheel excavators, water separation by heating	
Processing Location Following Extraction	Crater rim	
Propellant Delivery Location(s)	Three Scenarios: Lunar Surface, LLO, GEO	
Propellant Delivery Ops Concept	Round-trip for reusable LTV from lunar surface to LLO; Round-trip for reusable OTV from LLO to GEO	No information on how many round trips can be performed by each
Nominal Propellant Transporter Capacity (kg)	22,000 (LTV) 450 (OTV)	
Δv to Propellant Delivery Location (m/s)	*Lunar Surface-to-LLO:* 1,860 *LLO-to-GEO:* 2,050	
Inert Mass Fraction for Propellant Transporters	0.185 (LTV)	Inferred by calculation
I_{sp} for Propellant Transporter (s)	450	LOX/LH_2 propellant
Mine Aggregate Equipment Mass (kg)	20,940	Mass constrained to fit on cargo-variant LSAM
Mine Water Output (kg/year)	69,100	Based on 20 kg/hour operating continuously over 12 days/month
Propellant / Water Ratio	0.6875	Oxygen/Fuel mixture ratio of 5.5:1
Propellant Demand (kg/year)	*Lunar Surface:* 49,400 *LLO:* 21,000	Equal to the total output of ISRU propellant on the lunar surface. Sufficient to refuel two crewed LSAM descent stages per year. 25,100 kg of lunar ISRU propellant are used to deliver the LLO demand.
Water Demand (kg/year)	-	
O_2 Demand (kg/year)	-	
Maintenance and Repair Concept	-	
Spares Demand (kg/year)	-	
Transfer Losses/Boiloff (%)	*OTV:* 0.75%/day for LH2 0.25%/day for LOX	For up to 10 days

Launch Vehicle Payload From Earth (kg)	-	
Power Source for ISRU Processing	Primarily nuclear with some solar	
Power System Size (kW)	-	
The Bottom Line: Of the scenarios presented in this study, only the one in which delivery is taken on the lunar surface represents a potential market. The estimated breakeven price of a kilogram of propellant delivered on the lunar surface comes out to be about the same as the oft-quoted cost to launch a kilogram to LEO using the Space Shuttle (both in $FY19). Due to the capital costs of the propellant transporter vehicles and the significant propellant consumed in the process of delivering propellant from the lunar surface, the required market prices in LLO and GEO appear to preclude lunar ISRU economic viability.		

Synopsis of Kornuta, et al. (2018)

The business case analysis in the Kornuta, et al. collaborative study used a straightforward parametric model to determine the Net Present Value (NPV) for each of seven scenarios involving a stationary annual customer demand for propellant at various cislunar locations. In Scenarios 1, the demand comes from customers operating a reusable lunar cycler that shuttles crew and cargo between a lunar orbital platform and the lunar surface. In Scenario 2, the demand comes from customers seeking propellant at EML1 in support of human missions to Mars. In Scenario 3, the demand stems from customers seeking to refuel launch vehicle second stages in LEO to enable larger payloads to be delivered to GEO and beyond. Scenarios 4 through 7 represent different combinations of these customers. The total demand ranges from 100 mt/year in Scenario 1 to 1640 mt/year in Scenario 7.

The NPV was calculated in each scenario as the discounted year-over-year sum of revenues minus costs. Revenues were determined using sales prices that each customer would be willing to pay for propellant delivered on the lunar surface, taking into account the cost (driven by the underlying Δv) that the customer must also pay to deliver the propellant to the designated operational location. The willingness-to-pay price is also determined by cost competition with the alternative of having propellant delivered to that operational location from Earth. Consequently, propellant destined for operational use in LEO where it is worth $3,000 per kg has a sales price of approximately $500 per kg on the lunar surface.

Figure 2: A Lunar Thermal Mining Concept (Source: George Sowers)

A distinctive feature of the parametric model is the lack of a scaling of mine size with the total demand. Since the cost per kg of ISRU hardware development, production, and deployment to the lunar surface is also fixed, this implies a fixed total investment cost for all scenarios, despite the significant differences in the quantity of water to be mined across the scenarios.

The effects on the NPV of the average sales price and of the demand quantity on the lunar surface were systematically investigated. The structure of the parametric model allowed for further sensitivity analyses of the NPV with respect to ISRU hardware cost, ISRU aggregate equipment mass (mine size), cost of delivery to the lunar surface, annual operating costs, the discount rate, and years of operations.

Table 3: Attributes for Kornuta, et al. (2018)

Study: Kornuta, D., et al., "Commercial Lunar Propellant Architecture: A Collaborative Study of Lunar Propellant Production," Colorado School of Mines (CSM)/United Launch Alliance (ULA), 2018, pp. 99-110		
Attribute	**Attribute Value**	**Basis for Value**
Measure of Economic Performance	Net Present Value (NPV) *Scenario 1:* -$234 ($FY18M) -$241 ($FY19M) *Scenario 2:* $1,609 ($FY18M) $1,657 ($FY19M) *Scenario 3:* -$972 ($FY18M) -$1,001 ($FY19M) *Scenario 4:* $3,639 ($FY18M) $3,748 ($FY19M) *Scenario 5:* $5,481 ($FY18M) $5,645 ($FY19M) *Scenario 6:* $6,218 ($FY18M) $6,405 ($FY19M) *Scenario 7:* $10,092 ($FY18M) $10,395 ($FY19M)	Uses Excel's PV function less initial investment.
Discount Rate (percent/year)	10%	
Time Horizon (years)	10	Unspecified number years from start of development to IOC, then 10 years of operations
Equipment Development Cost ($)	$3,000 ($FY18M) $3,090 ($FY19M)	Based on $100,000 ($FY18) per kg of aggregate mine mass of 30,000 kg. Same for all scenarios.
Equipment Production Cost ($)	-	Included in development cost.

ISRU Equipment Transport Cost to Lunar Surface ($/kg)	$35,000 ($FY18) $36,050 ($FY19)	
Other Equipment Delivery Cost ($/flight)	-	
Propellant Transport Cost to Propellant Delivery Location ($/kg)	-	
Propellant Price at Delivery Location ($/kg)	Average sale price on the Lunar Surface (LS) *Scenario 1:* $7,500 ($FY18) $7,725 ($FY19) *Scenario 2:* $3,750 ($FY18) $3,862 ($FY19) *Scenario 3:* $500 ($FY18) $515 ($FY19) *Scenario 4:* $1,015 ($FY18) $1,045 ($FY19) *Scenario 5:* $1,091 ($FY18) $1,124 ($FY19) *Scenario 6:* $4,737 ($FY18) $4,879 ($FY19) *Scenario 7:* $1,482 ($FY18) $1,526 ($FY19)	The average sale price for each scenario was calculated as the weighted (by the quantity demanded) average of the sales price each customer would be willing to pay on the lunar surface.
Management/Operational Supervision Costs ($/year)	$20 ($FY18M) $20.6 ($FY19M)	Same for all scenarios
Spares Cost ($/year)	$109 ($FY18M) $112 ($FY19M)	Based on $100,000 per kg ($FY18) plus $35,000 per kg ($FY18) for delivery to the LS
Mining Location	Lunar South Pole PSR	
Regolith Density (kg/m^3)	-	
Regolith Percent Water by Weight (%)	-	
Mining Technology	-	
Processing Location Following Extraction	-	
Propellant Delivery Location(s)	*Scenario 1:* LS only *Scenario 2:* EML1 only *Scenario 3:* LEO only	Customer operational locations

	Scenario 4: LS + LEO *Scenario 5:* EML1 + LEO *Scenario 6:* LS + EML1 *Scenario 7:* LS + EML1 + LEO	
Propellant Delivery Ops Concept	-	
Nominal Propellant Transporter Capacity (kg)	-	
Δv to Propellant Delivery Location (m/s)	*Lunar Surface-to-EML1:* 2,520 *EML1-to-LEO:* 3,770	Typical Δv assumptions; no aero-braking when returning to LEO
Inert Mass Fraction for Propellant Transporters	-	
I_{sp} for Propellant Transporter (s)	450	LOX/LH_2 propellant
Mine Aggregate Equipment Mass (kg)	30,000	Same for all scenarios
Mine Water Output (kg/year)	Mine water output is propellant demand divided by the propellant-to-water ratio below	Inferred by calculation. For example in Scenario 7, mine water output needs to be 2,450,000 kg/year
Propellant / Water Ratio	0.669	
Propellant Demand (kg/year)	*Scenario 1:* 100,000 *Scenario 2:* 280,000 *Scenario 3:* 1,260,000 *Scenario 4:* 1,360,000 *Scenario 5:* 1,540,000 *Scenario 6:* 380,000 *Scenario 7:* 1,640,000	
Water Demand (kg/year)	-	
O_2 Demand (kg/year)	-	
Maintenance and Repair Concept	-	
Spares Demand (kg/year)	800	
Transfer Losses/Boiloff (%)	-	
Launch Vehicle Payload From Earth (kg)	-	
Power Source for ISRU Processing	-	
Power System Size (kW)	-	
The Bottom Line: Some results from this study seem counter-intuitive. Scenario 1 (operational use on the LS) has a negative NPV, while Scenario 2 (operational use at EML1) has a modest, but positive NPV (roughly $1.6 ($FY18B)). Combined in Scenario 6, the NPV is substantially		

positive, almost four times that of Scenario 2. When LEO demand is added, the NPV grows by another 50%, even though Scenario 3 (operational use in LEO) alone resulted in a $1.0 ($FY18B) loss. Some of this can be explained by the lack of scaling of the initial investment cost and annual operational costs with total demand (i.e., the long-run and short-run marginal costs of production are zero), and some by the model's assignment of sales prices for each customer.

Synopsis of Jones, et al. (2019)

This study examined the question: on the basis of costs, how does propellant delivered from Earth to an aggregation point in cislunar space compare to ISRU propellant delivered to the same point from the Moon? Six alternative architectures were modeled. In Architectures 1 and 2, the required propellant is delivered to the cislunar aggregation point from Earth, using the SLS and commercial heavy lift launch vehicles, respectively. In Architecture 3, ISRU propellant is delivered from the lunar surface to the cislunar aggregation point using a single reusable propellant transport vehicle; in Architecture 4, ISRU propellant is delivered using two reusable propellant transporter vehicles. One transporter ferries between the lunar surface and LLO, while another ferries between LLO and the cislunar aggregation point. (See Figure 2.) Architectures 5 and 6 are variants in which a "bootstrapping" approach is used to incrementally deliver ISRU equipment to the lunar surface by consuming early lunar-produced propellant.

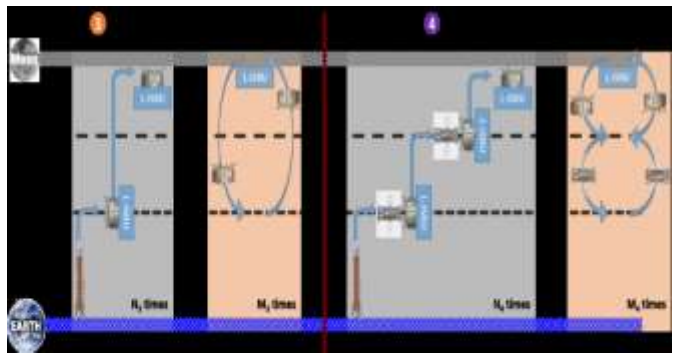

Figure 3: Concepts of Operations for Architectures 3 and 4

Demand for LOX/LH$_2$ propellant was based entirely on supporting the human Mars missions in NASA's Evolvable Mars Campaign. This resulting baseline demand rate was 59 mt/year for 14 years for all architectures. Given the dearth of sizing data to inform parametric sizing of ISRU equipment for lunar ice mining and processing, this study used parametric sizing relationships previously developed by Schreiner [4] for molten regolith electrolysis systems.

Development and production costs for the Earth-launched propellant tanks were estimated using a well-known commercial tool, while the costs for the reusable lunar lander and reusable in-space propellant transport vehicle were estimated using a NASA parametric cost estimating model. Commercial launch costs were based on the Launch Services Provider Catalog, while SLS launch costs were "a rough order of magnitude estimate." After sizing lunar ISRU equipment, their costs were estimated by analogy methods applied to Constellation Program systems. In general, costs estimates were not reported in the study.

The effects of uncertainty in some parameters on the cost per kg of delivered propellant were quantified using sensitivity analyses. The study examined a full range of values for the reusable lunar lander inert mass fraction (IMF), the nuclear power plant specific mass (kg/kW), the lunar ISRU processing plant specific mass ((kg of plant mass)/(kg/year of propellant produced)) and specific power (kW/kg of plant mass), and lastly, the number of years of operations.

Table 4: Attributes for Jones, et al. (2019)

Study: Jones, C., et al., "Cost Breakeven Analysis of Cis-lunar ISRU for Propellant," AIAA-2019-1372, SciTech Forum 2019		
Attribute	**Attribute Value**	**Basis for Value**
Measure of Economic Performance	For each architecture, the cost per kg of delivering propellant to a cislunar aggregation point	Comparison of lunar ISRU with delivery from Earth
Discount Rate (percent/year)	0%	Discounting of capital investments not implemented
Time Horizon (years)	14	Unspecified number years from start of development to IOC, then 14 years of operations
Equipment Development Cost ($)	-	
Equipment Production Cost ($)	-	
ISRU Equipment Transport Cost to Lunar Surface ($/kg)	-	SLS Block 2 or commercial HLLV delivery ISRU and power systems to cislunar aggregation point. Reusable Lunar Lander (RLL) then completes the delivery.
Other Equipment Delivery Cost ($/flight)	*SLS Block 2 (when delivering a filled zero-boil-off cryogenic tank):* $1,357 ($FY18M) $1,398 ($FY19M) *Commercial HLLV (when delivering a filled zero-boil-off cryogenic tank):* $590 ($FY18M) $608 ($FY19M)	Inferred by calculation. SLS fixed costs per year were assumed to be paid by the "ongoing human exploration campaign," so these values are intended to represent the marginal cost of a flight. Inferred by calculation based on four launches per year
Propellant Transport Cost to Propellant Delivery Location ($/kg)	-	
Propellant Price at Delivery Location ($/kg)	Arch 1: $46 ($FY18K) $47.4 ($FY19K) Arch 2: $40 ($FY18K) $41.2 ($FY19K) Arch 3: $101 ($FY18K) $104.0 ($FY19K)	

	Arch 4: \$80 (\$FY18K) \$82.4 (\$FY19K) Arch 5: \$78 (\$FY18K) \$80.3 (\$FY19K) Arch 6: \$202 (\$FY18K) \$208.1 (\$FY19K)	
Management/Operational Supervision Costs (\$/year)	\$0	
Spares Cost (\$/year)	\$0	Only the cost of launching the annual spares mass was included.
Mining Location	Lunar South Pole PSR	
Regolith Density (kg/m^3)	-	
Regolith Percent Water by Weight (%)	-	
Mining Technology	Ice Mining	
Processing Location Following Extraction	-	
Propellant Delivery Location(s)	Cislunar aggregation point consistent with being Earth-Moon Lagrange 1 (EML1)	
Propellant Delivery Ops Concept	*Architecture 1:* Delivery from Earth using SLS *Architecture 2:* Delivery from Earth using commercial HLLVs *Architecture 3:* Delivery by an RLL from lunar surface direct to cislunar aggregation point after all ISRU hardware has been deployed *Architecture 4:* Delivery by an RLL from lunar surface to LLO and then by a reusable in-space stage to a cislunar aggregation point after all ISRU hardware has been deployed *Architectures 5 and 6:* Same as Architectures 3 and 4 except ISRU hardware deployed in a "bootstrapping" approach	No information on how many round trips can be performed by each reusable vehicle was provided.

Nominal Propellant Transporter Capacity (kg)	*Reusable Lunar Lander:* 33,300 *In-Space Stage:* 39,150	Inferred by calculation based on maximum gross vehicle mass of 45,000 kg and the respective inert mass fraction
Δv to Propellant Delivery Location (m/s)	*Lunar Surface-to-LLO:* 1,870 *LLO-to-Cislunar Aggregation Point:* 640	Typical Δv assumption for lunar surface to LLO; 640 m/s Δv from LLO to the cislunar aggregation point is consistent with the latter being EML1
Inert Mass Fraction for Propellant Transporters	*Reusable Lunar Lander:* 0.26 *Reusable In-Space Stage:* 0.13	Assessed from the *Altair* lunar lander concept Assessed from the *Delta Cryogenic Second Stage*
I_{sp} for Propellant Transporter (s)	450	LOX/LH_2 propellant
Mine Aggregate Equipment Mass (kg)	*Architectures 1 and 2:* 0 *Architectures 3 through 6:* Varies by architecture	*Excavator:* Based on 10 kg/(mt/year of propellant produced). See Ref. [4, 5] *ISRU Plant:* Based on 109 kg/(mt/year of propellant produced). See Ref. [4, 5] *Power System:* Based on 75 kg/kW. See Ref. [6].
Mine Water Output (kg/year)	-	
Propellant / Water Ratio	-	
Propellant Demand (kg/year)	59,000	Based on supporting NASA's Evolvable Mars Campaign
Water Demand (kg/year)	-	
O_2 Demand (kg/year)	-	
Maintenance and Repair Concept	-	
Spares Demand (kg/year)	*Architectures 1 and 2:* 0 *Architectures 3 through 6:* Varies by architecture	Based on 10% of ISRU system mass per year
Transfer Losses/Boiloff (%)	0%	
Launch Vehicle Payload From Earth (kg)	*SLS Block 2:* 45,000 *Commercial HLLV:* 15,000	To cislunar aggregation point
Power Source for ISRU Processing	Nuclear	
Power System Size (kW)	*Architectures 1 and 2:* 0	

	Architectures 3 through 6: Varies by architecture	Based on 48 kW/mt of ISRU system mass. See Ref. [4, 5].
The Bottom Line: Using baseline assumptions and parameter values, this study concluded that lunar ISRU propellant delivered to a cislunar aggregation point like EML1 costs almost twice as much as delivering it from Earth using commercial HLLVs; and even with assumptions and parameters favorable to lunar ISRU, this was not likely to change in the near-term. Further, to breakeven with Earth delivery, it would take 35 years of human Mars operations, significantly above the 14-year baseline assumption. Except for Architecture 2, which uses commercial HLLVs exclusively, the flight rate for the SLS would range from 1.5 to over 3.5 flights/year, just to support propellant deliveries. As in the Charania and DePasquale study, lunar ISRU is handicapped from the cost perspective by the need to develop reusable propellant transporter vehicles and the significant propellant consumed in the process of delivering propellant from the lunar surface.		

Synopsis of Pelech, Roesler, and Saydam (2019)

This study introduced a non-financial, mass-based metric, called the Cumulative Propellant Payback Ratio (PPR). This metric gradually grows over the life of the mine as ISRU equipment is delivered to the mining site and propellant is returned to the cislunar delivery location. A final cumulative value greater than one signifies that a mining project can yield more than launching water directly from Earth. Pelech, et al, applied the Cumulative PPR metric to both asteroid and lunar ice mining, but this white paper deals only with the latter.

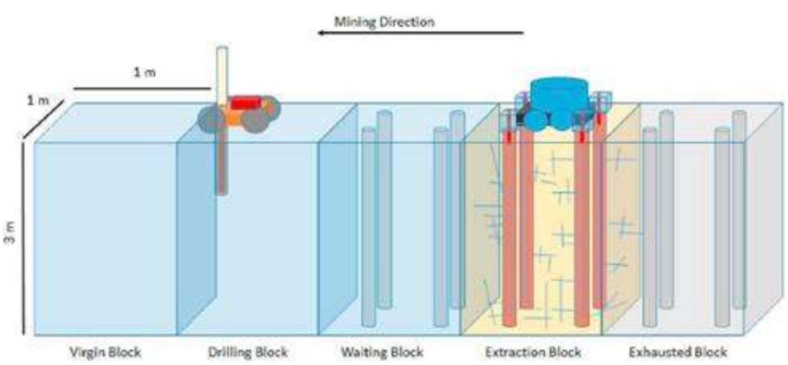

Figure 4: A Lunar Sublimation Concept Using Robotic Drills and Miners (Source: Ref. [8])

The study's primary delivery location was in LEO, where customers would receive water, not cryogenic propellants (LOX/LH_2). Demand was assumed to arise from Mars missions, circumlunar tourism, satellite servicing missions, and stationkeeping requirements for space stations or hotels. Each of these single events was assigned a quantity of water. A postulated number-of-events profile combined with the single event quantities generated the total demand over time. This, in effect, sized the quantity of lunar ISRU water to be produced over time.

With the above as an input, the study used detailed mining industry sizing equations to determine the mass, power, capacity, and quantity requirements of each ISRU equipment type. ISRU equipment cost was assumed negligible in relation to its launch costs to the lunar surface. To quantify ISRU equipment launch costs in this way, an "exchange rate" of 7.6 was used—that is, for each kg of mass delivered to the lunar surface, 7.6 kg of propellant could have delivered to LEO. This exchange rate was based on the payload capabilities of the Falcon-9H to both locations.

To determine its effect on the Cumulative PPR for a proposed lunar bucket-wheel strip mining technology ("Technology 1"), sensitivity analyses were performed varying the regolith percent water by weight from 0.5% to 15%, and the market demand by ± 90% of the baseline demand. Excursions of the model were also run to analyze the effect of a change in the delivery location from LEO to GEO, and of a change in the I_{sp} of the transportation system.

Table 5: Attributes for Pelech, Roesler, and Saydam (2019)

Study: Pelech, T., Roesler, G., Saydam, S., "Technical Evaluation of Off-Earth Ice Mining Scenarios Through an Opportunity Cost Approach,"*Acta Astronautica* 162 (2019) 388-404		
Attribute	**Attribute Value**	**Basis for Value**
Measure of Economic Performance	Cumulative Propellant Payback Ratio (PPR) *Technology 1 Cumulative PPR:* 0.08 *Technology 2 Cumulative PPR:* 0.33	Ratio of the propellant in the form of lunar ISRU water delivered from the lunar surface to the delivery location, relative to the propellant (water) that could have been delivered from Earth directly. The ratio is computed over a sufficiently long time horizon, such as the mine lifetime.
Discount Rate (percent/year)	0%	
Time Horizon (years)	*Technology 1:* 40 *Technology 2:* 22	For Technology 2, mine life is shorter as mineral reserves are exhausted earlier due to mining system constraints.
Equipment Development Cost ($)	-	
Equipment Production Cost ($)	-	
ISRU Equipment Transport Cost to Lunar Surface ($/kg)	-	
Other Equipment Delivery Cost ($/flight)	-	
Propellant Transport Cost to Propellant Delivery Location ($/kg)	-	
Propellant Price at Delivery Location ($/kg)	-	
Management/Operational Supervision Costs ($/year)	-	
Spares Cost ($/year)	-	
Mining Location	Lunar South Pole PSR	
Regolith Density (kg/m^3)	*Compacted Regolith:* 1900 *Loose Regolith:*	

	1600	
Regolith Percent Water by Weight (%)	*In Compacted Regolith:* 2.6% *In Loose Regolith:* 3.1%	Based on 5% by volume (50L H_2O/1000L regolith)
Mining Technology	*Technology 1:* Conventional strip mining using bucket-wheel excavator/processors *Technology 2:* *In situ* sublimation using drilling rovers and sublimation mining rovers	
Processing Location Following Extraction	-	
Propellant Delivery Location(s)	LEO	
Propellant Delivery Ops Concept	Reusable Lunar Lander	Launches every month and replaced after 10 years
Nominal Propellant Transporter Capacity (kg)	10,000	
Δv to Propellant Delivery Location (m/s)	*Lunar Surface-to-LEO:* 5,900	Propulsive capture (no aerobraking)
Inert Mass Fraction for Propellant Transporter	-	
I_{sp} for Propellant Transporter (s)	420	LOX/LH_2 propellant
Mine Aggregate Equipment Mass (kg)	Varies over time	*Technology 1:* Based on bucket-wheel excavator/processor mass of 4,300 kg each unit and *Technology 2:* Based on drilling rover mass of 780 kg each unit; and sublimation mining rover mass of 1,210 kg each unit
Mine Water Output (kg/year)	Varies over time	*Technology 1:* Based on bucket-wheel excavation rate of 15.5 m^3/h each unit *Technology 2:* Based on an effective sublimation rate of 3 kg H_2O/h each unit
Propellant / Water Ratio	-	
Propellant Demand (kg/year)	-	

Water Demand (kg/year)	Varies over time	Based on single-event quantities and a time profile of single events
O_2 Demand (kg/year)	-	
Maintenance and Repair Concept	-	Not discussed, but an availability factor of 0.6 to 0.7 was applied.
Spares Demand (kg/year)	-	10% surcharge, included in estimated ISRU equipment mass
Transfer Losses/Boiloff (%)	0%	Based on water as product
Launch Vehicle Payload From Earth (kg)	63,000 to LEO 8,300 to Lunar Surface	Based on Falcon-9H payload capabilities
Power Source for Water Extraction	Solar concentrators or microwave beaming	
Power System Size (kW)	-	
The Bottom Line: This study suggests, as have others [1, 2], that delivery of lunar-based ISRU propellant to LEO is uneconomic with current technologies. Using the Cumulative PPR metric, Technology 1 (conventional strip mining) was found to be less competitive than Technology 2 (*in situ* sublimation) due to equipment mass requirements, but neither system was as efficient on the basis of mass as direct launch of water from Earth. Interestingly, while the Cumulative PPR is not a financial metric, it may provide some insight into what the long-run *relative cost* of production and delivery would have to be in order for the lunar ISRU to compete with direct launch from Earth. By examining the time profile of the Cumulative PPR, one may also get a sense of the payback period needed to equilibrate these two approaches.		

Synopsis of Bennett, Ellender, and Dempster (2019)

This study is a re-imagined version of the Jones, et al. (2019) study discussed earlier. In that study, Jones, et al. present several architectures including two in which propellant is delivered from Earth to a cislunar aggregation point, and four in which ISRU propellant is lunar-sourced. Jones, et al. concluded that lunar-sourced ISRU propellant was far more costly than that delivered from Earth. Bennett, Ellener, and Dempster adopt the Jones, et al. Architecture 3 as their baseline, and investigate several variations. (Architecture 3 has delivery by a Reusable Lunar Lander (RLL) from the lunar surface direct to a cislunar aggregation point after all ISRU hardware has been deployed.) The architectural variants were selected in part to show how taking advantage of favorable non-linear scaling effects and better system deployment strategies dramatically lower the cost of lunar ISRU propellant, making it far more competitive with delivery from Earth.

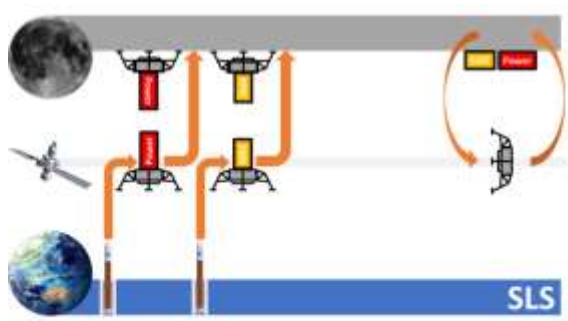

Figure 5: Architecture Variant 1 Bat Chart (Source: Ref. [9])

Architecture Variant 1 pairs a "maximal scale" ISRU plant with a Reusable Lunar Lander (RLL) and both are launched on an SLS. Next, a "maximal scale" nuclear reactor is paired with another RLL and also launched on an SLS. Architecture Variant 2 scales the ISRU plant to the maximum that can be accommodated on a commercial Heavy Lift Launch Vehicle (HLLV), and aggregates multiple such units in cislunar space. A separately launched RLL delivers the ISRU plant stack to the lunar surface, and a second RLL delivers a maximally scaled nuclear reactor. Architecture Variant 3 mixes the two scaling and aggregation strategies. Lastly, Architecture Variant 4 is the same as the baseline architecture, but with two specialized RLL propellant transports with a lower Inert Mass Fraction (IMF). This variant shows the sensitivity of the propellant cost at the cislunar aggregation point to the RLL IMF.

Propellant demand assumptions and many other parameters values are retained from the Jones, et al. study, but some cost parameters had to be "reverse engineered" from the Jones, et al. study in order to analyze the architecture variants.

In both studies, sizing parameters were applied to the ISRU plant and to the nuclear reactor that powers it. The sizing parameters for the ISRU plant were based on Schreiner's work [4, 5] on modeling Molten Regolith Electrolysis (MRE) for ISRU systems, though neither study claims that these sizing parameters would apply to lunar ice mining. For the nuclear reactor, both studies rely on the sizing work by Mason [6].

Table 6: Attributes for Bennett, Ellender, and Dempster (2019)

Study: Bennett, N., Ellender, D., Dempster, A., "Commercial Viability of Lunar *In Situ* Resource Utilization (ISRU)," submitted to *Planetary and Space Science*, 2019

Attribute	Attribute Value	Basis for Value
Measure of Economic Performance	For each architecture, the cost per kg of delivering propellant to a cislunar aggregation point	Comparison of lunar ISRU with delivery from Earth
Discount Rate (percent/year)	0%	Discounting of capital investments not implemented
Time Horizon (years)	14	Unspecified number years from start of development to IOC, then 14 years of operations
Equipment Development Cost ($)	Varies by architecture. *Baseline Architecture:* $19,320 ($FY18M) $19,900 ($FY19M) *Architecture Variant 1:* $5,757 ($FY18M) $5,930 ($FY19M) Architecture Variant 2: $5,918 ($FY18M) $6,096 ($FY19M) *Architecture Variant 3:* $5,757 ($FY18M) $5,930 ($FY19M)	Except for SNAP 50 nuclear reactor, based on $48,000 ($FY18) per kg of system mass. Factor is inferred from Ref. [3] and dependent on SLS cost per flight. SNAP 50 nuclear reactor based on $385,000 per kg ($FY18) of reactor mass, from Ref [7].

	Architecture Variant 4: $8,110 ($FY18M) $8,353 ($FY19M)	
Equipment Production Cost ($)	-	Included in development cost
ISRU Equipment Transport Cost to Lunar Surface ($/kg)	-	SLS Block 2 or commercial HLLV delivery ISRU and power systems to cislunar aggregation point. Reusable Lunar Lander (RLL) then completes the delivery.
Other Equipment Delivery Cost ($/flight)	*SLS Block 2 (when delivering a filled zero-boil-off cryogenic tank):* $2,070 ($FY18M) $2,132 ($FY19M) *Commercial HLLV (when delivering a filled zero-boil-off cryogenic tank):* $600 ($FY18M) $618 ($FY19M)	Inferred from Ref. [3].
Propellant Transport Cost to Propellant Delivery Location ($/kg)	-	
Propellant Price at Delivery Location ($/kg)	*Baseline Architecture:* $101 ($FY18K) $104.0 ($FY19K) *Architecture Variant 1:* $17.0 ($FY18K) $17.5 ($FY19K) *Architecture Variant 2:* $15.9 ($FY18K) $16.4 ($FY19K) *Architecture Variant 3:* $14.6 ($FY18K) $15.0 ($FY19K) *Architecture Variant 4:* $39.9 ($FY18K) $41.1 ($FY19K)	All prices reflect the baseline propellant demand of 59,000 kg/year. Excess capacity exists in the architecture variants, which could lower the price further, if the additional demand existed.
Management/Operational Supervision Costs ($/year)	$0	
Spares Cost ($/year)	$0	Only the cost of launching the annual spares mass was included.
Mining Location	Lunar South Pole PSR	
Regolith Density (kg/m^3)	-	

Regolith Percent Water by Weight (%)	-	
Mining Technology	Ice Mining	
Processing Location Following Extraction	-	
Propellant Delivery Location(s)	Cislunar aggregation point consistent with being Earth-Moon Lagrange 1 (EML1)	
Propellant Delivery Ops Concept	Delivery by a RLL from lunar surface direct to cislunar aggregation point. Same for all architectures.	
Nominal Propellant Transporter Capacity (kg)	Varies by reusable Lunar Lander Inert Mass Fraction (IMF)	
Δv to Propellant Delivery Location (m/s)	*Lunar Surface-to-Cislunar Aggregation Point:* 2,510	
Inert Mass Fraction for Propellant Transporter	*Baseline Architecture RLL:* 0.26 *Architecture Variants 1-3:* 0.15 Architecture Variant 4: 0.15 and 0.10	
I_{sp} for Propellant Transporter (s)	450	LOX/LH_2 propellant
Mine Aggregate Equipment Mass (kg)	Varies by architecture	*Excavator:* Based on 10 kg/(mt/year of propellant produced). See Ref. [4, 5] *ISRU Plant:* Based on 109 kg/(mt/year of propellant produced). See Ref. [4, 5] *Power System:* Based on 11.34 kg/kW for a SNAP 50 reactor design. See Ref. [7]
Mine Water Output (kg/year)	-	
Propellant / Water Ratio	-	
Propellant Demand (kg/year)	59,000	
Water Demand (kg/year)	-	
O_2 Demand (kg/year)	-	
Maintenance and Repair Concept	-	

Spares Demand (kg/year)	Varies by architecture	Based on 10% of ISRU system mass per year
Transfer Losses/Boiloff (%)	0	
Launch Vehicle Payload From Earth (kg)	*SLS Block 2:* 45,000 *Commercial HLLV:* 15,000	To cislunar aggregation point
Power Source for Water Extraction	Nuclear	
Power System Size (kW)	1000 kW	Based on use of a SNAP 50 reactor design. See Ref. [7]

The Bottom Line: This study investigated alternatives to those analyzed by Jones, et al., while retaining many of their assumptions and parameters. The results show a dramatic reduction in the average cost of lunar ISRU propellant delivered to a cislunar aggregation point. This is a consequence of posited non-linear scaling relationships, should they actually exist, that can be exploited by changes in the deployment strategy. These results appear to hold even if some of the costing parameters are significantly off the mark. The study also found it advantageous to deploy specialized propellant transporter RLLs, though the cost details on such a system may be overly optimistic. Overall, this study appears to refute the results of the Jones, et al. study even when using many of the same assumptions, parameters, and operations concepts.

Concluding Observations

Although I was able to compare only a few studies in this white paper, collectively the study authors have brought to the lunar ISRU debate new and imaginative alternatives, and creative approaches to analyzing them. Multiple regions of the large lunar ISRU tradespace have been explored, and some insights have been gained to guide future research.

In Table 7, I show the “results” of three studies (discussed in this white paper) that modeled the same basic lunar ISRU architecture and operations concept. One difference is the Δv needed to transport the lunar ISRU propellant to the delivery location. A factor of nearly twelve emerges between the lowest and highest estimated cost per kg of delivered propellant, and that factor only grows when the Δv adjustment is made. The wide range of quantitative results is a consequence of the different assumptions, parameters, and analysis methods used in the studies. Because of this, it is difficult to compare results from different studies on a truly equal footing, i.e., apples-to-apples. In obtaining these results, input assumptions that disfavored economic viability of lunar ISRU included: high discount rates, low regolith water content by weight, significant ISRU system development costs, lengthy deployment schedules, and low equipment availability. Input assumptions that favored economic viability included: low

Table 7: Comparison of Results From Three Studies

Reference No.	Delivery Location	“Best” Lunar ISRU Propellant Estimated Cost ($FY19K/kg)
1	LLO	$176.1
3	EML1	$80.3
9	EML1	$15.0

ISRU delivered equipment costs per kilogram, high degree of reusability of propellant transport vehicles, and inexpensive power.

How can the ISRU community narrow the disparity in these results? First, refining the economic and financial modeling of lunar ISRU is hampered by gaps in knowledge. Because the items below figure prominently in the economic outcomes, the ISRU community needs to understand better:

a. The "physics" of lunar volatiles, i.e., the properties, locations, distribution, and behavior of lunar water/ice;
b. The capital costs associated with ISRU hardware;
c. How such systems would operate in lunar mining environments over longer periods of time, especially with regard to reliability and maintainability;
d. How much power will, in fact, be needed for ISRU systems and how will it be supplied;
e. The limits of reusability of robotic landers and cyclers;
f. The sources of demand and associated quantities of ISRU products demanded; and
g. The marginal cost, payload capabilities, and achievable flight rates of government and commercial launches to cislunar space.

Second, there are also ways to improve our modeling capabilities, particularly in the treatment of uncertainties, both aleatory and epistemic. Moving forward calls for a more in-depth and transparent study taking in the best practices and analysis techniques developed by these previous studies. Challenges to assumptions and modeling parameter values are, of course, always possible; and weaknesses in any analysis, no doubt, can be found, but it is possible to address these, given sufficient resources.

Acknowledgements

This research was carried out at the Jet Propulsion Laboratory (JPL), California Institute of Technology, under a contract with the National Aeronautics and Space Administration (NASA).
© 2019 California Institute of Technology. Government sponsorship is acknowledged.

The author also acknowledges those study authors who provided clarifications of their work. The author, however, is solely responsible for the content of this white paper.

Disclaimer

The cost information contained in this paper is of a planning nature and is intended for informational and discussion purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.

References

[1] Charania, A.C., DePasquale, D., "Economic Analysis of a Lunar ISRU Propellant Services Market," IAC Paper 07-A5.1.03, 2007.

[2] Kornuta, D., et al., “Commercial Lunar Propellant Architecture: A Collaborative Study of Lunar Propellant Production,” Colorado School of Mines (CSM)/United Launch Alliance (ULA), 2018.

[3] Jones, C., et al., “Cost Breakeven Analysis of Cis-lunar ISRU for Propellant,” AIAA-2019-1372, SciTech Forum 2019.

[4] Schreiner, S., "Molten Regolith Electrolysis Reactor Modeling and Optimization of *In Situ* Resource Utilization Systems," M.S. Thesis, Aeronautics and Astronautics Dept., MIT, Cambridge, MA, 2015.

[5] Schreiner, S., Sibille, L., Dominguez, J., et al., “Development of a Molten Regolith Electrolysis Reactor Model for Lunar *In Situ* Resource Utilization,” 8th Symposium on Space Resource Utilization, AIAA SciTech Forum, Kissimmee, FL, January 2015.

[6] Mason, L., “Surface Nuclear Power for Human Mars Missions,” NASA/TM-1999-208894.

[7] Voss, S. “Space Nuclear Auxiliary Power (SNAP) Reactor Overview,” AFWL-TN-84-14, Air Force Weapons Laboratory, Kirtland AFB, NM, 1984.

[8] Pelech, T., Roesler, G., Saydam, S., “Technical Evaluation of Off-Earth Ice Mining Scenarios Through an Opportunity Cost Approach,”*Acta Astronautica* 162 (2019) 388-404.

[9] Bennett, N., Ellender, D., Dempster, A., “Commercial Viability of Lunar *In Situ* Resource Utilization (ISRU),” to be published in *Planetary and Space Science*, 2019.