Cost Breakeven Analysis of Cis-lunar ISRU for Propellant

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Human missions to Mars require hundreds of tonnes of propellant in space. Lunar ice has been suggested as a potential source for the production of that propellant. This study answers the question: should lunar-derived propellants be used for human Mars missions, independent of any ongoing lunar mission? A parametric model was developed to assess the costs of delivering propellant to cis-lunar space from Earth as compared to the cost of producing that propellant on the lunar surface and delivering it to cis-lunar space. This study found that lunar-derived propellants are more expensive than Earth-launched propellant based on current estimates of capabilities and costs. Sensitivity analysis was performed to show that significant improvement in capabilities relative to projected performance are necessary to achieve cost parity with Earth-launched propellant. While there may be benefits to using lunar in-situ resource utilization to support lunar missions, and while a lunar infrastructure may someday exist that could supply propellant, this study indicated that supporting human missions to Mars is not a sufficient reason to develop and deploy a lunar propellant production capability.

I. Nomenclature

ΔV = Delta-V
DRA = Design Reference Architecture
IMF = Inert Mass Fraction
ISRU = In-Situ Resource Utilization
LEO = Low Earth Orbit
LH_2 = Liquid Hydrogen
LLO = Low Lunar Orbit
LO_2 = Liquid Oxygen
NAFCOM = NASA/Air Force Cost Model
PCEC = Project Cost Estimating Capability
PRICE-H = Parametric Review of Information for Costing and Evaluation - Hardware
SLS = Space Launch System

II. Introduction

Human exploration missions to Mars require large quantities of propellant in space to enable the transportation of required elements from Earth to Mars. Current and proposed launch vehicles are incapable of launching all of the requisite mass on a single vehicle; hence, multiple launches and in-space aggregation are required to perform a Mars mission. The Evolvable Mars Campaign [1], a recent study by NASA to identify potential approaches to performing human Mars missions, required hundreds of tonnes of propellant over the course of its three missions to Mars [2].

Recent evidence has indicated the presence of ice on the lunar poles [3]. This, in conjunction with the lower gravity for launching from the Moon relative to launching from Earth, suggests potential savings from delivering propellant to cis-lunar space from the lunar surface. Lunar in-situ resource utilization (ISRU) could be used to produce and deliver liquid oxygen and liquid hydrogen from the lunar surface to a propellant aggregation location. Such an

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approach could lead to future Mars missions requiring only the launch of spares and new Mars payloads from Earth to cis-lunar space, with the propellant being supplied from the Moon.

While the Moon could serve as a source of propellant for future exploration missions, any architecture that extracted and used lunar ice would require the development of several capabilities, including: resource prospecting and acquisition; propellant production, storage, and transfer; and reusable vehicles moving between the lunar surface and the propellant aggregation location. In addition to developing these capabilities, the associated systems would need to be built, launched, and operated. While the resulting system may reduce the need to launch mass from Earth relative to launching all the propellant, it is unclear if the costs associated with that capability development and deployment trade favorably with the costs of launching the propellant from Earth [4].

This research examined the question: how does propellant delivered to cis-lunar space from Earth compare to propellant delivered from the Moon on the basis of cost? A model was developed and exercised that parametrically captured the factors influencing the relevant costs of delivering propellant to cis-lunar space from Earth and from the Moon. The costs of delivering propellant to cis-lunar space from each potential source were estimated under several scenarios. Because such a model must include systems and technologies that are not yet fully matured, the effects of uncertainty in the model parameters were evaluated through sensitivity analysis. This enabled an understanding of the most important factors influencing the trade.

III. Previous Studies

Several recent studies have examined the use of lunar ISRU for propellant production. Ishimatsu et al. [5] developed a campaign logistics framework to assess the value of using lunar-derived propellant for performing the NASA Design Reference Architecture 5.0 (DRA 5.0) mission to Mars [6]. In that study, the authors "found that the baseline solution improves the total launch mass to LEO [Low Earth Orbit] (TMLEO) by 68% from DRA 5.0, once the transportation and ISRU infrastructure are deployed and operational in the lunar vicinity and on the lunar surface." However, the study did not address time dependencies: by the nature of the model, lunar-manufactured propellants were used to deploy the lunar ISRU systems that would produce that propellant. In addition, the 68% mass savings does not account for the mass required to deploy and operate the lunar propellant production system; those savings are only realized in a future state when missions to Mars are occurring regularly, not for the initial mission. A follow on study by Ho addressed the time dependency but showed a reduced mass savings of 22% from DRA 5.0 while also requiring years of lead-time before the first Mars mission [7]. Additionally, neither study addressed cost, instead making the comparison solely on the basis of launch mass from Earth.

Miller et al. developed an Evolvable Lunar Architecture that would perform commercial mining of propellant from the lunar poles to be used for NASA missions to Mars [8]. The authors noted that "[a] commercial lunar base providing propellant in lunar orbit might substantially reduce the cost and risk [to] NASA of sending humans to Mars." The study required the deployment of significant human infrastructure to support lunar mining. In addition, it relied on the existence of a strong public-private partnership to achieve cost savings. Without that partnership, and with the need to develop human lunar capabilities, it is unclear how the proposed approach trades with launch of propellant from Earth directly to lunar orbit.

Kutter proposed an oxygen and hydrogen propellant-based architecture for travel between Earth and the Moon [9]. He observed that "[a] price for lunar derived LO_2 and LH_2 propellant of $3M/ton in LEO will enable a launch company like ULA [United Launch Alliance] to reduce the overall price per kg to GEO [Geosynchronous Earth Orbit] […] the business case is the same whether propellant is purchased in LEO for $3M/ton, or GEO for $1M/ton, or at the moon for $0.5M/ton." The proposed architecture requires the deployment of significant lunar infrastructure to support the requisite lunar mining (e.g. approximately 100 kW of wireless power beaming capability at the lunar poles). In addition, the author remarked that "the business case presented above makes no claim whether it is economically feasible to mine and process lunar propellants for $500,000 per ton." Thus, the proposed approach requires significant capability developments to enable an architecture that may not meet the proposed business case.

IV. Architectures

A set of architectures was developed to compare different approaches for supplying propellant to cis-lunar space from Earth and from the Moon. An annual propellant demand, derived from the Evolvable Mars Campaign, was used to compare the costs of delivering propellant from the two sources. The architectures were defined by where the propellant originated, the buildup strategy for the ISRU infrastructure, and how the propellant was transported. The complete list of architectures examined in this study include:

1. Propellant delivered from Earth via tanker(s) launched on the in-development NASA Space Launch System (SLS).
2. Propellant delivered from Earth via tanker(s) launched on a commercial vehicle.
3. Propellant delivered from the Moon using a reusable lunar lander between the Moon and cis-lunar aggregation. All-up deployment of ISRU infrastructure.
4. Propellant delivered from the Moon using a reusable lunar lander between the Moon and low Lunar orbit (LLO), and using a reusable in-space stage between LLO and cis-lunar aggregation. All-up deployment of ISRU infrastructure.
5. Propellant delivered from the Moon using a reusable lunar lander between the Moon and cis-lunar aggregation. Bootstrapped deployment of ISRU infrastructure.
6. Propellant delivered from the Moon using a reusable lunar lander between the Moon and LLO, and using a reusable in-space stage between LLO and cis-lunar aggregation. Bootstrapped deployment of ISRU infrastructure.

In Architecture 1 and Architecture 2, propellant was launched from Earth to the cis-lunar aggregation point using one or more launch vehicles, each carrying as a payload a tanker with propellant. As represented graphically in Fig. 1, Architecture 1 used the SLS to deliver the tankers, while Architecture 2 used commercial launch vehicles. These two architectures served as the basis against which the lunar ISRU propellant architectures were compared.

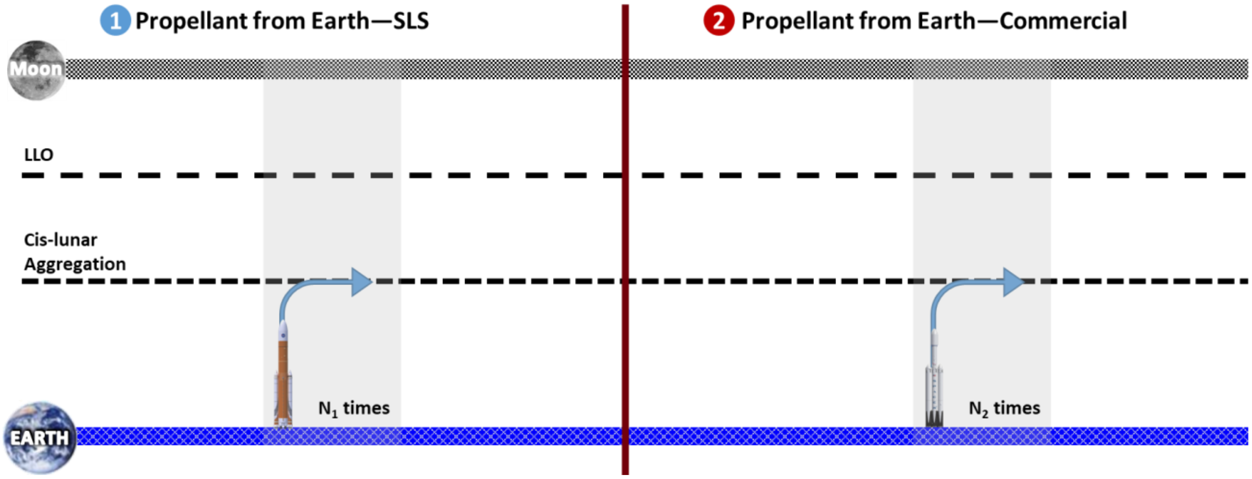

Fig. 1 Concepts of operations for delivery of propellant from Earth.

For lunar supplied propellant, four architectures were developed to examine multiple approaches for delivering the lunar infrastructure and transporting the propellant to cis-lunar space. In Architecture 3 and Architecture 4, the full propellant production capability required to meet the annual demand was delivered from Earth and deployed prior to the start of production. This approach, where all ISRU infrastructure was deployed using Earth-launched capabilities and prior to the start of lunar propellant production, was referred to as “All-Up”. The concepts of operations for the two All-Up architectures are shown in Fig. 2, with the distinction being either a one- or two-vehicle in-space transportation architecture. For the one-vehicle architecture (Architecture 3), a single reusable lunar lander delivered propellant directly from the lunar surface to the cis-lunar aggregation point. For the two-vehicle in-space architecture (Architecture 4), a reusable lunar lander delivered propellant from the lunar surface to a reusable in-space stage in LLO, where that stage then delivered propellant from LLO to the cis-lunar aggregation point.

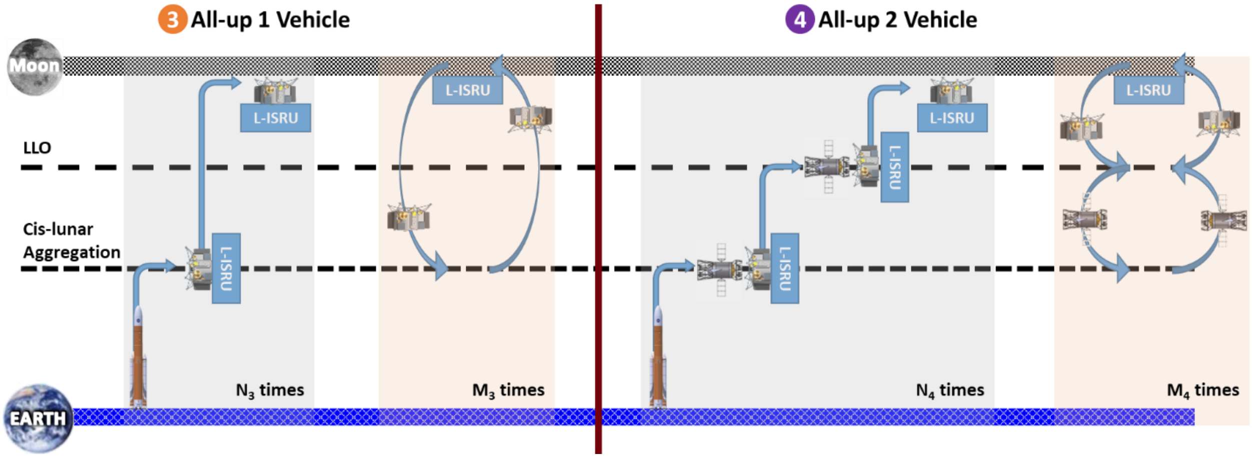

Fig. 2 Concepts of operations for All-Up delivery of lunar ISRU, using one or two vehicles for propellant transport.

Architecture 5 and Architecture 6 used an alternative approach to the "All-Up" strategy where a smaller initial ISRU system is deployed from Earth. This initial ISRU system produced propellant from lunar resources to enable the lander (and in Architecture 6, the in-space stage) to return to the cis-lunar aggregation point to retrieve additional ISRU systems and deliver them to the lunar surface. In this way, the lunar ISRU capability was built up over time, and the mass required from Earth to deliver the ISRU systems was reduced. This approach was referred to as "Bootstrapping" and is shown in the concepts of operations in Fig. 3.

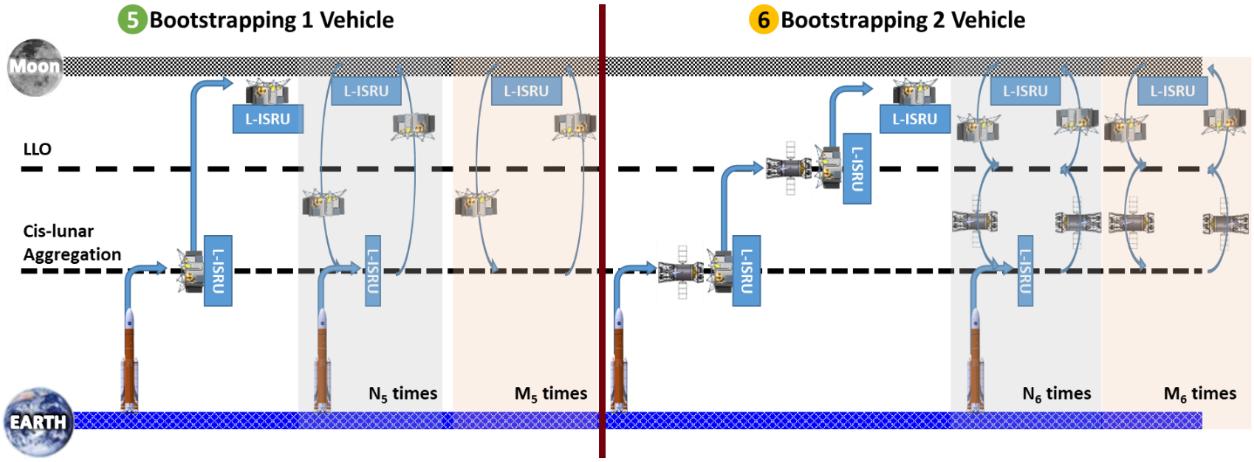

Fig. 3 Concepts of operations for Bootstrapping delivery of lunar ISRU, using one or two vehicles for propellant transport.

V. Element Sizing and Costing

Several ground rules and assumptions served as the basis to perform the assessment of the six architectures. First, the use of oxygen and hydrogen propellant was assumed. Previous analysis identified 59 tonnes/year (t/yr) of hydrogen/oxygen propellant for 14 years as an appropriate demand rate to perform the Evolvable Mars Campaign [2]. Next, the SLS Block 2 was used for launch of all lunar infrastructure, as well as the propellant in Architecture 1, with a capability of delivering 45 tonnes to the cis-lunar aggregation point. In Architecture 2, a next generation heavy lift commercial vehicle (e.g. Falcon Heavy, New Glenn), with an assumed launch capability of 15 tonnes to the cis-lunar aggregation point, was used for propellant delivery. The ΔV for transfer between the cis-lunar aggregation point and LLO was assumed to be 640 m/s, while the ΔV for transfer between LLO and the lunar surface was assumed to be 1,870 m/s. In the lunar ISRU architectures, a reusable lunar lander and (in Architectures 4 and 6) a reusable in-space stage were assumed both for delivering payloads to the lunar surface as well as for transporting propellant from the lunar surface to the cis-lunar aggregation point. Inert mass fraction (IMF) sizing was used for both the reusable lunar lander and the reusable in-space stage, with baseline values of 0.26 for the lander (based on the authors' assessment of the Altair lunar lander concept) and 0.13 for the in-space stage (based on the authors' assessment of the Delta Cryogenic Second Stage).

On the surface, a robotic, modular ISRU system with nuclear power would mine lunar ice, process it into hydrogen and oxygen, and liquefy and store the propellant for later use. This system was assumed to be capable of deploying, operating, and maintaining itself without physical human intervention. Zero boil off propellant storage and lossless transfer was assumed for the hydrogen and oxygen in all architectures (on the surface and in space). The mass of the nuclear power system was sized using a specific mass (in kg/kW), using the performance of a high power design from Mason of 75 kg/kW [10]. Little data exists in the literature to inform parametric sizing of integrated, large-scale lunar ice mining and processing systems; instead, parametric sizing of the system was performed using baseline values derived from a lunar molten regolith electrolysis system. Although lunar ice mining is a significantly different process from molten regolith electrolysis, the values served as starting points for the sensitivity analysis described below, as well as serving as potential capability targets for the development of lunar ice mining systems. An excavation system was sized based on a parameter of 10 kg of excavator mass per tonne/year of propellant produced on the lunar surface (kg/(t/yr)). The propellant production plant was sized based on a parameter of 109 kg of plant mass per tonne/year of propellant produced on the lunar surface (kg/(t/yr)). The power required by the ISRU system was sized based on a parameter of 48 kW required per tonne of ISRU system (kW/t). These values were taken from the work of Schreiner [11]. In addition, it was assumed that spares for the lunar infrastructure would be needed over the 14 years of operation; the value assumed in this study was 10% of the system mass per year was needed [5]. A summary of these values, as well as the ranges over which they were varied for sensitivity analysis, is shown in Table 1.

Table 1 Summary of key parameters and assumptions used in the analysis.

Parameter	Value	Sensitivity Range
Propellant demand, t/yr	59	10-1000
Propellant production duration, yr	14	5-40
Reusable lunar lander IMF	0.26	0.2-0.3
Reusable lunar lander maximum gross mass, t	45	N/A
Reusable in-space stage IMF	0.13	0.1-0.2
Reusable in-space stage maximum gross mass, t	45	-
SLS payload to cis-lunar aggregation point, t	45	-
Commercial LV payload to cis-lunar aggregation point, t	15	-
LOX-H_2 ISP, sec	450	-
Nuclear power plant specific mass, kg/kW	75	25-125
Excavator mass, kg/(t/yr)	10	-
Propellant plant mass, kg/(t/yr)	109	10-175
ISRU specific power, kW/t_{ISRU}	48	5-77
Spares (percent of system mass per year)	10%	-

The objective of this study was to compare architectures for supplying propellant to cis-lunar space from Earth and from the Moon on the basis of cost, rather than just mass. To compare architecture costs, individual element cost estimates were developed using multiple methodologies. For the propellant tankers, reusable lunar lander, and reusable in-space transportation stage, cost estimates were developed using two parametric cost models: the Project Cost Estimating Capability (PCEC) and the Parametric Review of Information for Costing and Evaluation - Hardware (PRICE-H). PCEC is a NASA-developed parametric cost tool, succeeding the NASA/Air Force Cost Model (NAFCOM), which estimates costs at a subsystem level. PRICE-H is a commercially developed, component-level modelling tool by PRICE Systems, Inc. PCEC was used to estimate the reusable lunar lander and in-space stages, while PRICE-H was used for the Earth-based propellant tankers. The launch costs for the commercial launch vehicles and SLS were based on the Launch Services Provider Catalog and a rough order of magnitude estimate, respectively. This study assumed an ongoing human exploration campaign concurrent with each of these architectures; this ongoing campaign would cover the fixed costs of the SLS program, while the costs included in this model were the marginal cost for each required SLS. Due to the uncertainty around this cost, the sensitivity of results to the marginal SLS cost was examined and was found to not change the trends or ordering of the results for the different architectures. The lunar surface infrastructure cost estimates were developed by leveraging previous architecture studies, specifically Constellation.

Learning curve improvements were not included in the cost estimate results presented in this paper; however, an initial assessment of the impact of learning curve improvements was performed, and the ordering of architectures on the basis of cost did not shift. The costs assessed in this study did not include flight and mission operations, technology advancement, spares (see Baseline Results section for further discussion on spares costs), or any of the Mars mission systems. Reserves were included in the cost estimates of all elements, with the exception of launch vehicles. All costs were evaluated in fiscal year 2018 dollars.

VI. Baseline Results

This study utilized a parametric modelling approach to allow for rapid exploration of performance and cost sensitivities of the six architectures. The metric for evaluating the architectures was the cost per kilogram of propellant delivered to cis-lunar space, calculated as the total architecture cost divided by the total propellant delivered to meet annual demand over the time horizon. The resulting costs per kilogram of each of the six architectures using the baseline values of the model parameters are presented in Fig. 4. The most cost effective architecture overall was Architecture 2 (commercial delivery from Earth) at $40,000/kg followed by Architecture 1 (SLS delivered propellant) at $46,000/kg. The least expensive lunar ISRU architecture was Architecture 5 (Bootstrapping with only the reusable lander) at a cost of $78,000/kg. In other words, lunar ISRU propellant was found to be 97% more expensive than Earth-based propellant. Therefore, under the assumptions used in this study, which the authors see are favorable towards lunar ISRU, the most cost effective approach to deliver propellant to cis-lunar space is to launch it from Earth. Table 2 shows the cost per kilogram of propellant for each of the six architectures under the baseline assumptions.

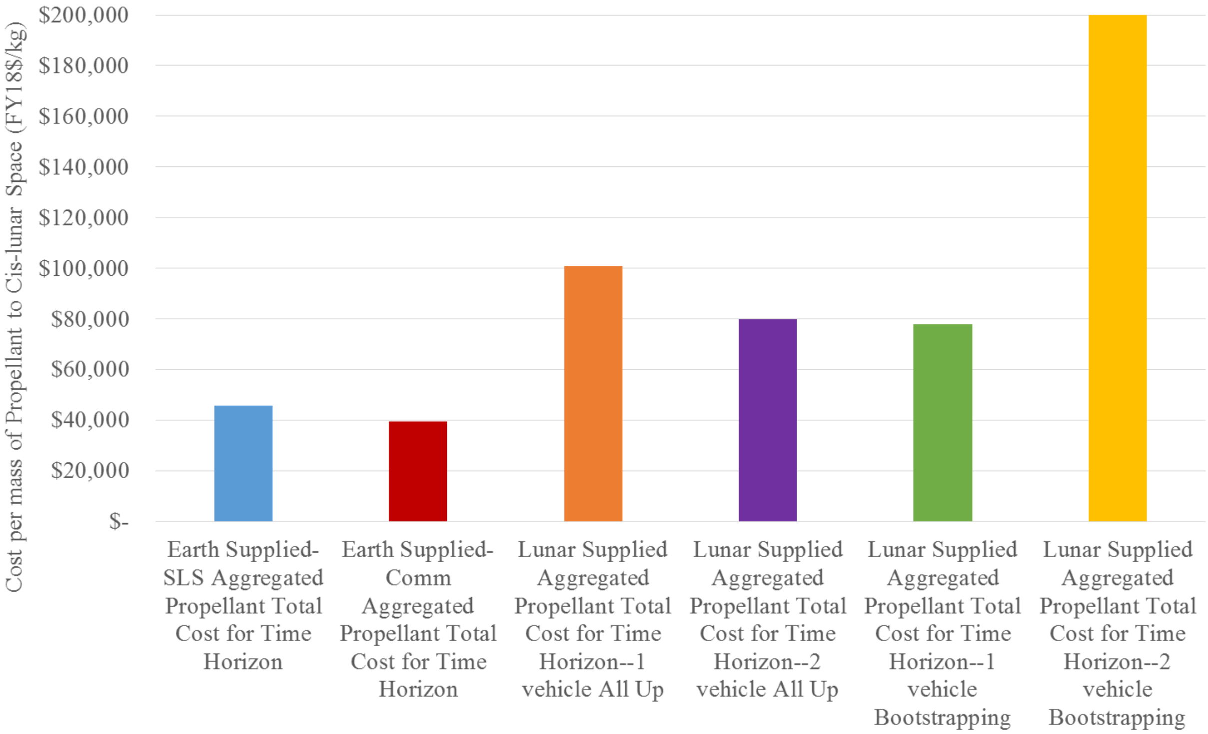

Fig. 4. Cost per mass of propellant delivered to cis-lunar space for the six architectures examined in this study using the baseline modeling parameter values.

The high cost per kilogram of Architecture 6 resulted from the large number of additional ISRU systems that were retrieved and delivered, the time it took to produce sufficient propellant using the existing capability to retrieve additional plants, and the number of spares required to support the growing lunar infrastructure during that time. Under the baseline assumptions, 262 additional plants were needed (each producing less than 6 t/yr of propellant) to meet the annual demand of 59 t/yr in cis-lunar space (which corresponds with a production rate on the lunar surface of 594 t/yr). Because of the slow rate at which lunar propellant production capacity was built up, Architecture 6 required 63 years from the initial delivery of an ISRU capability to reach full production. Over that time, 31 SLS flights were required to deliver the spares to meet the sparing rate in Table 1. These numbers resulted from the nature of the architecture model; a concept of operations that leverages more initial deployment prior to bootstrapping would likely reduce these numbers.

Table 3 includes two additional metrics for comparing the different architectures: the propellant efficiency and the total number of SLS launches for the 14-year time horizon. The propellant efficiency was used to compare the four lunar ISRU architectures and is defined as the ratio of usable propellant for Mars delivered to cis-lunar space to the total propellant produced on the Moon. The number shows how much propellant is required by the reusable lunar lander (and reusable in-space stage in Architecture 4 and Architecture 6) to meet the propellant demand. Based on the performance of the lander and the trajectory requirements, the efficiency varies from 10% to 19%.

Table 2 Cost per mass of propellant for each architecture under baseline assumptions.

Architecture	Cost ($/kg)
1	46,000
2	40,000
3	101,000
4	80,000
5	78,000
6	202,000

Table 3 Propellant efficiency and number of SLS launches for each architecture.

Architecture	Propellant Efficiency	Total SLS Launches
1	N/A	28
2	N/A	0
3	15%	32
4	19%	22
5	15%	21
6	10%	50

VII. Sensitivity Results

To identify the levels of required capability for lunar ISRU to reach cost parity with propellant delivered from Earth, and to address the uncertainty in the parametric modeling of the lunar ISRU architectures, sensitivity analysis was conducted on several parameters. The parameters analyzed were those in Table 1 with an identified sensitivity range. Fig. 5 shows the changes in the cost per kilogram metric as a function of changes in the reusable lunar lander IMF. Even significant improvements in lander performance relative to the baseline IMF value of 0.26 only lead to one architecture, Architecture 5 (Bootstrapping with only the reusable lander), reaching cost parity with Earth launch, at an IMF of 0.21.

Fig. 6 shows the sensitivity of the architecture costs relative to the nuclear power system performance. The baseline specific power assumed in this study of 75 kg/kW is more efficient than more recent, lower power designs, which exceed 125 kg/kW [12]. A factor of three improvement beyond this high-performing baseline in power system specific mass is required for the lunar-supplied propellant architectures to reach cost parity with Earth-launched propellant; at that improvement (25 kg/kW), only Architecture 5 breaks even.

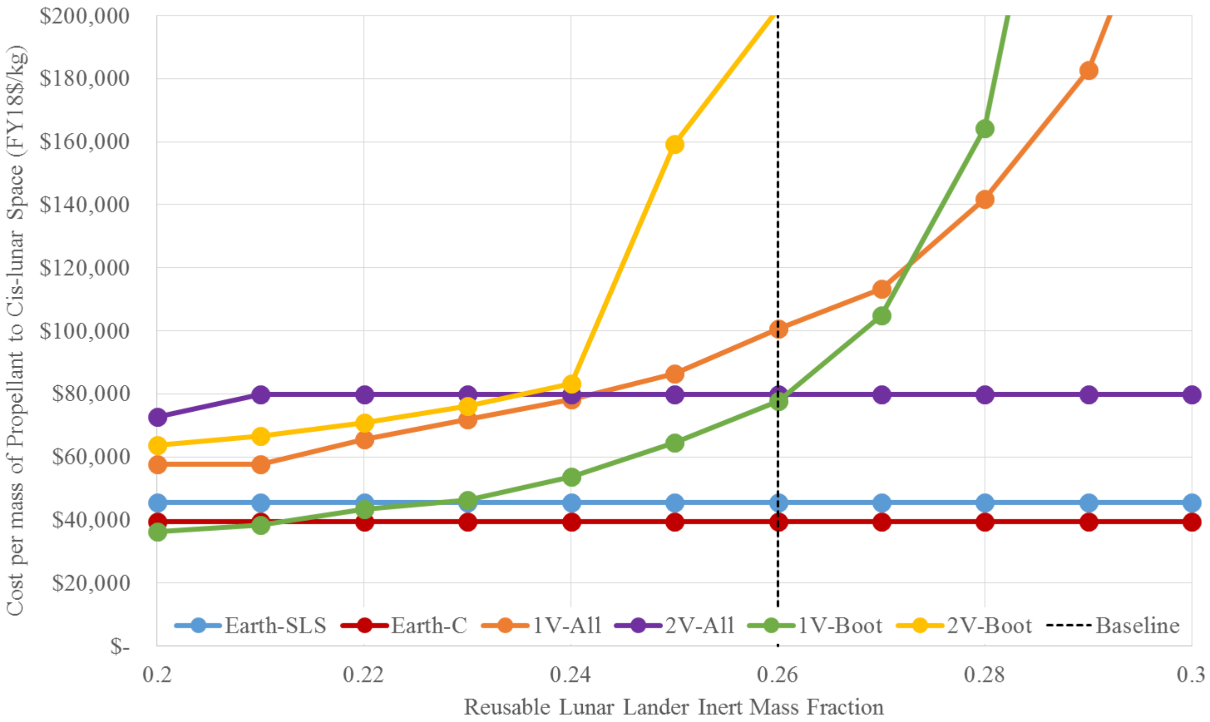

Fig. 5 Sensitivity of the cost per mass of propellant to cis-lunar space to the reusable lunar lander inert mass fraction.

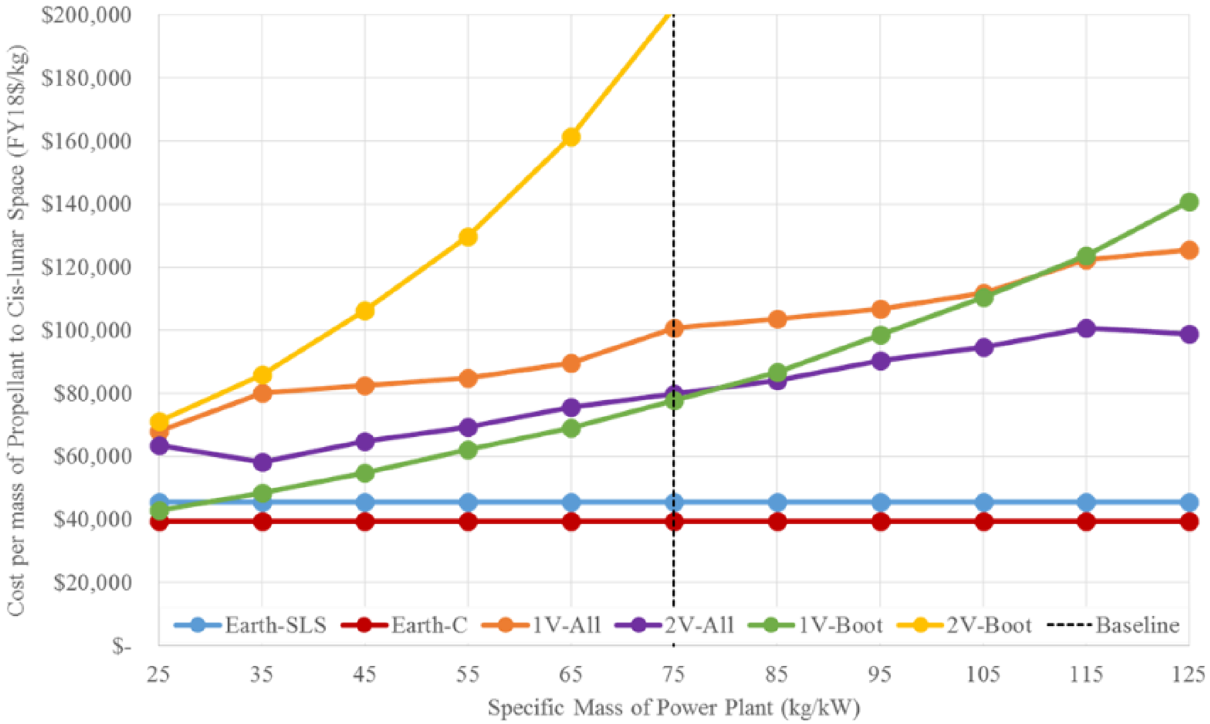

Fig. 6 Sensitivity of the cost per mass of propellant to cis-lunar space to the specific mass of the lunar power plant.

The lunar ISRU architectures were highly sensitive to the mass efficiency of the propellant production plant, as shown in Fig. 7. The baseline value of 109 kg plant mass per ton per year of propellant produced represents the mass efficiency of a molten regolith electrolysis system. A lunar ice ISRU system would need to be 2-3 times more efficient than this baseline for lunar-based propellant to become competitive with Earth-launched propellant. In other words, a lunar ice ISRU system as assumed in this study would need to be better than 50 kg/(t/yr) to reach cost parity. As shown in Fig. 8, the specific power of the ISRU system also has a significant impact on the cost per kilogram of the lunar ISRU architectures. The specific power would need to improve by 2-5 times (e.g. <20 kW/t_{ISRU}) relative to the molten-regolith-electrolysis-derived value for lunar based propellant to compare favorably with Earth-launched propellant.

Next, the time horizon was varied to find the breakeven point for when lunar ISRU propellant costs equal the costs of Earth-launched propellant. As seen in Fig. 9, for baseline values, the breakeven point occurs at 35 years of an annual propellant demand of 59 t/r; following the mission cadence of the Evolvable Mars Campaign, this equates to approximately seven human mission to Mars. Including the costs of spares and replacement of the reusable lunar landers and in-space stages, which were not included in this study, would push the breakeven point even further out.

Although the cost of spares was not included in this analysis, the cost to launch the additional mass was. The lack of spares costs is a major caveat of this study, as the full duration of the campaign to deploy lunar ISRU infrastructure and use it to execute the Evolvable Mars Campaign could extend to multiple decades. Similarly, the study did not include costs to replace the reusable landers, reusable in-space stages, and surface infrastructure. To determine if the sparing requirement described above significantly influenced the results between Earth-based and lunar-based propellant, the model was run with no sparing requirements. Even with a 0% sparing requirement, Earth-based propellant was still less expensive than any of the four lunar ISRU architectures, as shown in Table 4. The addition of spares costs would lead Earth-based propellant to trade even more favorably vs. lunar produced propellant. Including spares costs was identified as a priority for future work.

Table 4 Cost of each architecture under baseline assumptions with 0% sparing requirement.

Architecture	Cost at 0% Sparing ($/kg)
1	46,000
2	40,000
3	66,000
4	53,000
5	47,000
6	72,000

For each of the model parameters examined in Figs. 4-8, significant improvements are required in each single parameter to achieve cost parity. However, it is possible that incremental improvements to multiple parameters produce the necessary cumulative effect. Although in depth multivariate sensitivity analysis was not conducted in this study, a general percentage improvement to the key parameters above (reusable lunar lander IMF, specific mass of power plant, specific mass of propellant plant, and specific power of ISRU) was assessed. Fig. 10 displays the cost per kilogram of the six architectures for a range of percent increase and decrease in performance for these parameters (that is, each of the four parameters is changed by and equal percentage from their values in Table 1). An 11% improvement in each of the four parameters was required for the best lunar ISRU architecture, Architecture 5 (Bootstrapping with only a reusable lander), to achieve cost parity with Earth-supplied propellant. This improvement would be beyond the already favorable values in the baseline analysis.

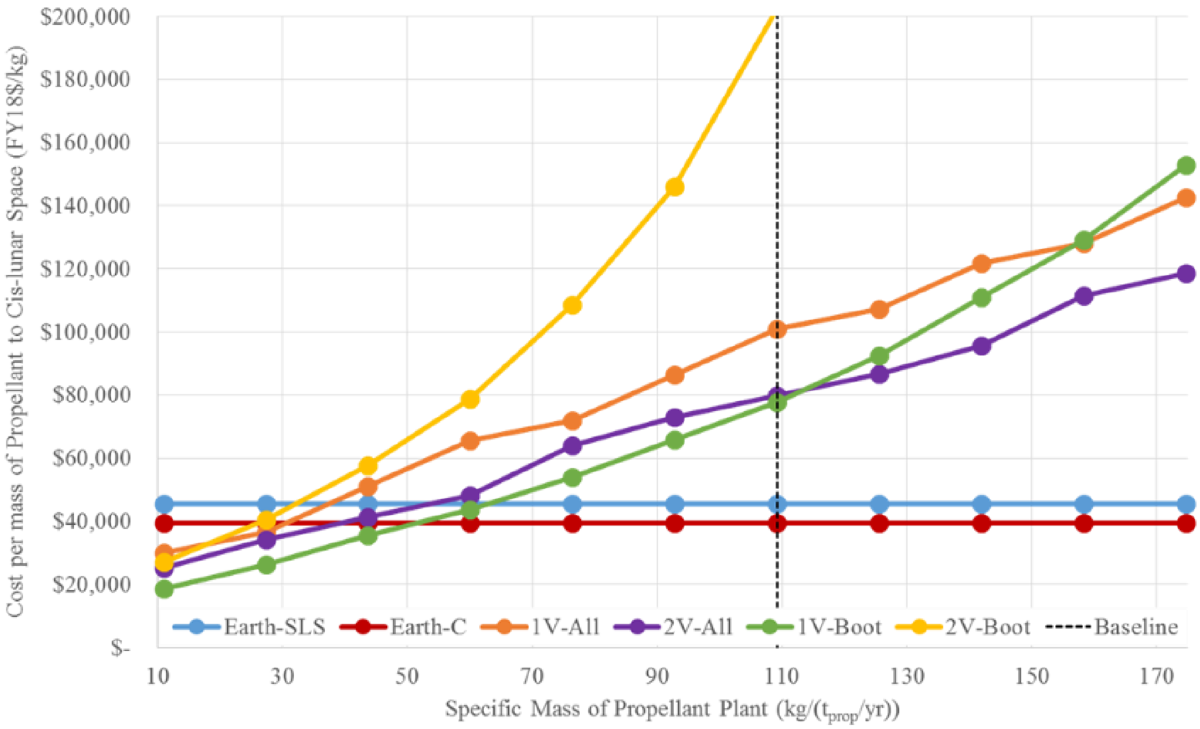

Fig. 7 Sensitivity of the cost per mass of propellant to cis-lunar space to the specific mass of the lunar ISRU propellant plant.

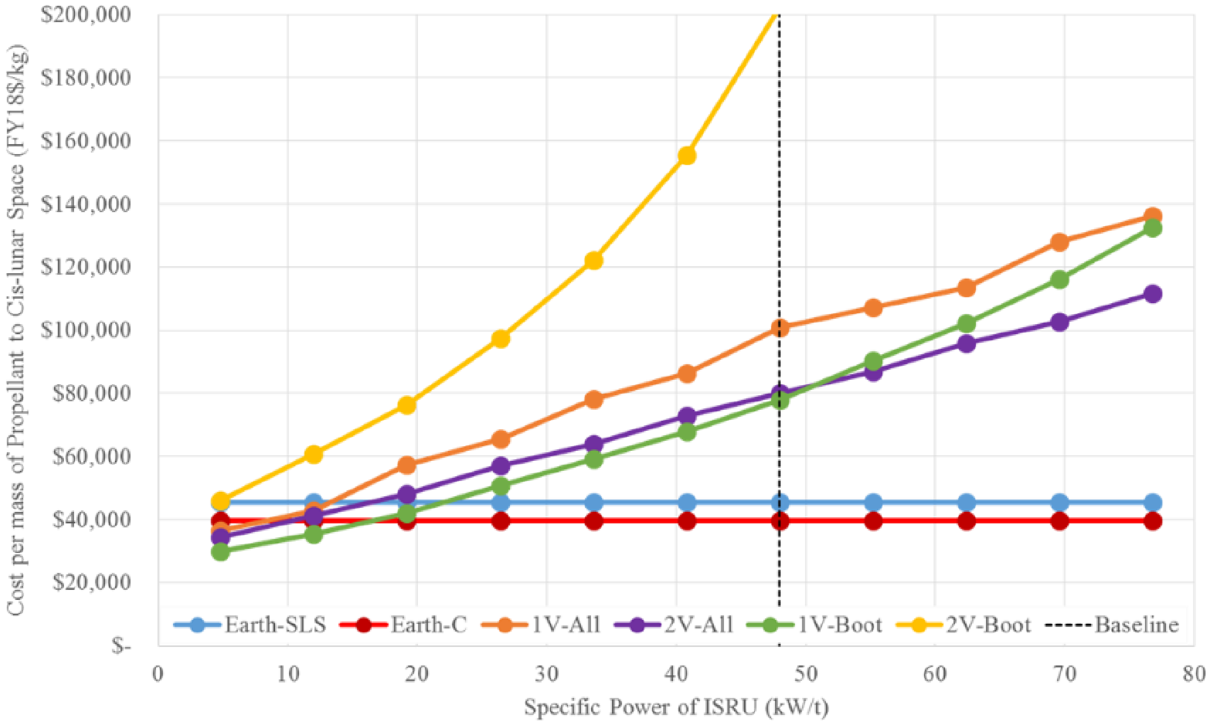

Fig. 8 Sensitivity of the cost per mass of propellant to cis-lunar space to specific power of the lunar ISRU propellant plant.

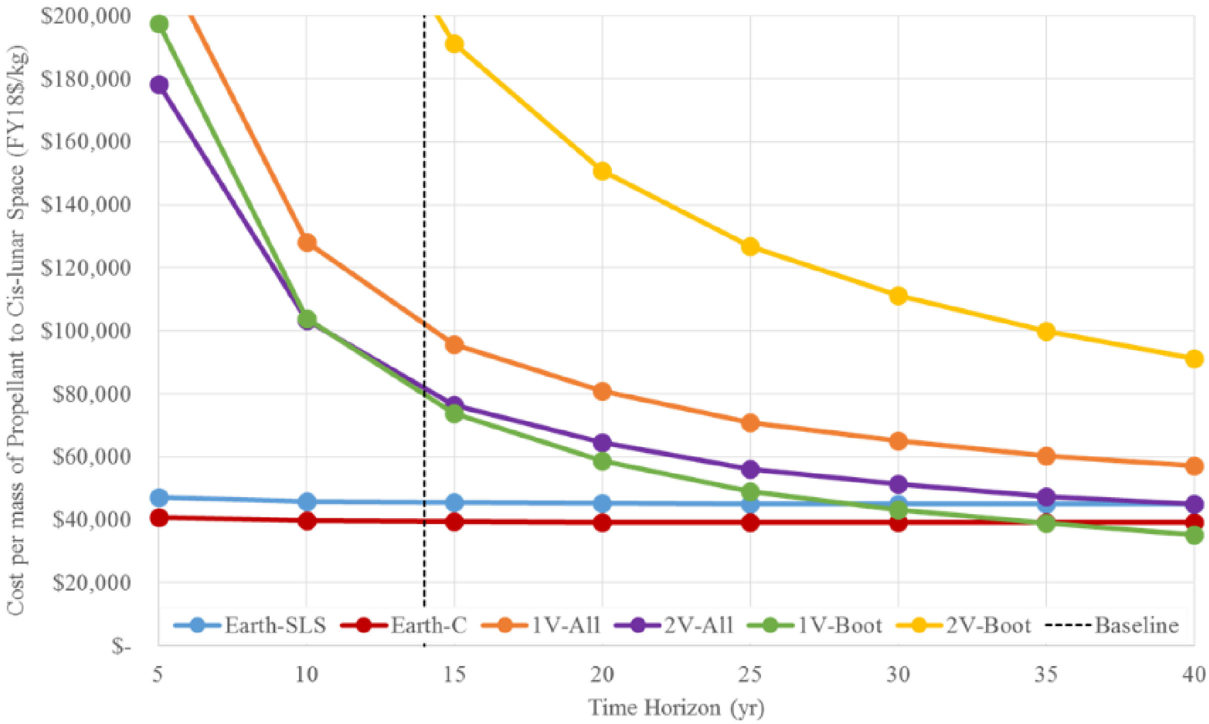

Fig. 9 Sensitivity of the cost per mass of propellant to cis-lunar space to the time horizon of the Mars campaign.

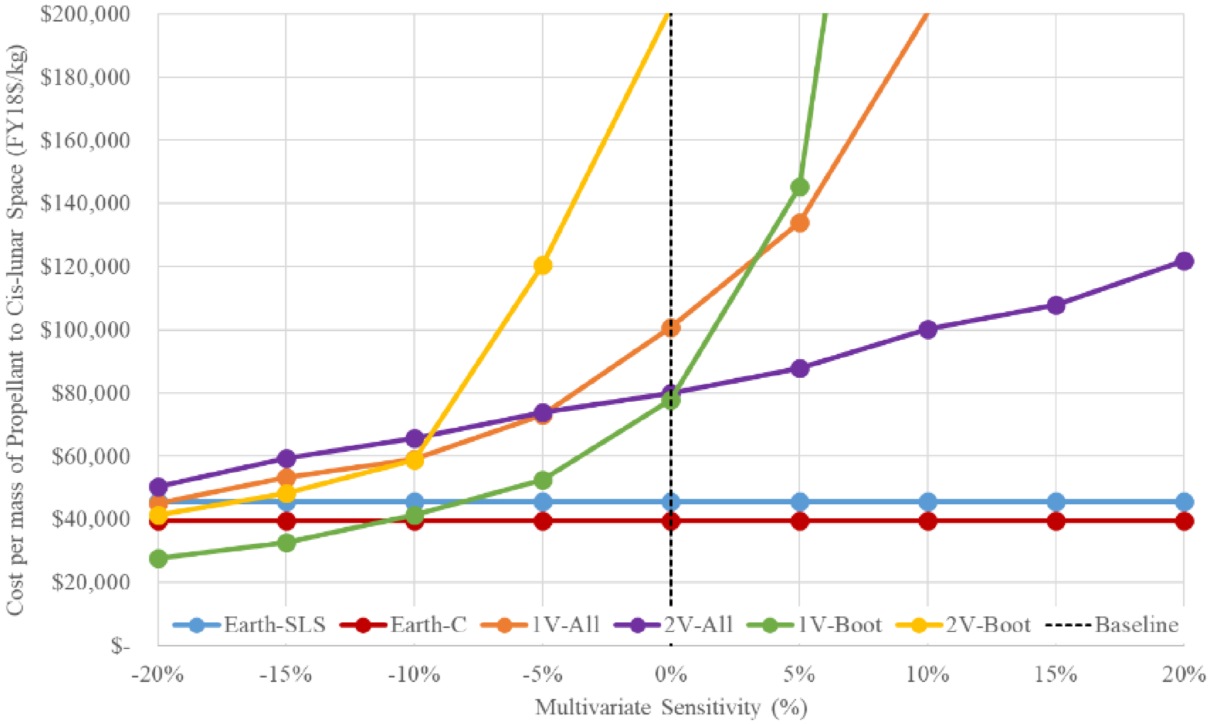

Fig. 10: Multivariate sensitivity of cost per kilogram delivered to cis-lunar space to changes in reusable lander IMF, specific mass of the power system, specific mass of the propellant plant, and specific power of the ISRU system.

The sensitivities of several other parameters were analyzed and showed either minimal sensitivity or no change in the ordering of the architectures. For example, the cost per kilogram showed almost no sensitivity to the inert mass fraction of the in-space stage, which was varied from 0.1 to 0.2. Similarly, varying annual propellant demand from between 10 and 1000 t/yr showed no crossover between lunar ISRU and Earth-based propellant cost; analysis showed that regardless of demand, the increased costs of launching and deploying additional ISRU capability exceeded the additional costs to launch more propellant from Earth.

VIII. Conclusion and Recommendations

For propellant requirements derived from the Evolvable Mars Campaign, lunar ISRU propellant is 97% more expensive than Earth-based propellant. For this model, the least expensive propellant option was commercial launch at $40,000/kg to cis-lunar space; for lunar ISRU to trade favorably, the cost for lunar propellant to be delivered to cis-lunar space would need to reach this point. Because the propellant efficiency of propellant delivered to cis-lunar space relative to propellant produced on the Moon varied from 10% to 19% across the four architectures, propellant would need to be produced at $4,000-$8,000/kg on the Moon. Even with favorable ISRU modeling assumptions, it is unlikely that lunar ISRU is a cost-effective approach to providing propellant in cis-lunar space in the near term.

In this study, lunar ISRU propellant production did not reach a cost breakeven in the baseline 14 years required to meet the propellant requirements derived from the Evolvable Mars Campaign. Instead, the breakeven point for lunar ISRU was 35 years, or approximately seven Mars missions. Although the cost of lunar ISRU was sensitive to time horizon, it does not depend on the annual demand for propellant in space; under the assumptions in this model, the increases in costs for additional ISRU infrastructure, including the launch costs to deploy it, exceeded the increases in cost for additional propellant launches from Earth. The breakeven time is also insensitive to annual demand.

The architectures evaluated here do not encompass the entire solution space; alternative architectures may improve the cost performance of lunar ISRU. Commercial launch vehicles would offer an opportunity to reduce the launch costs of the lunar infrastructure; however, the smaller payload capacities may necessitate an increase in additional launches such that the reduction in launch costs are exceeded by the costs associated with the number of additional systems. In addition, an approach between the All-Up and Bootstrapping described here (for example, with multiple launches to build an initial capability before bootstrapping begins) may combine some of the cost benefits of both approaches.

Whether hydrogen and oxygen is delivered to cis-lunar space from Earth or from the Moon, there are common capabilities that would be needed: cryogenic propellant storage, microgravity cryogenic propellant transfer, and cryogenic-propellant-burning engines capable of multiple restarts. Development of these capabilities would be enabling for a hydrogen/oxygen, propellant-transfer-based transportation architecture regardless of the source of the propellant.

Enabling lunar ISRU requires the maturation of multiple capabilities: reusability, autonomy, resource prospecting, resource acquisition, and propellant production. As the knowledge of these capabilities improves, the uncertainty in their performance and cost will decrease, enabling higher-fidelity analysis of lunar propellant production architectures. Other factors that merit further analysis include the impact of system reliability on the lunar propellant production trade (e.g. the reliability of reusable lunar landers over multiple flights), the impact of uncertainty in the cost estimates, and the performance of the previously described alternate concepts of operations.

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