

Cost Breakeven Analysis of Lunar ISRU for Human Lunar Surface Architectures

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Abstract

The return of humans to the lunar surface encompasses a range of possible architectures from brief Apollo-like sorties to long-term sustainment of human presence. Any architecture in this span requires propellant for the crew's ascent from the lunar surface, as well as consumables to support their presence on the Moon. Oxygen and hydrogen are candidates for the propellant for the ascent vehicle due to their high specific impulse and potential for production from lunar resources and also constitute important consumables for the crew. Thus, the production of oxygen and/or hydrogen from lunar resources could significantly reduce the mass that must be sent from Earth to enable future human lunar missions. To assess the merits of using lunar resources, the costs associated with developing, producing, launching, operating, and maintaining those systems must be considered relative to the costs of delivering the needed resources from Earth. The demand for those resources depends upon the nature of the lunar mission, while the costs of both Earth-derived and lunar-derived resources depend on the performance requirements and technology capabilities associated with each approach. Thus, determining which approach is more cost efficient requires modeling the performance and cost of the associated systems as well as the range of possible architectures over which such a determination might apply. This research proposes a model that parametrically captures the factors influencing the relevant costs of providing propellant and crew consumables on the lunar surface from Earth and from the Moon. Two ISRU system models are assessed relative to propellant delivery from Earth. In this model, lunar ISRU breaks even with propellant delivery from Earth at high propellant demands and mission durations with multi-year ISRU system lifetimes; however, the costs of developing the necessary technologies to support a highly reliable and autonomous lunar ISRU system were not included.

Keywords: ISRU, Architecture, Lunar, Cost, Technology

Nomenclature

T	= Duration of useful life (years)
m	= Mass (kg)
r	= Specific Mass Rate ((kg/year) / kg)
I_{sp}	= Specific Impulse (s)
ΔV	= Vehicle velocity change required (m/s)
t	= metric tons
yr	= year

Subscripts:

$isru$	= relating to the ISRU System
$spares$	= relating to the ISRU System spares
$payload$	= relating to the Lunar Lander Payload

Acronyms/Abbreviations

Design, Development, Testing, and Evaluation (DDTE), Environmental Control and Life Support (ECLS), In-Situ Resource Utilization (ISRU), Inert Mass Fraction (IMF), Low-Lunar Orbit (LLO), Molten Regolith Electrolysis Equivalent (MREE), National

Aeronautics and Space Administration (NASA), Oxygen-Fuel Ratio (O/F), Space Launch System (SLS), Technology Readiness Level (TRL), Trans-Lunar Injection (TLI).

1. Introduction

With the announcement of Space Policy Directive-1, there is a renewed focus on sustainable lunar exploration [1]. This goal will challenge NASA to deliver a significant amount of mass to the surface and support crew over multiple long-duration missions. In order to achieve a sustained human presence on the Moon, many past lunar surface architecture studies and plans have relied upon in-situ resource utilization (ISRU) systems to produce propellant and crew consumables in order to reduce the delivered mass that is required [2-4]. These studies assumed that the cost to develop, deliver, and operate a lunar ISRU plant on the surface would be less than the cost of delivering propellant and crew consumables over the duration of the campaign.

However, there has only been modest investment in ISRU systems over the last few decades, resulting in low technology readiness levels (TRL) with significant uncertainty in the reliability of these systems in a lunar environment. Multiple new commercial launch providers offer increasing access to the lunar surface at decreasing costs [5]. It is also noted that while Space Policy Directive-1 does challenge NASA to develop and execute “an innovative and sustainable program of exploration,” it does not define sustainability or what the specific exploration campaign will be. Given this lack of definition, it is prudent to examine the breakeven point of ISRU production versus the delivery of propellant and consumables for a range of potential campaigns. This breakeven point depends on the costs associated with developing, deploying, and operating a lunar ISRU system and the costs associated with directly delivering propellant and consumables from Earth. Based on the potential abundance of lunar ice at the poles of the Moon [6], oxygen and hydrogen are a candidate propellant combination that could be manufactured from lunar resources while also representing a source of consumables for the crew.

This study examines the costs of delivering propellant from Earth and producing propellant on the Moon for a variety of possible surface needs. The breakeven point is used to determine whether, for a given surface need (defined by the annual need for propellant and the number of years over which that need exists), propellant delivery or propellant production is lower cost. A parametric approach is used to model the launch vehicle capabilities, landers, and ISRU systems that enable these architectures. The results support future decisions about the value of lunar ISRU for enabling human missions on the lunar surface.

Section 2 describes the two architectures being assessed in further detail. Section 3 summarizes the approach for parametrically sizing and costing the elements of each architecture. Section 4 discusses the analysis method used to evaluate the two architectures across a range of propellant demands and mission durations. Section 5 presents the results of this analysis, including identifying the preferred launch vehicle, number of ISRU systems, total costs, and the ratio of the costs of propellant production to propellant delivery. Section 6 draws several conclusions about the value of lunar ISRU based on this analysis.

2. Architectures

Two competing architectures were assessed for providing propellant (as well as consumables, which would likely represent a small increase in the propellant demand) on the lunar surface. The first of these delivers propellant directly from Earth, while the other delivers ISRU systems that produce propellant from lunar resources. The architecture variables are represented

graphically in Figure 1; the propellant comes from either delivery from Earth or production on the lunar surface, and the delivery or production systems are launched on either NASA’s Space Launch System (SLS) or a commercial launch vehicle. The design of the client systems that maintain and use the propellant are beyond the scope of this study.

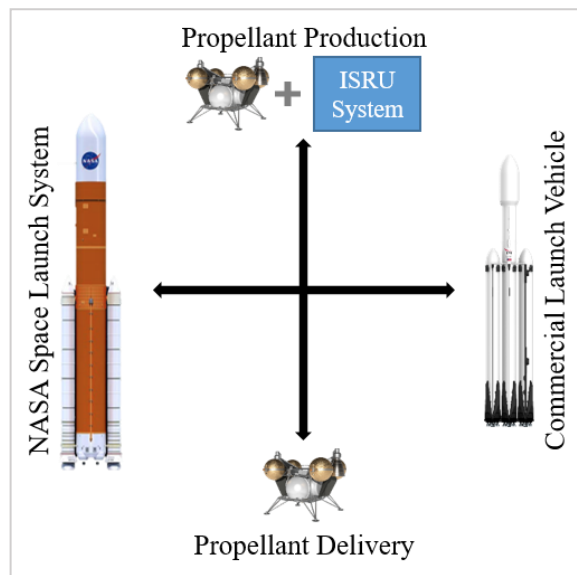


Figure 1: Variables traded in the architectural trade space: choice of launch vehicle and propellant delivery vs production

2.1. Propellant Delivery Architectures

Propellant is loaded into an expendable lunar lander vehicle and launched from the Earth’s surface by a NASA or commercial launch vehicle. Propellant delivery architectures are composed of two elements: the launch vehicle and the lunar lander vehicle. The lander is assumed to be capable of providing maintenance of the propellants in their cryogenic states through delivery to the lunar surface, at which point the propellant would be transferred to a system on the lunar surface for subsequent maintenance and transfer to client systems.

2.2. Propellant Production Architectures

ISRU systems (designed and manufactured on Earth) are loaded into an expendable lunar lander vehicle and launched from the Earth’s surface by a NASA or commercial launch vehicle. Once delivered to the lunar surface, the ISRU systems collect and process lunar ice. Propellant, produced from the water, is stored within tanks that are part of the ISRU systems. Propellant production architectures are composed of three elements: the launch vehicle, the lunar lander vehicle, and the ISRU system.

In this study, two models are used to parametrically size an integrated lunar ice processing system. The first

model assumes that a lunar ice processing system has similar mass and power to a molten regolith electrolysis system for a corresponding propellant production rate (this may be a conservative assumption with respect to the power needs, as lunar ice processing does not require the high temperatures needed for molten regolith electrolysis); this Molten Regolith Electrolysis Equivalent (MREE) model has previously been used to assess the value of lunar ISRU for supporting human missions to Mars [6]. The second model, based on the work of Duke et al. [7], linearly scales the mass and power of a proposed concept for lunar ice mining as propellant production rate varies. Both models are for systems that acquire ice, process it into oxygen and hydrogen, and liquefy both propellants. The relationship between mass (see Figure 2) and power (see Figure 3) and propellant production rate is illustrated for the MREE model and for the Duke model.

Both models assume the existence of highly reliable, autonomous ISRU systems that can acquire water, process it into propellant, and maintain it on the lunar surface; the costs of developing these technologies to a technology readiness level of 6 were not modeled, but these costs would impact the overall cost trade. In addition, both models assume the existence of a significant supply of accessible ice on the Moon; further prospecting is required to identify whether such a supply can be found in a location sufficiently close to human exploration regions of interest.

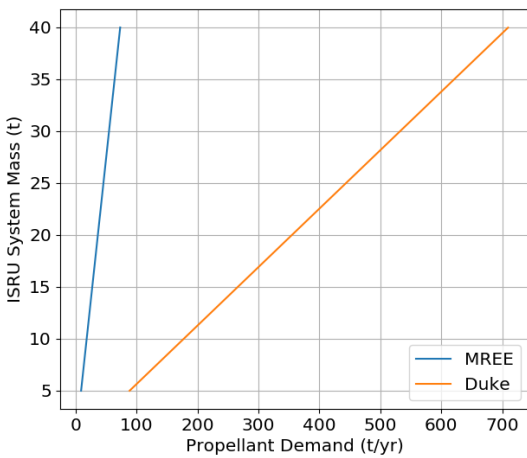


Figure 2: Relationship between the ISRU System Mass (t) and the Propellant Demand (t/yr) that can be met by an individual ISRU plant

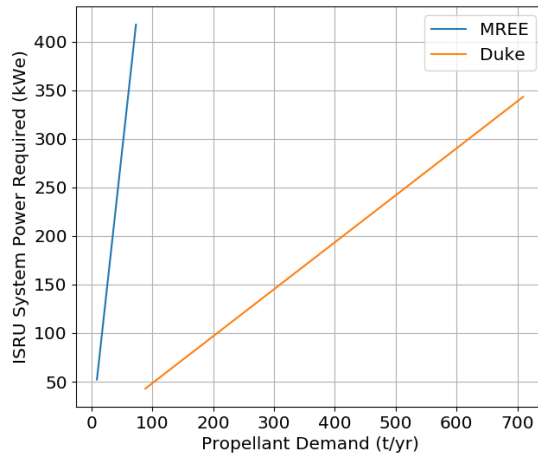


Figure 3: Relationship between the ISRU System Power Required (kWe) and the Propellant Demand (t/yr) that can be met by an individual ISRU plant

3. Element Sizing and Costing

Each element of each architecture was sized and costed based on the assumptions summarized in Table 1, and described in the subsections below.

Table 1. Key architecture assumptions

Variable	Assumption	Unit
Fuel	Liquid Hydrogen	-
Oxidizer	Liquid Oxygen	-
O/F Ratio	6.00	-
ΔV TLI-LLO	640.00	m/s
ΔV LLO-Surface	1,870.00	m/s
Lunar Lander Inert	0.26	-
Mass Fraction (IMF)		
Lunar Lander Specific	450.00	s
Impulse (I_{sp})		
Spares Mass	10.00	wt%/yr

3.1. Launch Vehicles

Within this study, a comparison between a notional commercial launch vehicle and expected capabilities for the NASA SLS Block 1B was made. The launch vehicle payload capacity for trans-lunar injection and the estimated launch costs are tabulated in Table 2; these values were used to constrain the size of lunar landers and contribute to the costs of architectures.

Table 2. Launch vehicle payload capacity to TLI with respective estimated cost [6], [8]

Launch Vehicle	Payload to TLI (t)	Est. Cost (\$M)
SLS Block 1B Cargo	40.0	1,000.00
Nominal Commercial	15.0	200.00

3.2. Lunar Lander

Once a launch vehicle was selected, the lunar lander with payload was sized using the rocket equation and inert mass fraction sizing to match the launch vehicle payload capacity to TLI mass value; the lunar lander was assumed to have an Inert Mass Fraction (IMF) of 0.26 and a specific impulse (I_{sp}) of 450 seconds, and was required to conduct two propulsive burns to insert from Trans-Lunar Injection (TLI) into Low-Lunar Orbit (LLO) ($\Delta V = 640 \text{ m/s}$) and to land ($\Delta V = 1870 \text{ m/s}$) on the lunar surface [6]. Alternative trajectories and concepts of operations that could reduce the ΔV requirement for the lander were not assessed in this study.

Lunar lander costs were estimated using the Project Cost Estimating Capability, a standard NASA cost estimating tool. Estimates of subsystem mass (e.g. structures, propulsion) were created for multiple landers based on a range of payload capacities, which were used to create a response surface model of cost (both development and unit) as a function of lander mass. Standard NASA development values were assumed for manufacturing methods, engineering management, funding availability, test approach, integration complexity, and pre-development study; the lander was assumed to be a 100% new design. Percentages for a contractor fee, contingency, vehicle level integration, and software were included. All costs were produced in fiscal year 2019 dollars.

3.3. ISRU System Models

Both the MREE and Duke ISRU models were sized using their respective sizing methodologies and performance parameters [6-7].

Cost for individual systems of the lunar ISRU architecture were modeled at the subsystem level using the Project Cost Estimating Capability. The costs for front-end loaders and haulers used to transport ice to a production plant reused cost estimating relationships developed previously by Jones et al. [6]. The masses of components of the water processing plant were mapped onto one of four categories within the cost model: structures, thermal control, environmental control and life support (ECLS), and tanks. The costs of spares was not modeled in the analysis. Estimates were created for multiple ISRU systems based on variations in propellant demand and system lifetime, which were used to create a response surface model of cost (both development and unit) as a function of ISRU mass and lifetime. Standard NASA development values were assumed, and the system was assumed to be a 100% new design.

The ISRU systems, including the necessary spares for the entire lifetime of the system, were sized to meet the payload capacity of the designed lunar lander. Equation 1 illustrates the relationship between system mass, ISRU lifetime, and lander payload capacity:

$$m_{isru} = m_{payload} \left(\frac{1}{1 + T_{isru} * r_{spares}} \right) \quad (1)$$

4. Analysis Method

In the propellant delivery architecture, the number and frequency of launches required (of a specific launch vehicle/lunar lander combination) is calculated so that the defined propellant demand on the lunar surface is met. For an ISRU architecture, the defined lunar surface propellant demand drives the number of ISRU systems that are required, based on the propellant production capability that could be delivered in a single launch vehicle/lunar lander combination. Subsequently, the lifetime of the ISRU system defines the replacement rate that must be achieved to maintain that defined lunar surface propellant demand over the duration of the lunar mission. Here, we define the duration of the mission as the length of time of a sustained human presence on the Moon, with a variable number of individual missions as part of a campaign. Based on the number of ISRU systems required, the number of launch vehicles/lunar landers pairs can be accounted for, which yields the costs incurred by the architecture through time.

A range of mission durations and propellant demands were assessed. For the mission duration parameter, 1920 intervals were taken between 0 and 10 years; for the propellant demand parameter, 500 intervals between 0 and 40 tonnes per year defined the range explored. In these ranges, ISRU system lifetimes of 1 year, 3 years, and 5 years were modeled.

For each combination of mission duration and propellant demand, the architectures were optimized in terms of the launch vehicle-lunar lander combination for propellant delivery, and the launch vehicle-lunar lander-ISRU System combination for propellant production to minimize the cumulative cost of providing the needed propellant for the duration. This data was then used as a baseline to assess whether or not the propellant production architecture would breakeven. Breakeven occurs at the time where the cumulative costs of delivering an equivalent amount of propellant to the lunar surface from Earth equal the cumulative costs associated with producing propellant via ISRU. In both the propellant delivery and ISRU architectures, unit costs for systems are accrued in the year the systems are launched, while Design, Development, Testing, and Evaluation (DDTE) costs are all accrued in the initial year of the architecture.

5. Results

5.1. Propellant Delivery Architecture

The lowest cost propellant delivery architecture was identified for each interval of the trade space. Figure 4 shows the cumulative cost through time for a range of propellant demands and mission durations, and Figure 5

shows the regions in which a certain launch vehicle is the least expensive. As the propellant demand and mission duration increase, the SLS-based approach to delivering propellant more frequently becomes the less expensive approach relative to commercial delivery of propellant. Although in this model the cost per kilogram of payload to TLI is always less for commercial launch than for the SLS (see Table 2), the coupling between the propellant demand and the launch vehicle-lunar lander pair define the required launch cadence for a particular propellant demand and mission duration combination. Each lander always delivers its maximum payload capacity (where the payload is propellant), because the cost of propellant on Earth is insignificant relative to launch and lander costs. As a result, at any point in time there may be propellant reserved for future use on the lunar surface for which delivery costs have already been paid (effectively increasing the specific cost to deliver propellant). Thus, at certain points throughout the mission duration, the propellant demand can be better met by a whole number of launches of a specific launch vehicle-lunar lander pair. More optimal matching between the propellant demand, the mission duration, and the launch vehicle-lunar lander combinations can decrease the specific cost of delivery. This phenomena is shown by the alternating bands seen in Figure 5.

Based on the specific cost (cost-per-kilogram-delivered) relationship between the two launch vehicle options (as shown in Table 2), this behavior is non-intuitive. Upon initial investigation, the specific cost of the SLS Block 1B launch vehicle is almost double that of the commercial launch vehicle. In the presented analysis, however, the launch cost is not the only factor at play; other costs that are accounted for include the DDTE and unit costs of the lander, Economies of scale and amortization of the cumulative costs result in the banding phenomenon shown in Figures Figure 4 and Figure 5. The economies of scale are due to the small difference between the unit costs of landers sized for each of the launch vehicles. Amortization of the DDTE cost of the lander over an increasing number of launches/deliveries has an impact on the specific cost per launch and how quickly it converges to its steady state. As the launch frequency is higher for the commercial vehicle architecture, its specific cost converges faster, however, the SLS Block 1B delivery architecture ultimately converges to a lower specific cost.

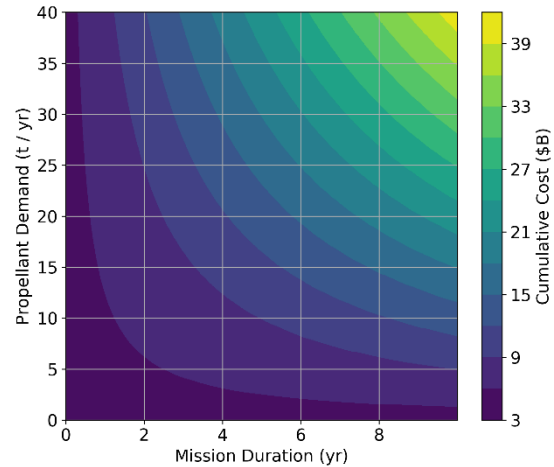


Figure 4: Cumulative cost for Earth propellant delivery architectures

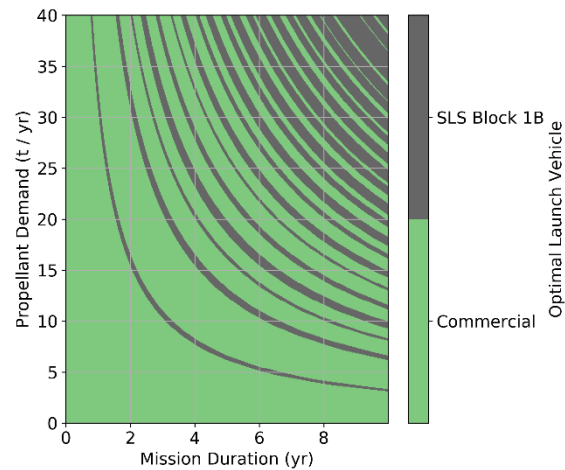


Figure 5: Optimal launch vehicle to minimize architecture cumulative cost for Earth propellant delivery architectures

5.2. ISRU Propellant Production Architecture

The results of the analysis exhibit step-wise behaviors along both the x- and y-axis, as shown in Figures Figure 6 to Figure 25. Horizontal steps result from the discrete nature of the ISRU system lifetime. Vertical steps in the MREE model occur when the propellant demand reaches a threshold such that a different number and size of ISRU systems is more optimal for meeting that demand. The hashed region of the following figures represent combinations of propellant demand and mission duration where no breakeven occurs. In varying the ISRU system lifetime, the vertical steps in the contour area of the results (shown in the figures in this section) are slightly different across a single ISRU model; this is more clearly noticeable in the figures for the MREE model. The reason for this is the ISRU system mass that can be landed per

launch varies with ISRU lifetime (according to Equation 1), leading to a reduction in the production rate of a single system as its lifetime increases.

5.2.1. Duke Plant

The Duke ISRU system model enables propellant production architectures to breakeven for all three of the selected ISRU system lifetimes assessed; this breakeven occurs in the non-hatched regions of the cumulative cost plots for the model (see Figure 6, Figure 7, and Figure 8 for lifetimes of 1, 3, and 5 years, respectively). For all combinations of propellant demand and mission duration examined in this study, the preferred launch vehicle was the SLS (see Figure 9, Figure 10, and Figure 11), and the number of ISRU systems required was 1 (see Figure 12, Figure 13, and Figure 14).

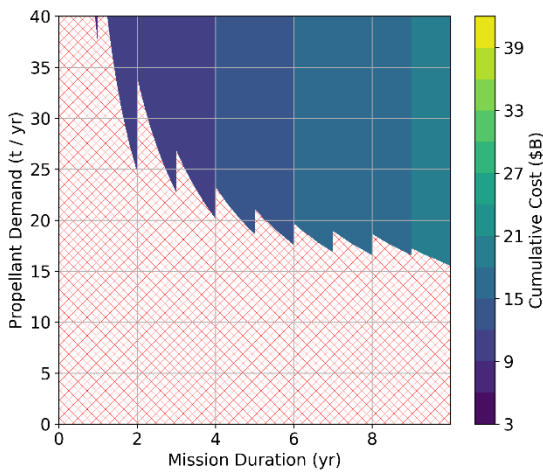


Figure 6: Cumulative cost for Duke ISRU production architecture with a 1-year lifetime

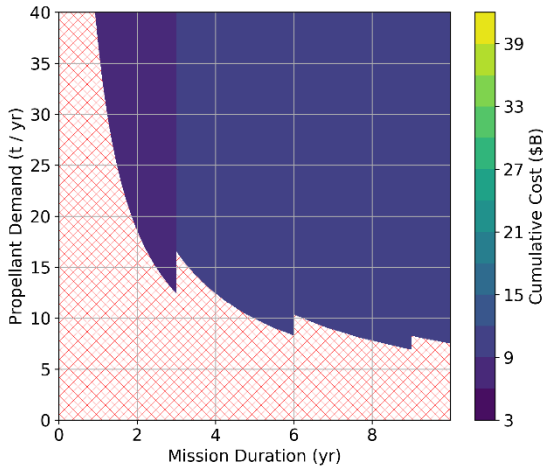


Figure 7: Cumulative cost for Duke ISRU production architecture with a 3-year lifetime

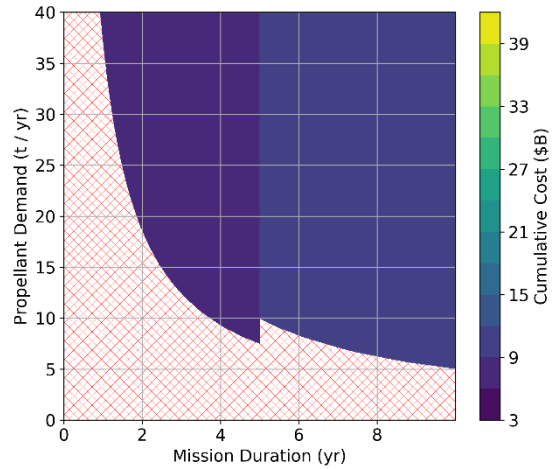


Figure 8: Cumulative cost for Duke ISRU production architecture with a 5-year lifetime

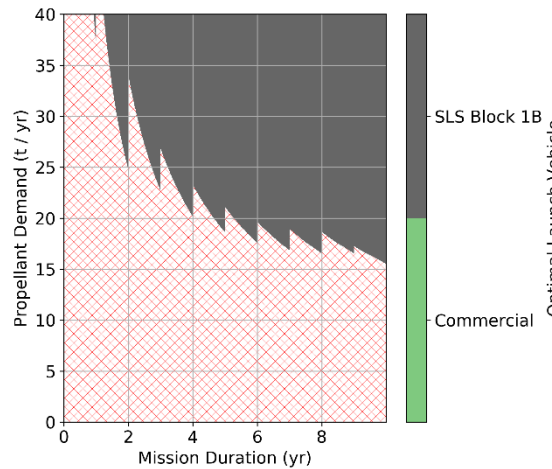


Figure 9: Optimal launch vehicle for Duke ISRU architecture with a 1-year lifetime

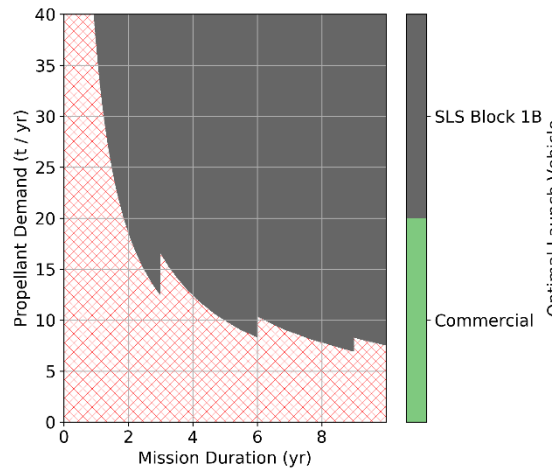


Figure 10: Optimal launch vehicle for Duke ISRU architecture with a 3-year lifetime

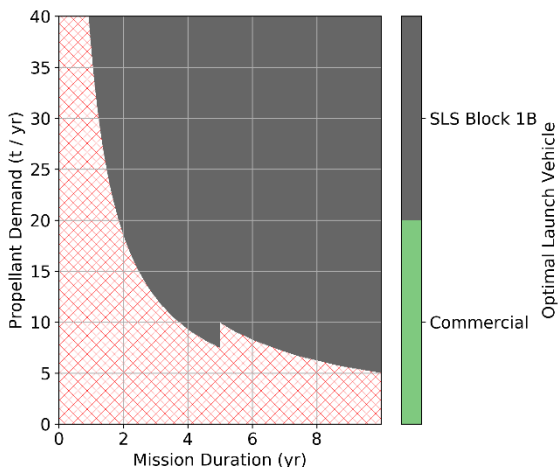


Figure 11: Optimal launch vehicle for Duke ISRU architecture with a 5-year lifetime

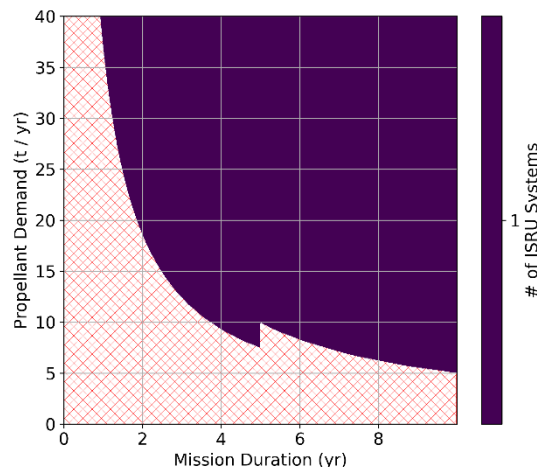


Figure 14: Number of ISRU systems in operation for the Duke ISRU architecture with a 5-year lifetime

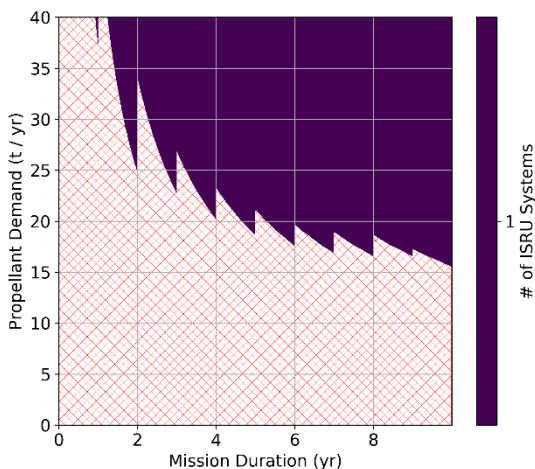


Figure 12: Number of ISRU systems in operation for the Duke ISRU architecture with a 1-year lifetime

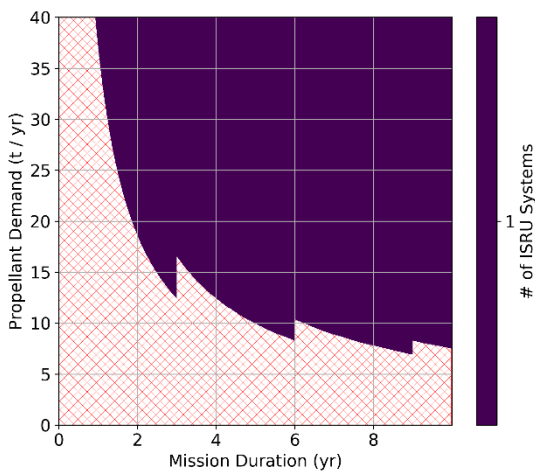


Figure 13: Number of ISRU systems in operation for the Duke ISRU architecture with a 3-year lifetime

5.2.2. MREE (Molten Regolith Electrolysis Equivalent) Plant

For the MREE ISRU model, an ISRU lifetime of 1-year is not sufficient to enable the ISRU propellant production architecture to break even relative to propellant delivery from Earth; thus, no results are shown. The lower mass and power efficiencies with respect to propellant production rate of the MREE model as compared to the Duke model yield fewer combinations of propellant demand and mission duration where ISRU breaks even with propellant delivery. In addition, the discrete nature of the ISRU lifetime and the behavior of launch vehicle/lunar lander/ISRU system optimization yields discontinuities in the breakeven space, represented as hashed areas in the following figures. Thus, small changes in either propellant demand or mission duration can lead to significant increases in the cost of an ISRU architecture, such that it no longer breaks even with the cost of a corresponding propellant delivery architecture. Figure 15 and Figure 16 show the cumulative cost at ISRU lifetimes of 3 and 5 years, respectively. Figure 17 and Figure 18 show the optimal launch vehicle, while Figure 19 and Figure 20 show the number of ISRU systems in operation to meet the propellant demand.

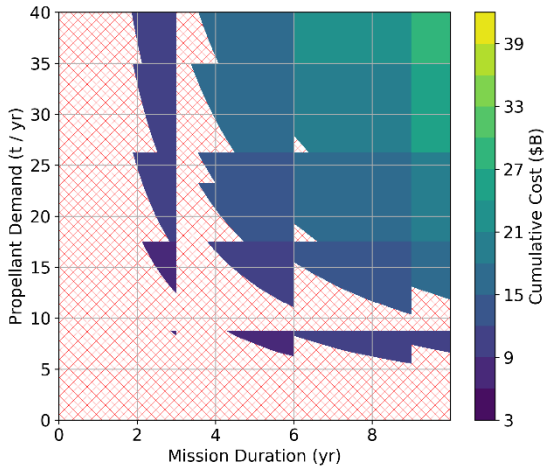


Figure 15: Cumulative cost for MREE ISRU architecture with a 3-year lifetime

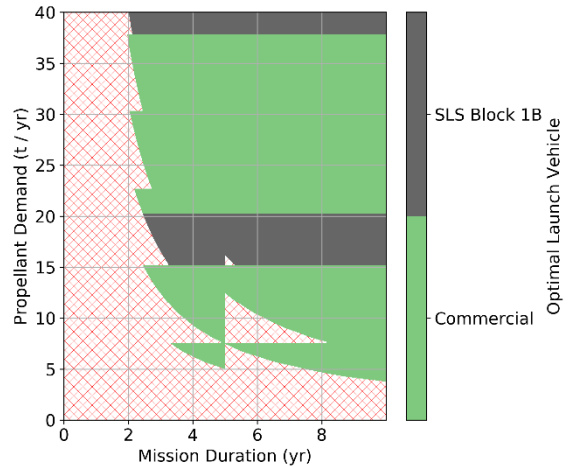


Figure 18: Optimal launch vehicle for MREE ISRU architecture with a 5-year lifetime

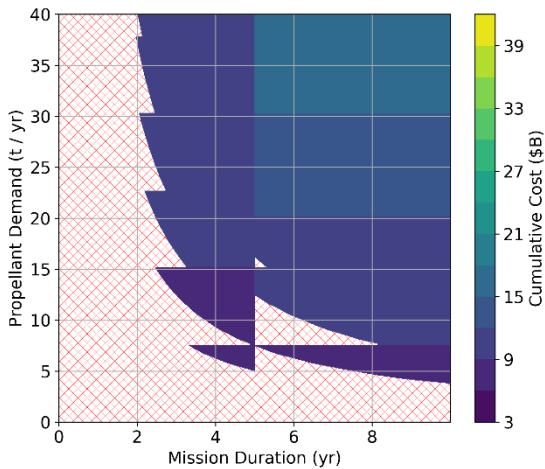


Figure 16: Cumulative cost for MREE ISRU architecture with a 5-year lifetime

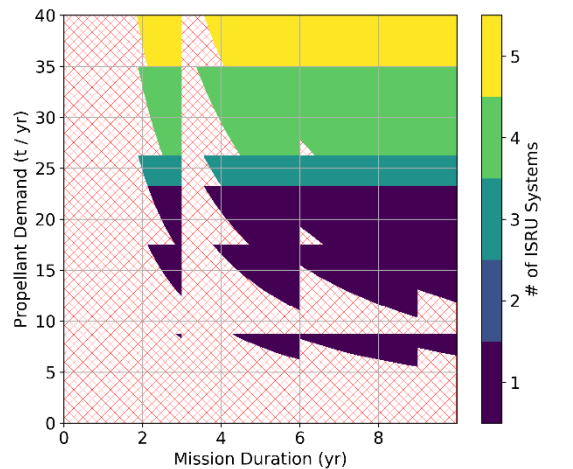


Figure 19: Number of ISRU systems in operation for the MREE ISRU architecture with a 3-year lifetime

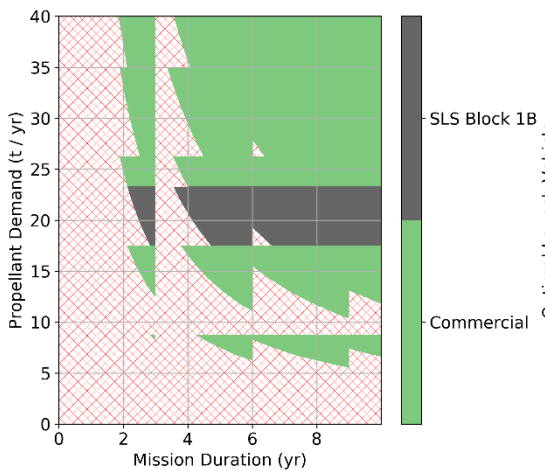


Figure 17: Optimal launch vehicle for MREE ISRU architecture with a 3-year lifetime

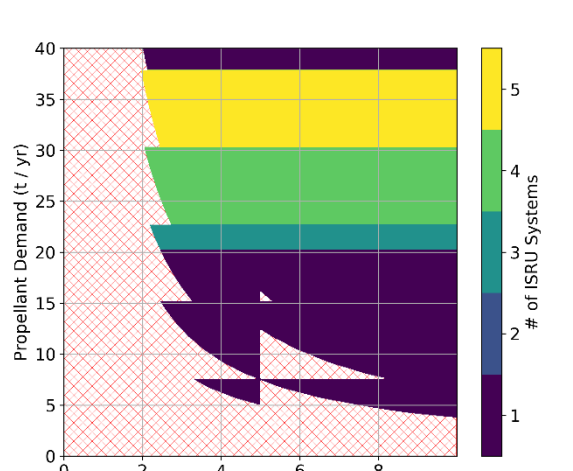


Figure 20: Number of ISRU systems in operation for the MREE ISRU architecture with a 5-year lifetime

5.3. Propellant Demand

An assessment of a reusable lunar lander concept estimated that a reusable lunar lander vehicle, refueled on the lunar surface, could lift a crew of two from the Moon to cis-lunar space and return to the surface; this lander would be supported by a tug that performed a fraction of the descent ΔV with propellant delivered to cis-lunar space. For a single mission, 17.0 t of propellant is required on the lunar surface, which could either be delivered from Earth or produced in-situ from lunar resources. Three notional demands were selected to represent a mission cadence of once every two years (8.5 t/yr of propellant), once per year (17.0 t/yr), and twice per year (34.0 t/yr).

Table 3 shows the time for an ISRU architecture (producing propellant at rates of 8.5, 17.0, and 34.0 t/yr) to break even relative to a corresponding propellant delivery architecture. Due to the stepwise nature of the modeling of the architectures, mission durations longer than the breakeven times in Table 3 may lead to propellant delivery becoming less expensive than propellant production; the durations represent the earliest duration over which ISRU propellant production reaches a breakeven point.

Table 3: Time to reach breakeven at three notional propellant demands related to notional future lunar architectures

ISRU Plant	ISRU Lifetime (yr)	Prop Demand (t/yr)		
		8.5	17.0	34.0
MREE	1	N/A	N/A	N/A
	3	2.9	2.2	2.0
	5	4.4	2.9	2.2
Duke	1	N/A	6.9	1.5
	3	5.8	2.2	1.1
	5	4.4	2.2	1.1

5.4. Cumulative Cost Ratio

Figure 21 to Figure 25 show the Cumulative Cost Ratio (CCR), defined as the ratio of the cumulative cost of the propellant production architecture to the cumulative cost of the propellant delivery architecture and the propellant delivery architectures. The filled contour area indicates the combinations of mission duration and propellant demand that yield an ISRU architecture that breaks even within the duration of the mission, with a lower contour value indicating a greater savings for ISRU relative to propellant delivery from Earth. The labelled white lines indicate constant values of cumulative cost ratio. Conversely, the hatched area represents architectures that do not break even. As the propellant demand and mission duration increase, ISRU generally becomes the less expensive approach to providing propellant on the lunar surface.

In this model, increases in ISRU system lifetime have a significant effect on the value of propellant production by lunar ISRU. Table 4 shows the fraction of the trade space where the cumulative cost ratio is less than 1 and less than 0.5, as a function of ISRU Lifetime. The CCR threshold of 0.5 is chosen as a level at which even if the cost of the propellant production architecture is inaccurate by a factor of two, breakeven is still achieved. As can be seen for the Duke ISRU architecture, increasing the lifetime from 1 year to 5 years increases the number of architectures that will break even from 42% to 66%. Over the same range of lifetimes, the MREE plants went from not breaking even at all to breaking even in 62% of the mission duration and propellant demand space.

A limitation of this analysis is the non-optimal matching of ISRU system size to propellant demand. As propellant demand increases in the MREE ISRU architecture, either the number of ISRU systems or the size of each individual ISRU system increases to match the demand (thus manifesting on a larger lunar lander/launch vehicle pair); this can lead to non-intuitive results, such as the gaps and non-continuous behaviors in the cumulative cost ratio figures. The Duke ISRU architecture does not scale in the same way due to its performance capabilities; a single ISRU system (and associated lander and launch vehicle) is required to meet all propellant demands examined in this analysis. However, because the model is constrained to have a floor for the sizing of the ISRU system, the resulting system cannot fully use its capability for propellant production, effectively reducing the cost efficiency of propellant production. Future work will improve the matching of the ISRU system to both propellant demand and a launch vehicle/lunar lander pair.

Table 4: Effect of ISRU system lifetime on the percentage of architectures that break even (where the cumulative cost ratio (CCR) is less than 1.0) and break even well (where the CCR is less than 0.5)

ISRU Plant	ISRU Lifetime (yr)	Fraction of Trade Space where CCR is less than:	
		1.0	0.5
MREE	1	0%	0%
	3	49%	0%
	5	62%	3%
Duke	1	42%	<1%
	3	63%	20%
	5	66%	28%

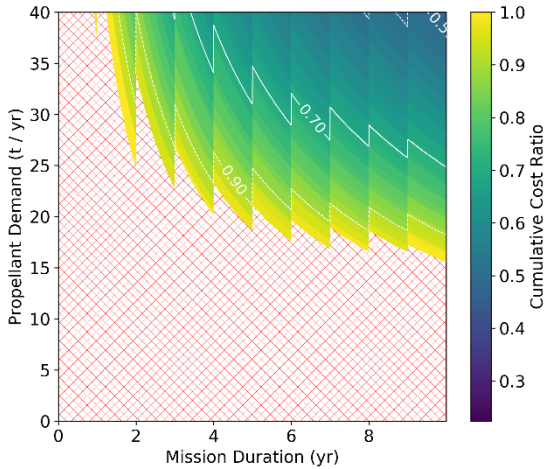


Figure 21: Cumulative cost ratio showing breakeven regions based on Duke model with a 1-year lifetime

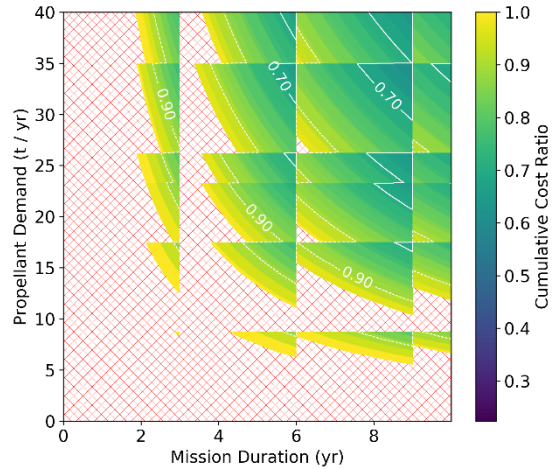


Figure 24: Cumulative cost ratio showing breakeven regions based on the MREE model with a 3-year lifetime

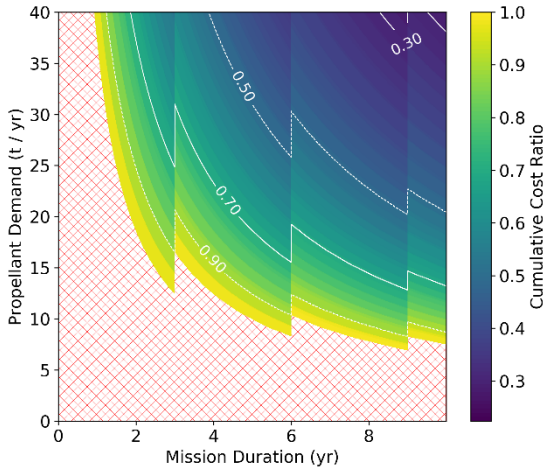


Figure 22: Cumulative cost ratio showing breakeven regions based on Duke model with a 3-year lifetime

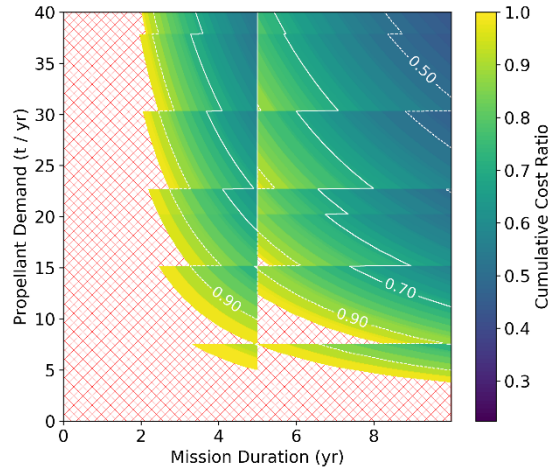


Figure 25: Cumulative cost ratio showing breakeven regions based on the MREE model with a 5-year lifetime

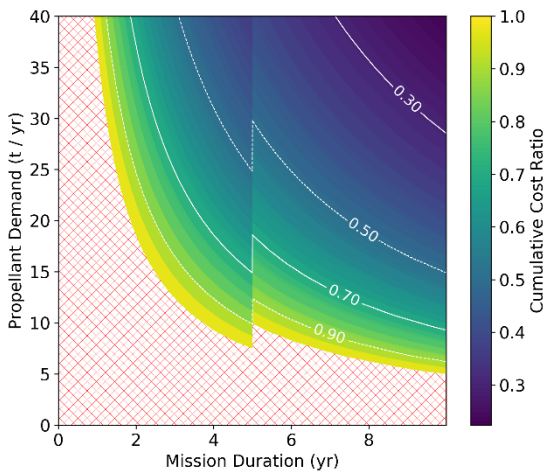


Figure 23: Cumulative cost ratio showing breakeven regions based on Duke model with a 5-year lifetime

5.5. Breakeven Relative to ISRU System Lifetime

For the previously presented notional architectures (with propellant demands of 8.5, 17.0, and 34.0 t/yr), Figure 26 and Figure 27 show how quickly breakeven can be achieved over a range of ISRU system lifetimes for both the Duke and MREE ISRU model respectively.

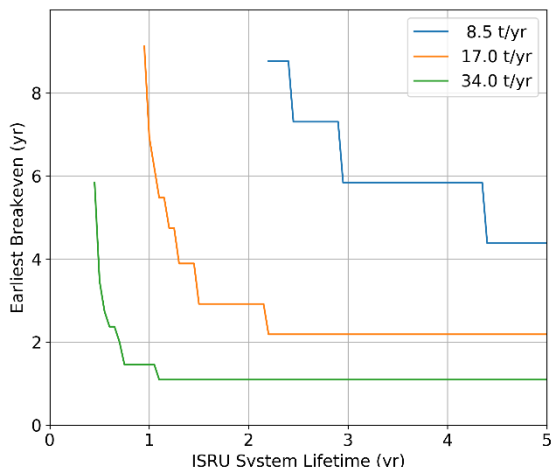


Figure 26: Relative performance of architectures in terms of the propellant demand, ISRU system lifetime, and the earliest breakeven time for the Duke ISRU model

Over the range of ISRU system lifetimes investigated, an interesting phenomena related to how the problem was modelled arose. In Figure 27, there is a break in continuity of the 8.5 t/yr propellant demand curve between ISRU lifetimes of approximately 3.3 and 3.75 (where breakeven does not occur within 10 years). This results from the stepwise nature of the model. As the ISRU system lifetime is increased, the amount of spares to be manifested on a lander increases while the mass of the ISRU system itself must be reduced to accommodate this change. A smaller ISRU system produces less propellant per year than a larger one; at a constant demand but an increasing ISRU lifetime (decreasing production rate per system), there comes a point where the number of ISRU systems required to meet that demand must be incremented by one. For the MREE ISRU model that point is reached at a lifetime of approximately 3.3 years, as seen in all three propellant demand curves.

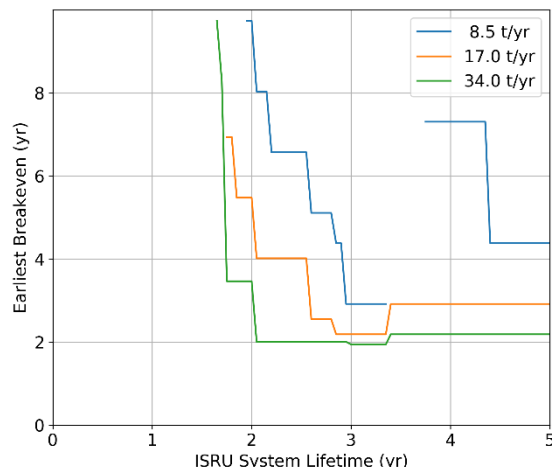


Figure 27: Relative performance of architectures in terms of the propellant demand, ISRU system lifetime, and the earliest breakeven time for the MREE ISRU model

6. Conclusions

The purpose of this study was to investigate what architectural conditions enable ISRU to breakeven with delivery from Earth for lunar propellant needs. This provides a better understanding of the value of lunar ISRU for lunar missions and architectures. By modeling two propellant production systems and comparing them to propellant delivery across a range of annual propellant demands and mission durations, this study assessed when and to what degree lunar ISRU compared favorably on the basis of cost. The use of both the SLS and commercial heavy lift capabilities was considered, with the optimal launch vehicle for each point in architectural space identified. The minimum number of ISRU systems required to meet the needs at each point in architectural space was also identified.

In this model, for high performing (on the basis of mass and power efficiency relative to propellant production rate) lunar ISRU systems with multi-year lifetimes, propellant production architectures break even within several years compared to propellant delivery from Earth. The ISRU system lifetime has a significant effect on breakeven points; an increase from 1-year to 3-year lifetimes increases the number of architectures that break even in the more conservative MREE model from 0% to 49% and in the more optimistic Duke model from 42% to 63%.

Based on this analysis, at a cadence of one human lunar mission per year (with an estimated demand of 17 t/yr), lunar ISRU could reach breakeven in as quickly as three missions if the ISRU system lifetime approaches three years. As propellant demand and/or mission duration increase, the savings realized compared to propellant delivery generally increase; however, the discontinuous increase in costs resulting from the addition of additional ISRU systems leads to regions

where breakeven does not occur. Alternative approaches to optimizing the launch vehicle-lunar lander-ISRU system triad could lead to more continuous mission requirement space.

For less frequent missions having a lower annual propellant demand, or for lunar campaigns with a shorter mission duration, lunar ISRU did not breakeven under either propellant production model. Thus, lunar ISRU is most useful for frequent visits to the same location on the Moon over several years; the scope of future plans to revisit the Moon will determine whether investing in lunar ISRU breaks even on the basis of cost with delivering propellant and consumables from Earth.

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