Cost Breakeven Analysis of Lunar In-Situ Propellant Production for Human Missions to the Moon and Mars

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NASA is preparing to return humans to the lunar surface as a first step to a human exploration campaign of Mars. Both a sustained lunar campaign and a campaign of missions to Mars will require tens to hundreds of tonnes of propellant. Although this propellant could be delivered from Earth, an alternative approach is to use the potentially vast quantities of lunar ice to enable in-situ propellant production on the lunar surface. This study evaluates the cost breakeven for using lunar-derived propellants, as opposed to those delivered from Earth, in support of an extended human exploration campaign with both a multi-year presence on the Moon as well as multiple crewed missions to Mars. In so doing, the value of lunar propellant production is considered in the context of future exploration priorities, addressing the question: over what range of human missions to the lunar surface and Mars does in-situ propellant production trade favorably with propellant delivery from Earth on the basis of cost? The results of this analysis show that the magnitude and duration of the lunar campaign, more so than the Mars campaign, drive the breakeven and that without long lifetime ISRU systems, with greater than 5 years of autonomous operation before replacement, the demand in cis-lunar space for a Mars campaign favors propellant delivery from Earth.

I. Nomenclature

a, b, c, d	=	Lander Cost Estimating Relationship Coefficients
C	=	Cost in FY19 $M
CERs	=	Cost Estimating Relationships
DDT&E	=	Design, Development, Testing, and Evaluation
ΔV	=	Velocity change magnitude for orbital maneuver
DRA	=	Design Reference Architecture
ECLS	=	Environmental Control and Life Support
GEO	=	Geosynchronous Earth Orbit
IMF	=	Inert Mass Fraction, a factor that influences a vehicle's performance/capability
I_{sp}	=	Specific Impulse, a measure of a vehicle's propulsive performance
ISRU	=	In-Situ Resource Utilization
l	=	Design Lifetime in Months
LEO	=	Low Earth Orbit
LH_2	=	Liquid Hydrogen

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LLO	=	Low Lunar Orbit
LO_2	=	Liquid Oxygen
L1	=	Lagrange Point 1 for the Earth-Moon System
m	=	Mass in kg
MREE	=	Molten Regolith Electrolysis Equivalent
n	=	Number of Units
NASA	=	National Aeronautics and Space Administration
PCEC	=	Project Cost Estimating Capability
RCTA	=	Reusable Cislunar Transportation Architecture
TMLEO	=	Total Mass to Low Earth Orbit
SNAP-50	=	System for Nuclear Auxiliary Power, SNAP-50 is a variant of the SNAP reactor
TLI	=	Trans-Lunar Injection
TRL	=	Technology Readiness Level
ULA	=	United Launch Alliance

II. Introduction

With the announcement of Space Policy Directive-1, there is a renewed focus on sustainable lunar exploration; it further calls the return to the Moon a "foundation for an eventual mission to Mars [1]." Due to the exponential nature of the rocket equation and the realities of current propulsion capabilities, both destinations will require tens to hundreds of tonnes of total mission propellant. This propellant, in turn, must be emplaced where it is needed, notably at the lunar surface for crew ascent [2], and in cis-lunar space as the current staging point for the journey to Mars [3, 4]. The simplest option, that requires less technical maturation, is to deliver that propellant in a series of launches from Earth to its respective destinations; the blossoming commercial launch market makes this a more economically attractive alternative than in the earlier days of spaceflight [5].

An alternative approach results from recent evidence of ice at the lunar poles [6]: propellant could be produced from lunar resources and used either on the lunar surface [2, 7–9] or in cis-lunar space [4, 10–13]. Producing propellant at the location of demand has been shown to enable self-sufficiency [14] and reduce the need for propellant to be pushed through the 15+ km/s of ΔV required to reach the lunar surface from Earth. For Mars, the ΔV difference between the two sources is still substantial (13+ km/s from Earth's surface to cis-lunar space, while 2+ km/s from the Moon). For a sustained campaign to Mars, propellant quantities approaching a thousand tonnes over a decade and a half [3] are needed, only magnifying that disparity. Thus, sustained in-situ resource utilization (ISRU) of lunar ice has a potential to deliver magnitudes of mass savings to a combined campaign to explore the Moon and Mars relative to propellant delivery from Earth.

However, there are several challenges that must be addressed to achieve those savings. To date, there only been modest investment in ISRU systems over the last few decades, resulting in low technology readiness levels with significant uncertainty in the performance and reliability of these systems in a lunar environment. 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 capable of conveying propellant to its final destination. Further, the existence of such an architecture hinges on the abundance of accessible lunar ice, which has not yet been verified. For these reasons, the question of whether lunar ISRU is the right approach to enabling human exploration of the Moon and Mars cannot be settled solely by a consideration of orbital mechanics or mass savings.

Contingent upon the existence of significant quantities and concentrations of usable lunar ice, there are costs to developing, building, launching, operating, and maintaining the capabilities that would enable its use. Delivery from Earth has its own costs as well, but they are primarily tied to the number of launch vehicles and landers needed to deliver propellant to its destination; an ISRU approach entails these as well as the other costs. Thus, it is worth considering the cost breakeven between using lunar ISRU or propellant delivery from Earth for a campaign of missions to the Moon and Mars. As the exact nature of both the associated systems and the campaigns themselves are at present unknown, the question is: over what range of system capabilities and human missions to the lunar surface and Mars does in-situ propellant production on the Moon trade favorably with propellant delivery from Earth on the basis of cost?

This study examines the costs of delivering propellant from Earth compared to the cost of producing propellant on the Moon for a campaign of missions to the lunar surface and to Mars over a variation in several system technical parameters. The breakeven is defined as whether, over the duration of the entire campaign, the costs of propellant

production are less than those of propellant delivery. A parametric approach is used to model the launch vehicle capabilities, landers, and ISRU systems that enable these architectures. The results will support future decisions about the value of lunar ISRU for enabling human missions on the lunar surface, either from the perspective of maturing technologies or evaluating the implications of campaign duration on the value of those technologies.

Section III of this paper summarizes several previous considerations of the value of lunar ISRU to contextualize the analysis. Section IV parametrically defines an exploration campaign for the analysis. Section V describes the element sizing and costing used for both architectures to develop the key metric: the cumulative cost ratio across the campaign's duration of the costs of propellant production to propellant delivery. Section VI presents the results of this analysis, both for a canonical case derived from two previous studies and for sensitivities to system capabilities and campaign parameters. Finally, Section VII draws several conclusions about the value of lunar ISRU based on this analysis and lays out a forward path for further research.

III. Background

A. Lunar ISRU for Lunar Missions

In recent studies on the use of lunar-produced propellant for lunar exploration missions, the delivery location is most frequently the lunar surface or lunar orbit; however, assumptions for other parameters can vary greatly, leading to a wide range of conclusions on the affordability of a lunar ISRU-based architecture. Although several reports have presented ISRU as a critical piece of human exploration of the moon [7, 8], the specific choices made for the mission architectures can dramatically change the operations and cost.

In 2007, Charania and DePasquale [15] evaluated the cost breakeven prices in several scenarios where lunar-produced propellant was delivered to the lunar surface, low lunar orbit (LLO), or geosynchronous Earth orbit (GEO). Their model was based on demand from both a series of human lunar missions and commercial satellite operators in GEO, and the cost uncertainties were systematically examined using Monte Carlo analysis. However, the results showed that the cost of the propellant transporters and propellant consumed to deliver the propellant off the lunar surface were barriers to affordability. Only one scenario presented, where the propellant was delivered directly on the lunar surface, represented a potential market.

Soon after, Chepko et al. [16] collaborated with a NASA ISRU team to apply a gradient-based search optimization algorithm for evaluating detailed engineering-based ISRU models for lunar oxygen extraction. Their results searched for the optimal ISRU system design for oxygen production, and they showed that the oxygen production systems exhibit economy at scale. However, while their study also showed that cargo demand to support a surface mission is significantly reduced when ISRU produces all the consumable oxygen required, the findings did not extend to addressing other architectural factors such as how systems would be delivered to the lunar surface or how power would be supplied.

Then, in 2011, Bienhoff [17] evaluated the impact of ISRU on a reusable cislunar transportation architecture (RCTA), which begins transitioning to fully lunar-derived propellant by year 11 of operations, compared to NASA's Constellation architecture for a human lunar outpost. Bienhoff concluded that once lunar-derived propellant supplied all RCTA propellant, the Earth-to-orbit (ETO) mass each year plummeted to only 10% and new hardware mass was less than 50% of that required for Constellation. In addition, the architecture could both export additional propellant to L1 and LEO as well as provide water for crew consumption. However, the propellant losses due to both the rocket engines' non-stoichiometric mixture ratios and imperfect transfer were a significant barrier to efficiency. These architectures also required the delivery of human infrastructure for the outpost as well as the use of depots in LEO and/or cislunar, so it is unclear how the results compare to an entirely autonomous ISRU architecture or to direct delivery of propellant from Earth. Additionally, the feasibility of ISRU technologies to satisfy the production rates assumed in the study was not fully assessed, as only Earth-to-orbit mass was used as a surrogate to compare the cost of the architectures.

By 2019, Chen et al. [18] proved that a multi-fidelity optimization model can consider both space transportation planning and subsystem-level design of the ISRU plant to minimize cost over the lunar exploration campaign. However, no results were presented on architectures with no ISRU, so it is not clear how their architectures compare to direct delivery of propellant from Earth.

Shishko, Stoica, and Mrozinski [19] made the case for building a detailed engineering-based production rate model before a defensible business case assessment. Their results reiterated the impact of variability in aspects of production as well as reliability and maintainability, which can impact the overall production tempo and therefore impact the business case.

Finally, Jones et al. [2] utilized parametric sizing of ISRU systems and expendable lunar lander vehicles to assess

the affordability of ISRU propellant delivered on the lunar surface compared to propellant delivery from Earth. The authors found that savings increase as propellant demand or mission duration increase, and that cost breakeven might be achieved as quickly as after three missions. The results also showed that breakeven is significantly impacted by the ISRU system lifetime. However, the analysis was limited to architectures using expendable landers and only delivering propellant on the lunar surface. This paper will further employ the sizing methods presented in [2] to explore new architecture options, such as incorporating propellant demand for Mars missions.

B. Lunar ISRU for Mars Missions

Several recent studies have examined the use of lunar-produced propellant for exploration missions (primarily to Mars). Ishimatsu et al [20] developed a campaign logistics framework to assess the use of lunar-derived propellants for performing the NASA Design Reference Architecture 5.0 (DRA 5.0) mission to Mars [10]. 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, rather than 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 [11]. Additionally, neither study addressed cost, instead making the comparison solely on the basis of launch mass from Earth.

Miller et al. [12] developed an Evolvable Lunar Architecture that would perform commercial mining of propellant from the lunar poles to be used for NASA missions to Mars. 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 the 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 to support long-term lunar mining, it is unclear how the proposed approach trades with launch of propellant from Earth directly to lunar orbit.

Kutter [13] proposed an oxygen and hydrogen propellant-based architecture for travel between Earth and the Moon. 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.

Jones et al. [4] examined two architectures for delivering propellant to cis-lunar space from Earth and four architectures for providing that propellant from potential lunar ice on the basis of the cost to meet a constant demand of 59 tonnes per year for 14 years. The authors found that even with favorable ISRU modeling assumptions, it was unlikely that lunar ISRU would be a cost-effective approach to providing propellant to cis-lunar space in the near term; lunar ISRU propellant was 97% more expensive than Earth-based propellant. Under the modeling assumptions used in their study, the authors found that even as the propellant demand in cis-lunar space increased, the costs for additional ISRU infrastructure, including the launch costs to deploy it, exceeded the increases in cost for propellant launches from Earth. However, the analysis was limited to only situations in which the entire cost of developing a propellant production hardware were paid by the Mars campaign; it did not include an assessment of how an existing lunar infrastructure might impact the cost trade.

Finally, Bennett, Ellender, and Dempster [21] performed a follow-on study to explore three architectural strategies for improving the results originally presented by Jones et al. [4], including: taking advantage of nonlinear scaling laws to achieve dramatic improvements to the ISRU and nuclear power plants required to be delivered, using a tanker-specific reusable lander with an improved inert mass fraction, and switching to the SNAP-50 nuclear reactor to reduce mass. The authors assert that these strategies provided significant advantages, such as reducing the number of launches required and increasing the payload mass able to be delivered by each lander, while generally using the same assumptions as [4].

In this paper, the authors consider a more efficient lunar ISRU system than that used by Jones et al. [2] while

continuing to examine a single lander design for both cargo delivery and propellant transfer; a subsequent paper will assess how the allocation of different lander functions across multiple vehicles can impact the cost breakeven [22].

IV. Definition of a Campaign and Analysis Method

A. The Campaign Demand Model

This study uses a location- and time-dependent propellant demand model to model the combined human lunar and Mars exploration campaign. The two assessed locations are the lunar surface and cislunar space; each location has a constant propellant demand rate that the architecture must meet in order to sustain the overarching exploration campaign objectives. The time-dependent element of the demand model defines when a step change in the location-dependent propellant demands can occur; the step change in demands is defined by the amount of time since the start of the campaign that elapses prior to the step transition in propellant demands. This represents, for example, a transition from only needing propellant on the lunar surface (in support of a campaign of missions there) to needing propellant in cis-lunar space (in support of a campaign of missions to Mars).

Figure 1 shows a graphical representation of the implemented demand model. The x-axis represents time, and the the y-axis represents the propellant demand rate magnitude required to sustain the exploration campaign. The horizontal blue and green lines represent the propellant demand rate in cislunar space and on the lunar surface, respectively. The pre-transition duration represents the amount of time from the start of the campaign to the step change in propellant demands, and the post-transition duration represents the amount of time from the transition point to the end of the exploration campaign. The dashed line represents the possibility that lunar surface demand will maintain at pre-transition levels, or go to zero, depending on the particular scenario being examined. In this analysis, these are the two phases of the campaign that are considered; future analysis could examine the impact of additional phases with corresponding demands, or more gradual transitions between demands.

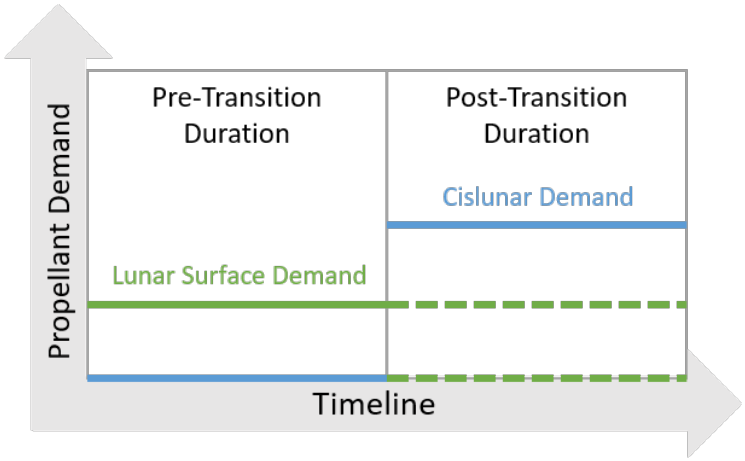


Fig. 1 Propellant demand model for the combined human lunar and Mars campaign.

B. The Canonical Case

The campaign demand model in this analysis uses six parameters (the Lunar Surface and Cislunar Demand before and after transition). Because NASA is continuing to define its future human exploration plans for both sustaining a more permanent presence on the Moon and continuing to Mars, exact values for these parameters are not yet established. In this study, a canonical case is defined based on earlier work to serve as a reference for the values of these parameters, and the sensitivity of the resulting cost breakeven to those parameters is examined to illustrate how the breakeven varies as a function of NASA's human exploration plans.

NASA previously published the Evolvable Mars Campaign to identify potential approaches to performing a campaign of three human Mars missions [23]. Previous analysis showed that, to perform the same set of missions on the same timeline, 59 tonnes of oxygen and hydrogen propellant would be needed every year for 14 years to complete the campaign [3]; this provides three of the six values for the parameters above (assuming no propellant is accumulated in cis-lunar

space prior to the transition to the Mars campaign). In a previous study, the authors established that an annual roundtrip mission between cis-lunar space and the lunar surface for transporting two crew would require 17 tonnes of oxygen and hydrogen propellant each year [2]; this value is used for the Pre-Transition Lunar Surface Demand. In this study, it is assumed that the Post-Transition Lunar Surface Demand goes to 0 tonnes per year (t/yr), representing a choice by NASA to focus on human Mars missions; a sensitivity to sustaining a lunar campaign while operating the Mars campaign was also examined to assess its impact. Because the length of the human lunar surface campaign is still to be determined by NASA, the Pre-Transition Duration is a variable that was explored throughout the analysis, across a range of 5 to 15 years. These parameters are summarized in Table 1 below.

Table 1 Key Campaign Parameters for the Canonical Case

Campaign Parameter	Value	Unit
Pre-Transition Duration	5 – 15	years
Post-Transition Duration	14	years
Pre-Transition Lunar Surface Demand	17	t/yr
Post-Transition Lunar Surface Demand	0	t/yr
Pre-Transition Cislunar Demand	0	t/yr
Post-Transition Cislunar Demand	59	t/yr

V. Element Sizing and Costing

A. Key Architecture Assumptions

Several assumptions were made in this study to allow for the exploration of the impact of changes in both the system technical parameters related to the capabilities of the launch vehicles, landers, and ISRU systems, and to the nature of the human exploration campaign. Limited data exists in literature to inform parametric sizing and operations of large-scale ISRU systems on the Moon. Thus, the authors have made assumptions that could be considered favorable to ISRU; an actual implementation of lunar ISRU will likely require greater cost than what is estimated here. Lossless transfer and zero boiloff propellant storage were assumed in all vehicles, on the lunar surface, and in space. It was also assumed that the landers and ISRU plant are autonomous and highly reliable; this impacts the maintainability requirements, including the frequency that vehicles and the ISRU plants must be replaced as well as the spares rate, which are described in Table 2. Finally, it is assumed that mining and production is performed near a location of relevance to NASA's human exploration program to minimize transportation needs from propellant production to propellant usage location, and that lunar ice is sufficiently abundant and accessible to meet the propellant demand each year.

Table 2 Key Assumptions

Parameter	Value	Unit
Propellant Losses (i.e. transfer and boil-off)	0	%
Vehicle Reusability	5	# of flights prior to replacement
ISRU System Lifetime	1–5	years
ISRU Spares Rate	0.1	kg/kg of system/year
Mining Location Relative to Human Base	Co-located	-

Development costs are incorporated in the estimates described in following sections, but the cost to advance low-TRL technologies and the time until initial operational capability are not considered; instead, the mission duration begins at some point in time where the ISRU systems are fully operational on the lunar surface. Additionally, annual operations costs as well as the cost of spares and maintenance operations are not considered. However, the cost to launch the spares mass is included in the total architecture cost.

B. Launch Vehicles

Two potential launch vehicles were assessed within both the propellant production and propellant delivery architectures: the Space Launch System (SLS) being developed by NASA, and a representative commercial heavy lift launch vehicle. Table 3 presents the assumed payload capacity to Trans-Lunar Injection (TLI) orbit and launch cost for each launch vehicle option [2]. For each launch vehicle, it is assumed that the necessary number of launch vehicles of either type that are needed to meet the needs of the campaign can be acquired at the estimated cost; no constraint on a number of available launch vehicles per year was assumed.

Table 3 Launch Vehicle Modeling and Cost Parameters

Launch Vehicle	Payload to TLI (t)	Est. Cost ($M)
SLS BLock 1B Cargo	40.0	1000.00
Nominal Commercial	15.0	200.00

C. Multi-Functional Lander Vehicles

The multi-functional lander vehicle's role within the architecture is to deliver cargo to the lunar surface, as well as deliver propellant to cislunar space and to the lunar surface. The vehicle is sized to maximize the cargo payload mass delivered to the lunar surface for an assumed Inert Mass Fraction (IMF), Specific Impulse (I_{sp}), and a gross mass constraint set by the launch vehicle. The assumed lander performance parameters used in this study are shown in Table 4; a range of IMF values are investigated in this study to understand how the efficiency of the design of a reusable multi-functional lander impacts the cost breakeven.

Table 4 Lander Vehicle Modeling Parameters.

Parameter	Value	Units
Inert Mass Fraction (IMF)	0.20 – 0.30	-
Specific Impulse (I_{sp})	450	s

D. ISRU System Models

ISRU systems, designed and manufactured on Earth, are loaded into a multi-functional lander vehicle and launched by either 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.

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 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 for assessments of the value of lunar ISRU for supporting human missions to Mars and on the lunar surface [2, 4]. The second model, based on the work of Duke et al. [24], also linearly scales the mass and power of a proposed concept for lunar ice mining as propellant production rate varies, albeit at greater efficiencies than in the MREE model. Both models are for systems that acquire ice, process it into oxygen and hydrogen, and liquefy both propellants. In both cases, surface nuclear fission power is assumed, using as many copies as needed of the 40 kWe system, with a specific mass of 174 kg/kWe, described by Mason [25]. The parametric relationship between mass and power and propellant production rate for both models is summarized in Table 5.

The relative sizing of the launch vehicle, lander, and ISRU system payload is shown in the pyramid schematic in Figure 2. For one of the two specified launch vehicles, the lander is sized to exactly match the launch vehicle's rated payload capacity to TLI. The ISRU system, however, is not sized to exactly match the lander's rated payload capacity; instead, the ISRU system is sized to meet the initial needed propellant production rate in the minimum number of individual plants that fit within the payload capacity constraint of the lander vehicle. If multiple ISRU plants are

Table 5 ISRU System Modeling Parameters

Parameter	MREE	Duke	Units
ISRU Plant Specific Mass	1.1101	0.1331	t of plant mass per t/yr produced
ISRU Plant Specific Power	5.6976	0.6174	kWe per t/yr produced

required to meet a propellant demand, each ISRU plant is manifested on its own lander (and in turn, each lander is manifested on its own launch vehicle). The white space between the green ISRU triangle and the outer dashed line represents the potential for unused lander payload capacity.

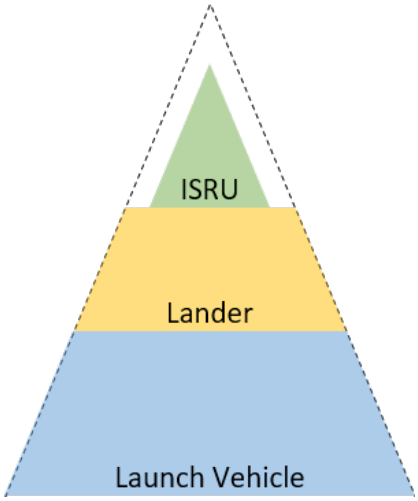


Fig. 2 Diagram of how the launch vehicle, lander, and ISRU systems are sized relative to capacities.

E. Cost Estimation

Lunar lander costs were estimated with the Project Cost Estimating Capability (PCEC) cost estimating tool, commonly used by NASA. A third-degree polynomial in inert mass was fit to a set of cost estimates and used for the Cost Estimating Relationships (CERs) for the Design, Development, Testing, and Evaluation (DDT&E) and unit production costs; see Equation (1). The coefficients for the polynomial depended on whether the inert mass of the lander was greater than or less than 15 tonnes. The coefficients are given in Table 6 below.

$$\text{Cost (FY19 \$M)} = a{m_{\text{inert}}}^3 + b{m_{\text{inert}}}^2 + cm_{\text{inert}} + d \tag{1}$$

Table 6 Coefficients for Lander CER

Inert Mass	Cost Type	a	b	c	d
$>$ 15 t	DDT&E	0	−3.13e−6	1.68e−1	3.93e3
	Unit	0	−9.90e−7	5.08e−2	2.24e2
$\leq$ 15 t	DDT&E	9.61e−10	2.45e−5	2.30e−1	3.99e3
	Unit	3.16e−10	7.81e−6	7.07e−2	2.43e2

Individual costs for the systems of the lunar ISRU architectures were also primarily modeled using PCEC Version 1.1, reusing CERs developed by Jones et al. [2]. Twelve cases of a sample plant were used to develop CERs for the water processing plant. The initial case was sized to enable production of 2200 kg of H_2 per month with a design lifetime of 2

years. The system mass was split into 4 subsystem masses for the PCEC model: structures, tanks, radiation and thermal control, and environmental control and life support (ECLS), where ECLS acted as an analog for the water extraction reactor, electrolyzer, and oxygen and hydrogen liquifiers. This case was then modified for cases with doubled and tripled subsystem masses to determine the effects of raising propellant demand. Those three mass options were then assessed for additional design lifetimes of 4, 6, and 8 years, giving a total of 12 cases. Cases were modeled using typical cost assumptions for the development of space systems. It was also assumed that the systems had no heritage and were 100% novel designs. Additional costs for vehicle integration, contractor fees, and contingency were also included. These assumptions were used with the PCEC model to develop a response surface model of cost for both development and unit costs as a function of ISRU water processing plant mass and design lifetime, where all costs were in fiscal year 2019 million dollars.

As seen in Figures 3 and 4, the ISRU plant structures and tank costs did not vary with design lifetime, as these parts of the system were not expected to undergo dynamics changes during operation. Total costs shown here also include costs for vehicle integration, a contractor fee, and contingency.

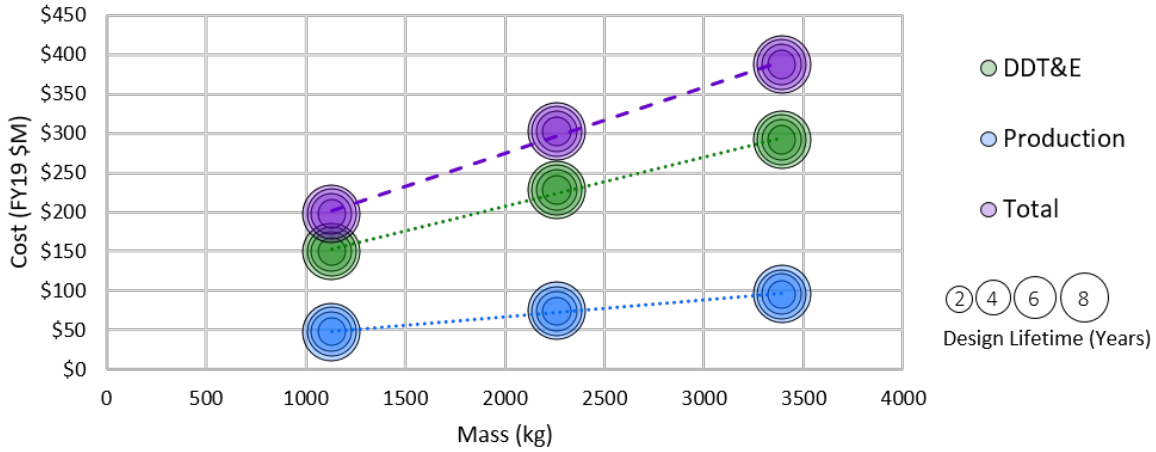


Fig. 3 Lunar ISRU plant structures DDT&E and unit production costs by mass and design lifetime.

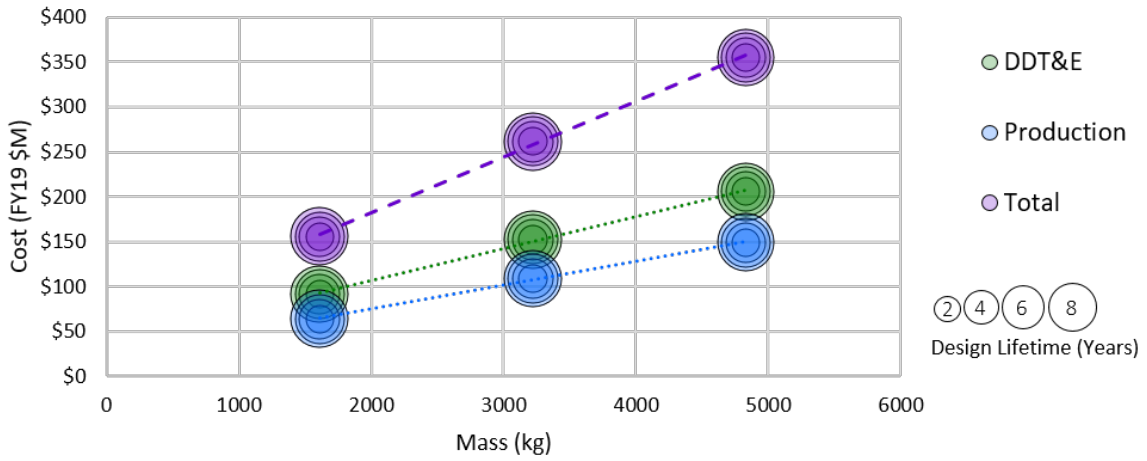


Fig. 4 Lunar ISRU plant tank DDT&E and unit production costs by mass and design lifetime.

The ISRU plant radiation and thermal control subsystem costs were found to vary with both mass and design lifetime, with the lifetime effect resulting from the dynamic operation of the thermal management. Figure 5 shows the cost impact of variations in lifetime as well as cost; thus, the CERs for this subsystem are based on both variables. Table 7 shows the resulting CERs for each subsystem.

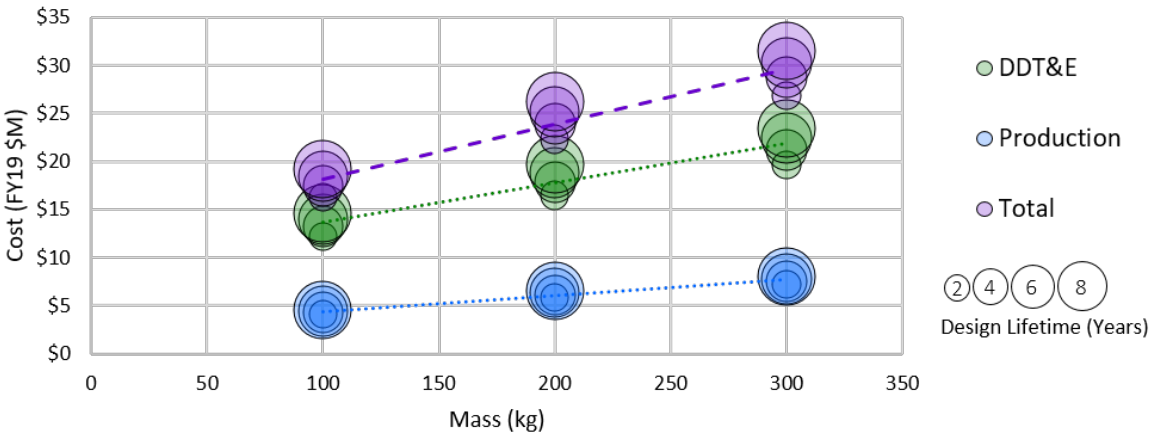


Fig. 5 Lunar ISRU plant thermal control DDT&E and unit production costs by mass and design lifetime.

The production cost for the ECLS subsystem was found in the PCEC cost model to have a minimal dependency on mass. Engineering judgement by the authors determined that there should be a mass dependency; thus, a modified ECLS Production Cost CER was developed. This modified CER used the CERs for the structures and tank subsystems to inform an update to the coefficients of the ECLS Production Cost CER.

Cost estimates for the front-end loaders and haulers utilized in the architecture to transport ice to the water processing plant used a fixed estimate for the DDT&E cost, and a unit cost that scaled as a function of the number of front-end loaders and haulers needed to meet the propellant demand. Similarly, the DDT&E cost for the fission surface power system used a fixed estimate from Mason et al. [25], while unit cost was scaled as a function of the number of 40 kWe units needed to meet the ISRU power needs. The subsystem DDT&E and Unit CERs are shown in Table 7.

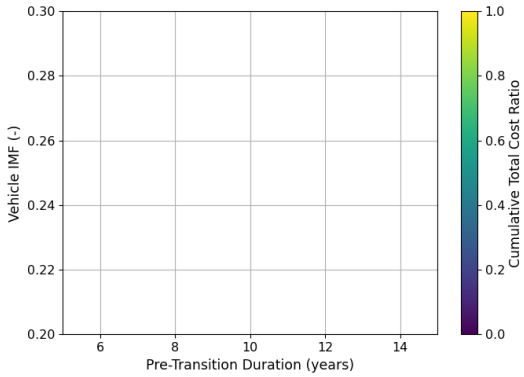
Table 7 Lunar ISRU Water Processing Plant Cost Estimating Relationships where Costs (C) are in FY19 $M, Mass ($m$) is in kg, Design Lifetime (l) is in Months, and Number of Units (n) is dimensionless

Subsystem	Development Cost (FY19 $M)	Unit Cost (FY19 $M)
Structures	$C = 0.0628m + 81.48$	$C = 0.0211m + 24.933$
Tank	$C = 0.0355m + 35.984$	$C = 0.0264m + 22.351$
Thermal Control	$C = 0.0409m + 0.0439l + 6.9816$	$C = 0.0165m + 0.0089l + 2.23236$
ECLS	$C = 0.0559m + 346.2$	$C = 0.0218m + 26.7675$
Front-End Loaders and Haulers	$C = 473.73$	$C = 32.27n$
40 kWe Fission Power System	$C = 1726$	$C = 265n$

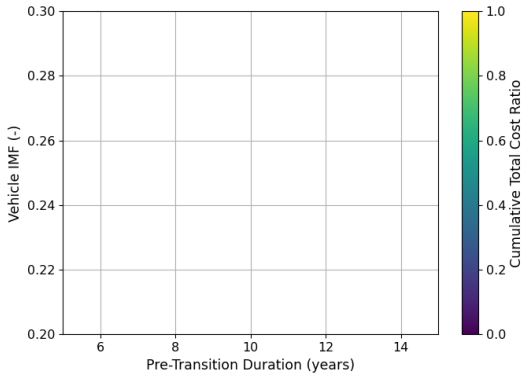
VI. Results

A. Canonical Case

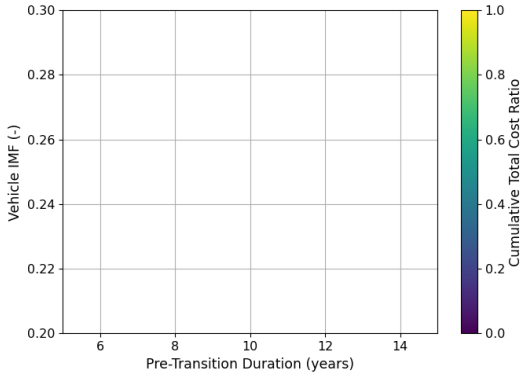
The canonical case results are used to assess the degree to which the ISRU and transportation vehicle performance and the duration of the lunar campaign impact the breakeven of propellant production relative to propellant delivery. The architectures were analyzed varying delivery vehicle IMF with respect to Pre-Transition Duration for different ISRU lifetimes of 1, 3, or 5 years. The lunar surface propellant demand is 17 tonnes per year and the cislunar propellant demand to support a Mars campaign is 59 tonnes per year. This analysis was done for both the MREE and Duke ISRU models. See Figure 6 for results.



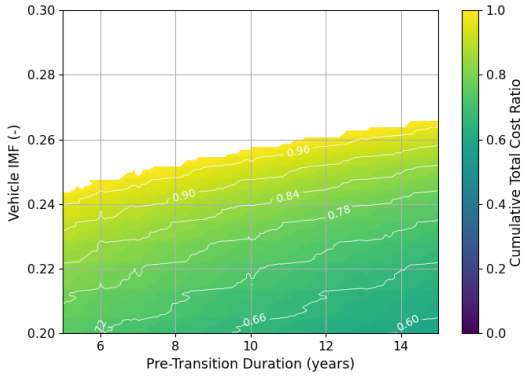
(a) MREE plant with lifetime of 1 year



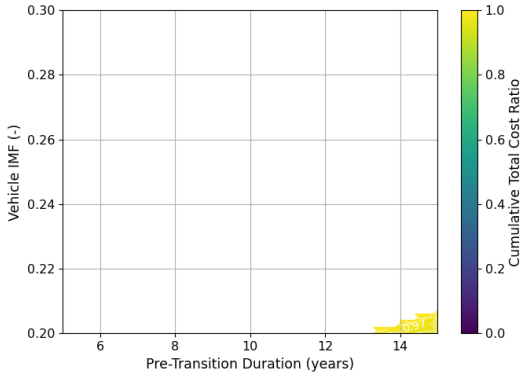
(b) Duke plant with lifetime of 1 year



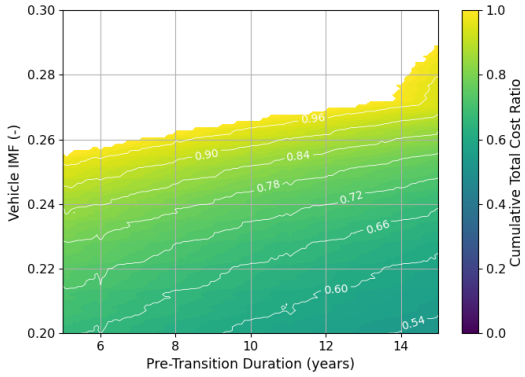
(c) MREE plant with lifetime of 3 years



(d) Duke plant with lifetime of 3 years



(e) MREE plant with lifetime of 5 years



(f) Duke plant with lifetime of 5 years

Fig. 6 Canonical Case, MREE left column and Duke right column, lifetimes of 1, 3, and 5 years. The x-axis is the pre-transition duration (years), and the y-axis is the multi-functional lander vehicle inert mass fraction (dimensionless). The white space in the sub-figures represent cases where propellant production does not breakeven relative to propellant delivery.

The results show the cumulative total cost ratio: the total cost of the ISRU architecture relative to the Earth propellant delivery architecture, where a value greater than one represents a case where the ISRU architecture does not breakeven (the white space in the plot). The Duke model yields more breakeven cases than the MREE model due to its relative efficiency; it is approximately 8.3 times more mass efficient, often requiring only a single plant to meet the demand, whereas the MREE model typically requires multiple plants. The decrease in the number of plants, landers, and launch

vehicles needed in the Duke model make ISRU architectures more advantageous over a wider range of pre-transition durations and inert mass fractions than in the corresponding MREE architectures. The longer the ISRU system can operate independently and reliably, the greater the range over which ISRU achieves breakeven. There is a minimum ISRU reliability required for the ISRU architecture to breakeven: at lifetimes of 1 year (top plots) ISRU does not breakeven in the canonical case, while the range of cases and the magnitude of the breakeven both increase for the Duke model as the lifetime goes from 3 years (middle plots) to 5 years (bottom plots); for the MREE model, there are only a small set of breakeven cases at 5 years ISRU lifetime. Beyond the ISRU technology, for an ISRU architecture to provide savings the transportation vehicle performance must exceed some value to be enable the cost-effective placement and operation of the ISRU plants on the lunar surface. The longer the campaign spends focusing on meeting lunar surface demands, as opposed to cislunar space demands, the more significant the savings; as shown in Jones et al. [2], longer human lunar campaigns decrease the cumulative total cost ratio and thus improve ISRU's performance relative to propellant delivery from Earth.

As the pre-transition duration (and thus the total campaign duration) increase, there will sometimes be a sharp increase in the vehicle IMFs that lead to a breakeven (see Figure 6(f) for an example). This behavior is linked directly to the transition from the lunar-focused to the Mars-focused campaign. Meeting cislunar propellant demands to support Mars campaigns requires ISRU propellant production rates that can meet the propellant demand itself and to fuel the vehicles that deliver propellant from the lunar surface to cislunar space. Additionally, as the vehicle IMF increases, the ratio between the amount of propellant delivered to cislunar space and the amount of propellant required to make the delivery decreases (to as low as 10% of the propellant produced being delivered as payload; see Jones et al. [4]), further increasing the required ISRU propellant production rate.

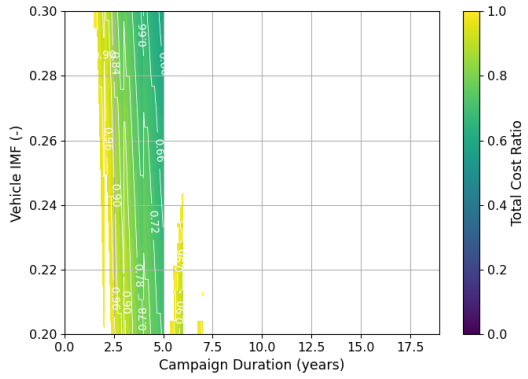
The propellant production rate of an ISRU plant is set to match the initial propellant demand rate in the minimum number of plants that individually fit within the payload capacity of a lunar surface lander. A significant propellant demand change across the transition can shock the system: suddenly, many landers are launched from Earth, each delivering a single ISRU plant to the lunar surface. The instantaneous cost of adjusting to the new post-transition demand is significant; however, since the ISRU lifetime is effectively infinite and there is a newly arrived excess of reusable landers on the lunar surface, there is a period of time in which the propellant production architecture incurs no additional costs from replacing landers. The sharp increase (or, as seen in subsequent figures, 'bubble') that appears is an artifact of this behavior in the model; it represents the cases where this abundance of landers is more economical than the corresponding propellant delivery architecture.

B. Canonical Case - Time History

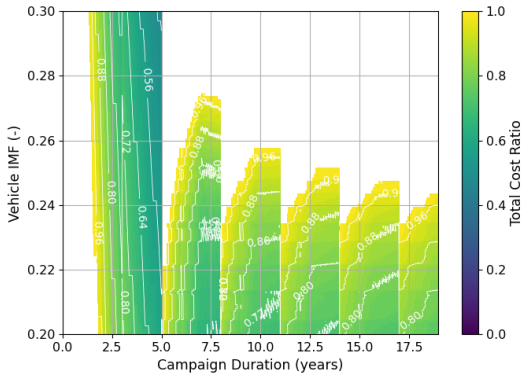
The previous result shows that, for a constant ISRU lifetime and vehicle inert mass fraction, a longer human exploration campaign on the Moon (and thus a longer campaign in total) decreases the cumulative total cost ratio. This suggested that the cost ratio during the campaign (that is, prior to the end when it becomes the cumulative total), might also not be constant. Analysis of the time history of the cost ratio throughout the campaign was conducted for a lifetime of 1 years and 3 years for both ISRU system models (MREE and Duke), and a set of three pre-transition durations of 5, 10, and 15 years (note that the post-transition duration remains constant at 14 years). The vehicle IMF was varied within the architectures to understand what impact it might have on the breakeven performance time history. See Figures 7 and 8 for results.

It was previously found that increasing the pre-transition duration increases the likelihood that breakeven will be achieved at the end of the campaign; the time history results show that breakeven is much more difficult to achieve during the post-transition segment of the campaign relative to the pre-transition segment. This indicates that delivering propellant to the lunar surface is more expensive than delivering the ISRU systems and using them to produce propellant on the lunar surface; however, delivering propellant to cislunar space is less expensive that implementing a full propellant production architecture without infinitely reusable vehicles.

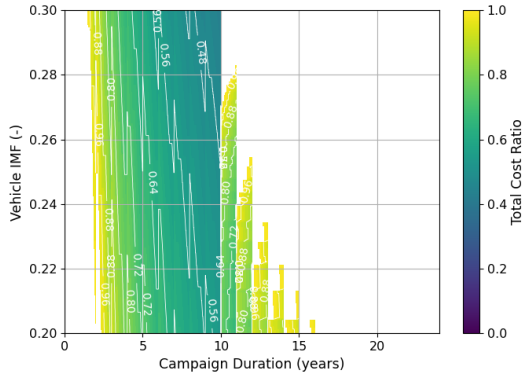
The impact that ISRU lifetime has on breakeven is significant (left versus right plots), especially when the propellant production rates must be increased significantly and launched from the surface to meet cislunar propellant demands. In both models, the breakeven performance drops off almost instantaneously after the demand model transition for the one-year system lifetime. In the Duke model, the three-year lifetime is capable of maintaining moderate but unsustainable breakeven performance to the end of the campaign; following the trend shown in the right set of plots, if the Mars campaign duration extended beyond 14 years, there would come a point where propellant production did not breakeven with respect to propellant delivery. In the MREE model, the breakeven ends shortly after the transition to delivery to cislunar space.



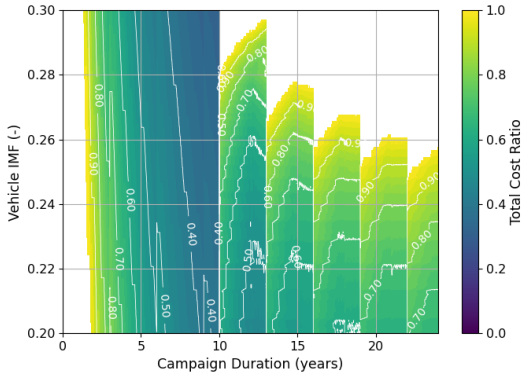
(a) Pre-transition duration of 5 years and ISRU lifetime of 1 year



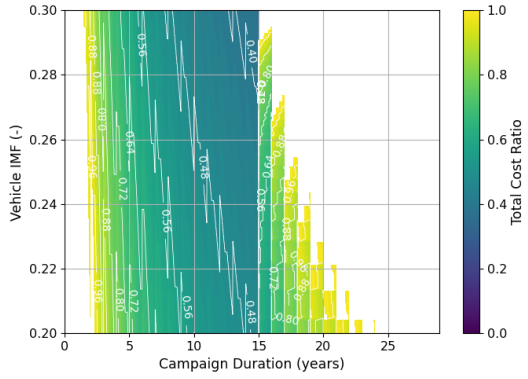
(b) Pre-transition duration of 5 years and ISRU lifetime of 3 years



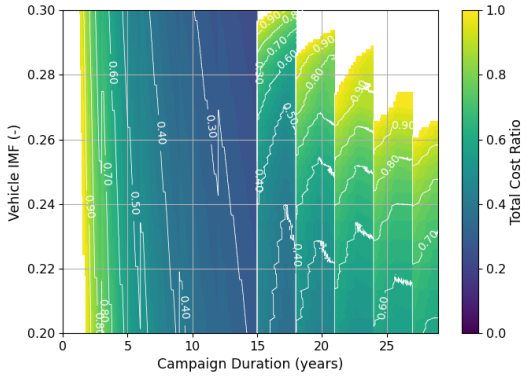
(c) Pre-transition duration of 10 years and ISRU lifetime of 1 year



(d) Pre-transition duration of 10 years and ISRU lifetime of 3 years



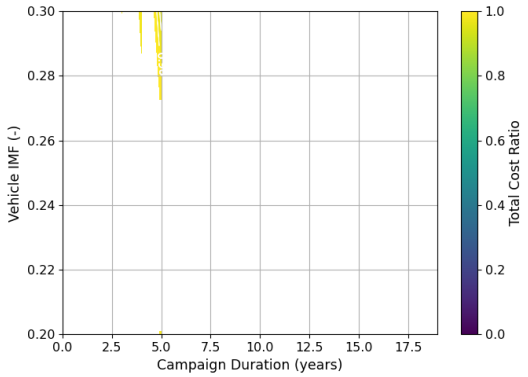
(e) Pre-transition duration of 15 years and ISRU lifetime of 1 year



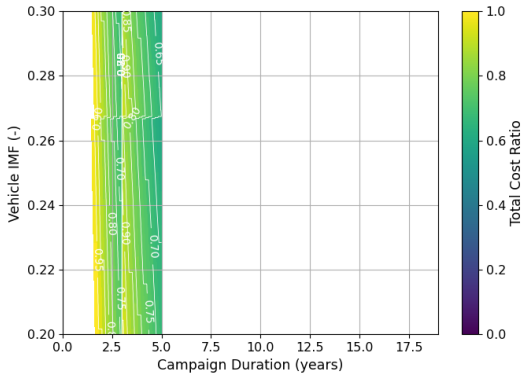
(f) Pre-transition duration of 15 years and ISRU lifetime of 3 years

Fig. 7 Time history of the cost ratio to date for the Duke Architecture, for ISRU Lifetimes of 1 year and 3 years, for pre-transition durations of 5, 10, and 15 years.

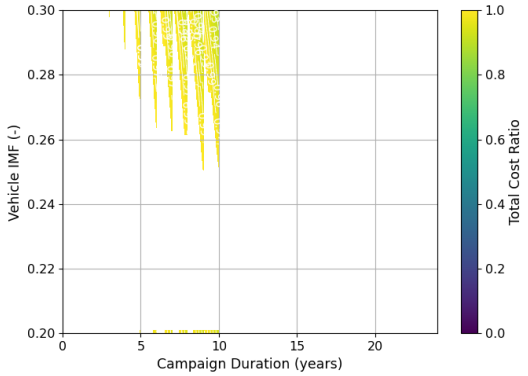
A notable trend in Figures 7 and 8 is how increasing the IMF makes the ISRU architectures more favorable prior to the demand model transition. Gradual increases in the IMF reduce the payload capacity and increase the unit and development cost of the lander vehicles, which lead to a higher specific cost to deliver propellant and payload to the lunar surface. Since the ISRU plants are sized based on a propellant demand, the mass of the plants is fixed at a value equal to or smaller than the lander payload capacity; the reduction in lander payload capacity may not trigger an ISRU plant redesign, so costs for the propellant production architecture may remain unchanged as propellant delivery costs grow.



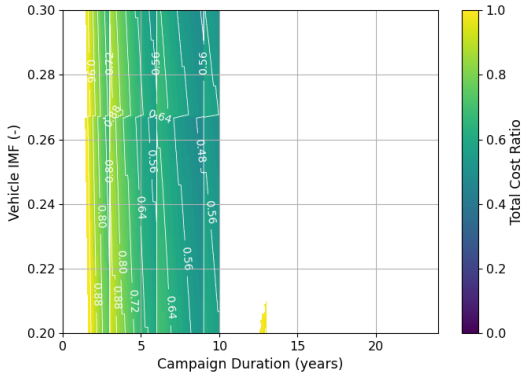
(a) Pre-transition duration of 5 years and ISRU lifetime of 1 year



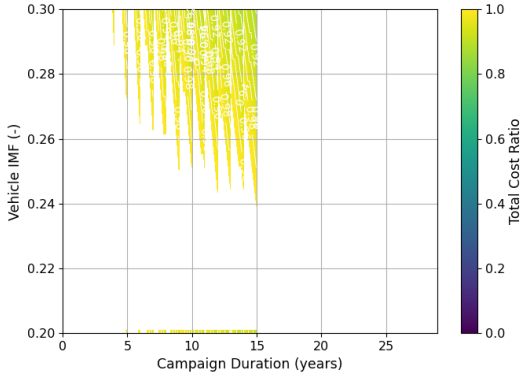
(b) Pre-transition duration of 5 years and ISRU lifetime of 3 years



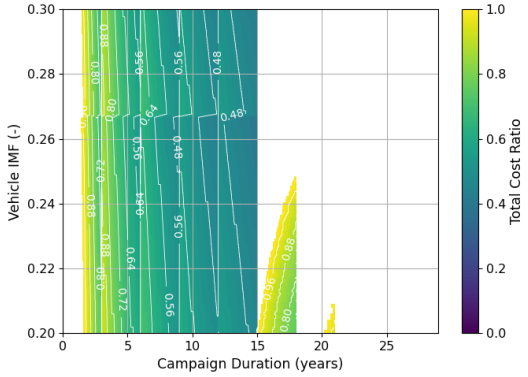
(c) Pre-transition duration of 10 years and ISRU lifetime of 1 year



(d) Pre-transition duration of 10 years and ISRU lifetime of 3 years



(e) Pre-transition duration of 15 years and ISRU lifetime of 1 year



(f) Pre-transition duration of 15 years and ISRU lifetime of 3 years

Fig. 8 Time history of the cost ratio to date for the MREE Architecture, for ISRU Lifetimes of 1 year and 3 years, for pre-transition durations of 5, 10, and 15 years.

After the demand model transition, the trend is immediately reversed as soon as the landers that delivered the ISRU plants to the lunar surface are reused to deliver propellant to cislunar space. Additionally, for the MREE architecture with 1 year ISRU system lifetime, there is a sliver of breakeven that occurs as the IMF reaches 0.2, resulting from the interaction of the number of plants needed to meet demand and the lander capacity at those IMFs.

C. Campaign Sensitivities

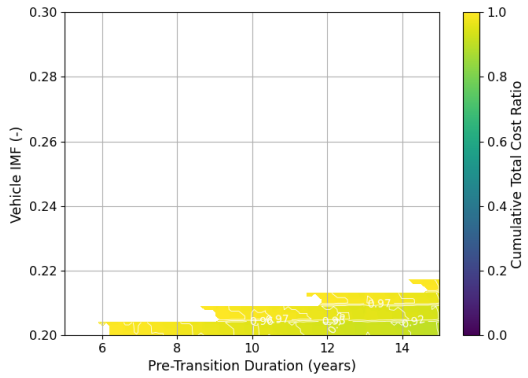
A set of sensitivities were explored on the canonical case to determine the impact of variations in the:

1) lunar surface propellant demand to support lunar exploration campaign,
2) cislunar propellant demand to support Mars exploration campaign,
3) duration of the Mars exploration campaign,
4) duration of the Mars exploration campaign with infinite ISRU lifetime,
5) lunar surface and cislunar propellant demands, simultaneously,
6) continuous lunar surface demand,
7) reusability of delivery vehicle

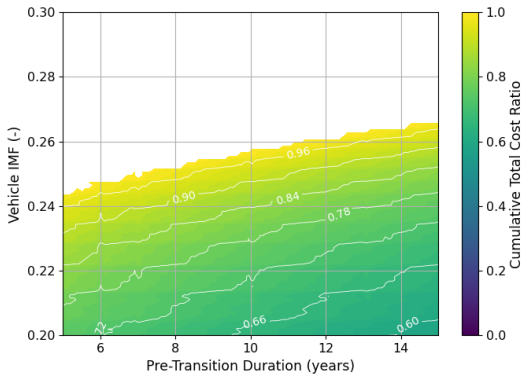
Due to the limited range over which the MREE model achieves breakeven, the sensitivities all explore only the results of the Duke model.

1. Lunar Surface Propellant Demand to support Lunar Exploration Campaign

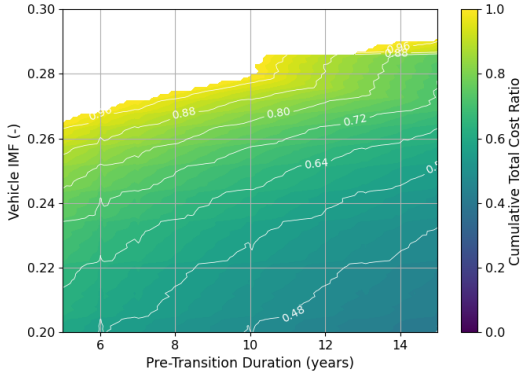
The lunar propellant demand sensitivity was assessed by varying the lunar propellant demand prior to transition at three levels: 8.5, 17, and 34 tonnes per year, where 17 is the nominal case. This variation represents a delta in campaign cadence, roughly equivalent to a human lunar mission every 2, 1, and 0.5 years, respectively [2]. After transition the lunar propellant decreases to 0 tonnes per year. The ISRU lifetime is assumed to be 3 years for this sensitivity.



(a) 8.5 t/yr pre-transition surface demand (representing a mission every 2 years)



(b) 17.0 t/yr pre-transition surface demand (representing a mission every 1 years)



(c) 34.0 t/yr pre-transition surface demand (representing a mission every 0.5 years)

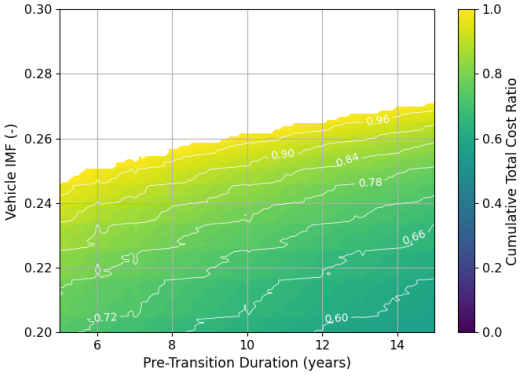
Fig. 9 Lunar propellant demand sensitivity, demands of 8.5, 17, and 34 tonnes per year. The x-axis is the pre-transition duration (years), and the y-axis is the vehicle inert mass fraction (dimensionless).

The implications of variations on the lunar surface demand are significant to the architecture. Reducing the pre-transition lunar surface demand from 17 to 8.5 tonnes per year yields very few cases that breakeven; at such low demands, propellant delivery is less expensive than propellant production over most combinations of campaign duration and vehicle efficiency. On the other hand, an increase in lunar surface pre-transition propellant demand from 17 to 34 tonnes per year increases the range of cases that breakeven.

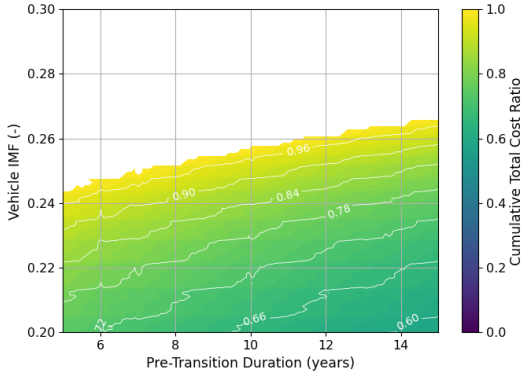
However, as the inert mass fraction of the lander increases, the size of the ISRU system it can deliver decreases. As the ISRU system size decreases, there is a step function where an additional ISRU system and lander is needed, causing a discontinuity in the cost of the propellant production architecture relative to propellant delivery. This discontinuity is reflected by the sharp line at inert mass fractions of ~0.285 in Figure 9(c) .

2. Cislunar Propellant Demand to support Mars Exploration Campaign

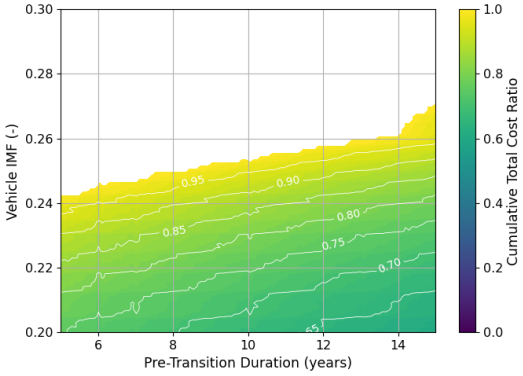
A similar sensitivity was conducted to understand the impact of varying the post-transition cislunar demand, representing changes propellant demands in support of Mars exploration campaigns. The nominal cislunar demand case is 59 tonnes per year for 14 years; demands of 47 tonnes per year and 71 tonnes per year for were examined. Both the ISRU lifetime (3 years) and the post-transition duration (14 years) were held constant.



(a) 47.0 t/yr post-transition cislunar propellant demand



(b) 59.0 t/yr post-transition cislunar propellant demand



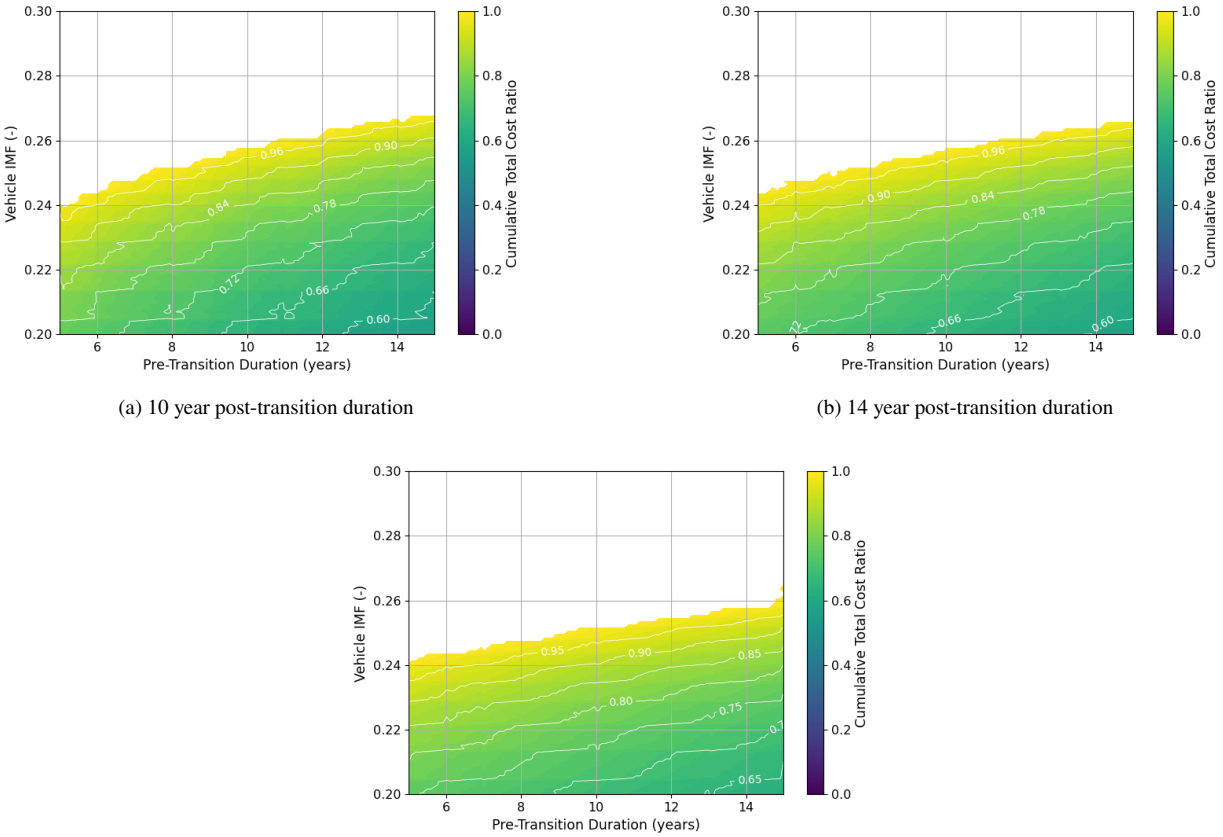
(c) 71.0 t/yr post-transition cislunar propellant demand

Fig. 10 Mars propellant demand sensitivity, cis-lunar demands of 47, 59, and 71 tonnes per year. The x-axis is the pre-transition duration (years), and the y-axis is the vehicle inert mass fraction (dimensionless).

Relative to the pre-transition lunar surface propellant demand sensitivity, the trends identified are the opposite, although much less significant: propellant delivery is less expensive to cis-lunar space than the corresponding propellant production architecture, so increases in the magnitude of the cis-lunar propellant demand reduce the range of breakeven cases for some values of IMF and pre-transition duration.

3. Duration of Mars Exploration Campaign

To evaluate the impact that the duration of the Mars exploration campaign has on the breakeven of the ISRU architecture, the post-transition was examined at 10 years and 20 years. The cislunar propellant demand remained constant at 59 tonnes per year, and results are shown for an ISRU system lifetime of 3 years.



(a) 10 year post-transition duration

(b) 14 year post-transition duration

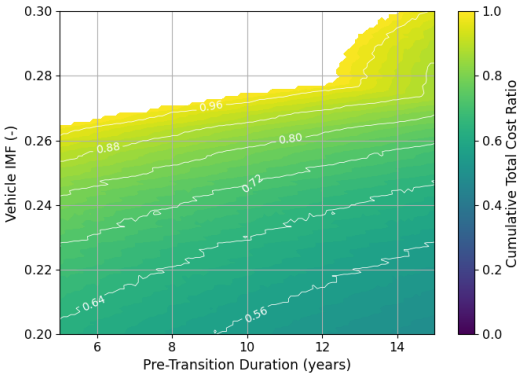
(c) 20 year post-transition duration

Fig. 11 Mars campaign duration sensitivity, Mars campaign durations of 10, 14, and 20 years. The x-axis is the pre-transition duration (years), and the y-axis is the vehicle inert mass fraction (dimensionless).

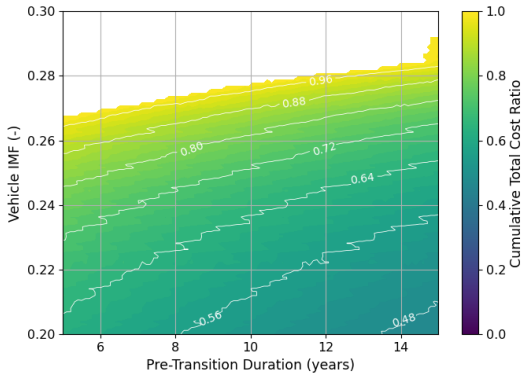
Like the cislunar propellant demand sensitivity, reductions in the post-transition duration increase the magnitude of breakeven and somewhat increase number of architecture cases that achieve breakeven. Thus, while using lunar-derived propellant in cis-lunar space to support Mars exploration can benefit from a pre-existing lunar ISRU architecture supporting human missions on the Moon, the range of breakeven cases decreases as the scope of the Mars campaign increases. This non-intuitive result results from the need to continue to replace both the ISRU systems and the reusable landers throughout the combined human exploration campaign; under the modeling assumptions here, these costs exceed those of propellant delivery to cis-lunar space such that a longer Mars campaign favors delivery from Earth.

4. Duration of Mars Exploration Campaign, with infinite ISRU Lifetime

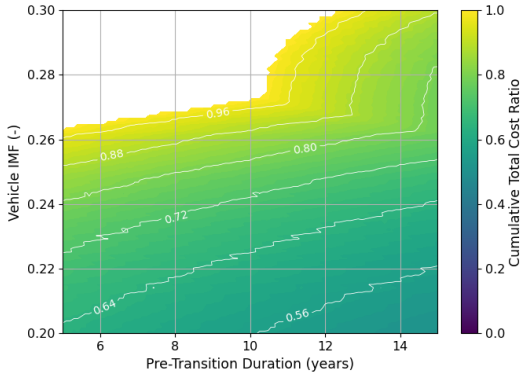
The above conclusion can be illustrated by removing the need to replace ISRU systems during the campaign, and instead assuming they are effectively infinitely reliable. As before, the duration of the Mars exploration campaign was examined at 10, 14, and 20 years, with the cislunar propellant demand is kept constant at 59 tonnes per year. The ISRU lifetime is increased from the nominal 3 years to effectively infinite.



(a) 10 year post-transition duration



(b) 14 year post-transition duration



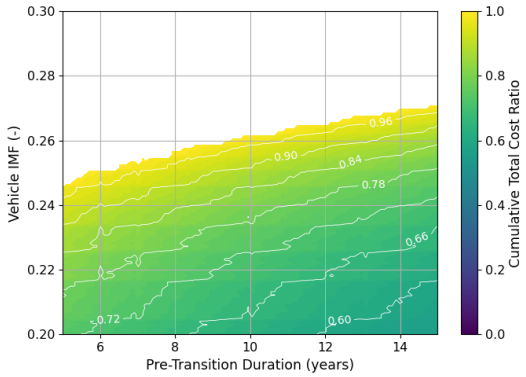
(c) 20 year post-transition duration

Fig. 12 Mars campaign duration sensitivity, Mars campaign durations of 10, 14, and 20 years with an infinitely reliable ISRU system. The x-axis is the pre-transition duration (years), and the y-axis is the vehicle inert mass fraction (dimensionless).

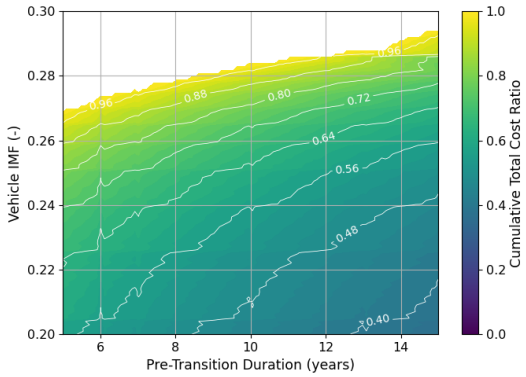
As expected, increasing the ISRU lifetime to effectively infinite increases the number of cases that breakeven, and produces the intuitive finding that a longer campaign offers the opportunity for propellant production to breakeven relative to propellant delivery (as observed in Jones et al. [4]).

5. Lunar Surface and Cislunar Propellant Demand Variations

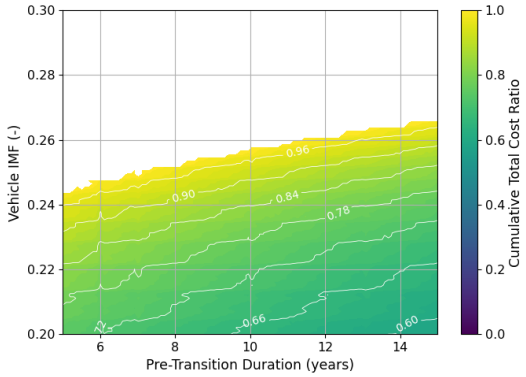
The lunar surface and cislunar propellant demand are varied together to understand which demand has a larger effect on the breakeven trade space, if any. The analysis varied the lunar surface propellant demand at 17, and 34 tonnes per year and the cislunar propellant demand at 47, 59, and 71 tonnes per year. This was done assuming an ISRU lifetime of 3 years.



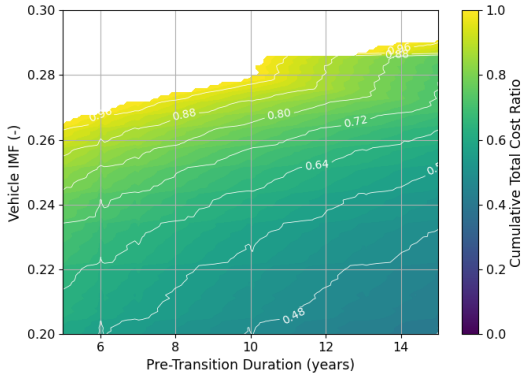
(a) Pre-transition surface propellant demand of 17.0 t/yr and post-transition cislunar propellant demand of 47.0 t/yr



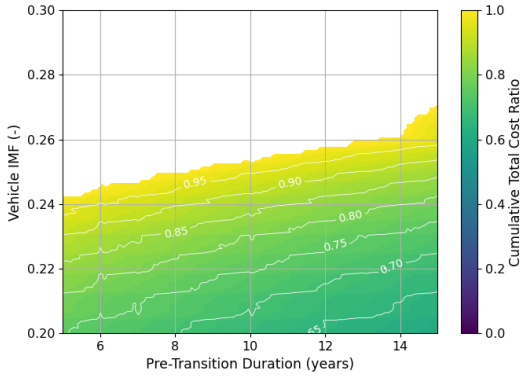
(b) Pre-transition surface propellant demand of 34.0 t/yr and post-transition cislunar propellant demand of 47.0 t/yr



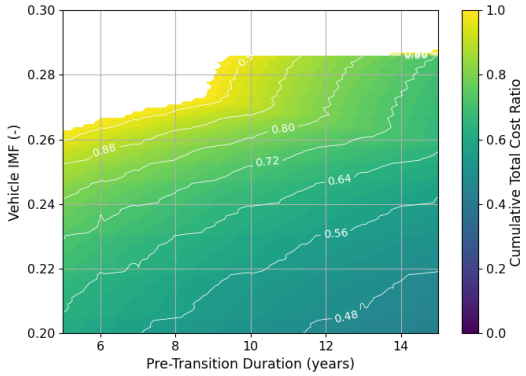
(c) Pre-transition surface propellant demand of 17.0 t/yr and post-transition cislunar propellant demand of 59.0 t/yr



(d) Pre-transition surface propellant demand of 34.0 t/yr and post-transition cislunar propellant demand of 59.0 t/yr



(e) Pre-transition surface propellant demand of 17.0 t/yr and post-transition cislunar propellant demand of 71.0 t/yr



(f) Pre-transition surface propellant demand of 34.0 t/yr and post-transition cislunar propellant demand of 71.0 t/yr

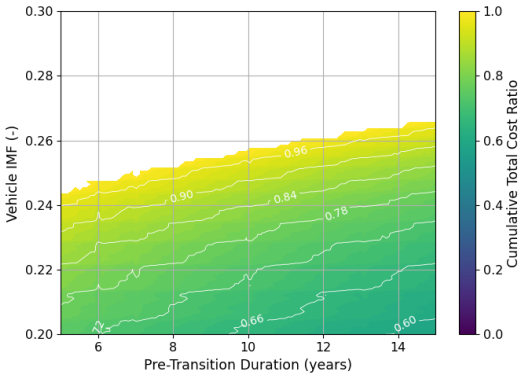
Fig. 13 Lunar and Mars propellant demand Duke Architecture sensitivity, Lunar demand 17 tonnes per year left column and 34 tonnes per year right column, for Mars propellant demands of 47, 59, and 71 tonnes per year. The x-axis is the pre-transition duration (years), and the y-axis is the vehicle inert mass fraction (dimensionless).

The number of breakeven cases is more sensitive to the lunar surface demand than the cislunar surface demand; there is significantly greater shift in plots moving left to right than moving top to bottom. A lunar surface demand of 8.5 tonnes per year did not yield any breakeven cases and thus is not shown; regardless of how long the lunar campaign is, if the lunar surface propellant demand is not high enough then the cost of establishing an ISRU architecture will not

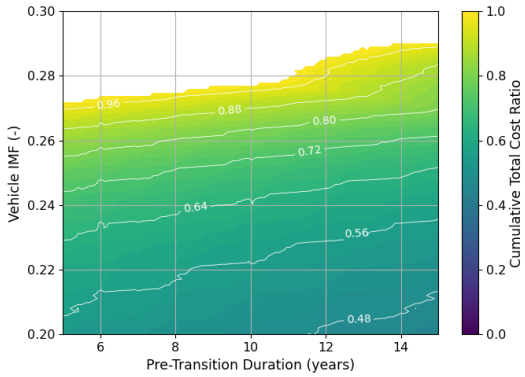
be favorable. These results indicate that the savings in using lunar ISRU for a Mars campaign depend much more on getting value out of the architecture for human lunar missions prior to transition, rather than on the magnitude of the Mars campaign itself. As before, the discontinuity in the cumulative total cost ratio at higher inert mass fractions and higher lunar surface propellant demands is due to the mass constraint imposed by the lunar lander on the ISRU system, and the subsequent increase in the number of landers and ISRU systems required.

6. Continuous Lunar Surface Demand

As additional evidence that it is the scope of the human lunar campaign that significantly determines whether propellant production achieves breakeven with propellant production, a comparison was made between the canonical case in which the lunar surface demands decreases to 0 tonnes per year and a campaign where the lunar surface demand stays constant after transition at 17 tonnes per year while still meeting the cis-lunar demand of 59 tonnes per year.



(a) Pre-transition surface propellant demand of 17.0t/yr and post-transition surface propellant demand of 0.0 t/yr



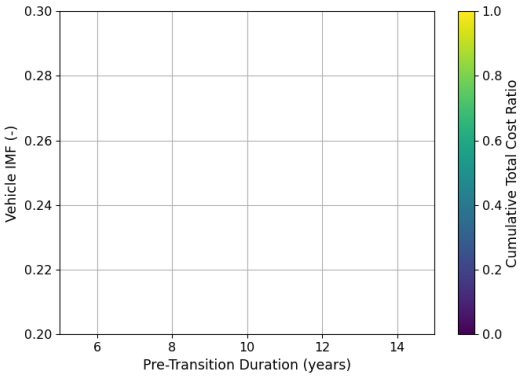
(b) Pre-transition surface propellant demand of 17.0t/yr and post-transition surface propellant demand of 17.0 t/yr

Fig. 14 Lunar surface propellant demand sensitivity, with a post-transition surface demand of 0 or 17 tonnes per year, with an ISRU system lifetime of 3 years. The x-axis is the pre-transition duration (years), and the y-axis is the vehicle inert mass fraction (dimensionless).

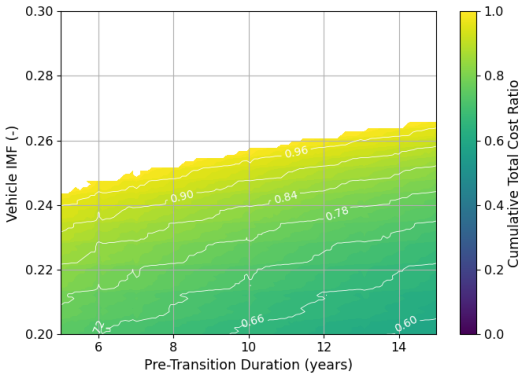
The breakeven cases increase significantly when the lunar propellant demand stays constant after the transition. As lunar ISRU trades more favorably as the lunar surface demand increases (in magnitude, duration, or both), it is unsurprising that this effect continues if the lunar demand endures beyond the transition. It is worth noting that although the breakeven cases increase with additional demand, the overall cost of the both architectures to meet the higher demand are increased as well; if an ambitious campaign of both lunar and Mars missions is to be attempted, then lunar ISRU can trade favorably, but any approach to supplying the necessary propellant will be more expensive than for a more modest campaign.

7. Reusability of Vehicle

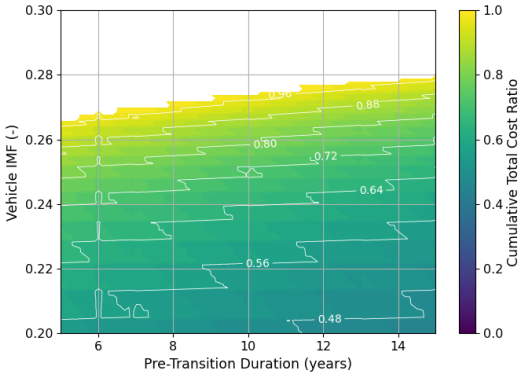
Like the ISRU system lifetime, the reusability of the multi-functional lander vehicle has an impact on the cost breakeven. The vehicle reusability parameter was varied at 1 flight, 5 flights, and 50 flights to understand the magnitude of the impact, while keeping the ISRU lifetime fixed at 3 years. Note that the reusability is defined in terms of number of missions before the vehicle needs to be replaced, not the number of years of life (as is the case for the ISRU system lifetime parameter).



(a) Duke architecture with 1 lander reuse.



(b) Duke architecture with 5 lander reuses.



(c) Duke architecture with 50 lander reuses.

Fig. 15 Vehicle reliability sensitivity, with a vehicle reusability of 1, 5, or 50 flights before replacement. The x-axis is the pre-transition duration (years), and the y-axis is the vehicle inert mass fraction (dimensionless).

There needs to be a minimum level of vehicle reusability for an ISRU architecture to breakeven. For both ISRU models, increasing the reusability from 1 to 5 flights has a greater increase in the number of breakeven cases as opposed to the change from 5 to 50 flights. As the number of flights that a lander can make increases, there is a diminishing return in the cost savings achieved per additional flight; thus, although additional reusability does improve the cost breakeven, the impact is modest enough that it may not justify the necessary capability investments.

VII. Conclusions

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 breakeven compared to propellant delivery from Earth as the efficiency of reusable multi-functional lander vehicles increases (i.e. the inert mass fraction decreases) and as the duration of the human lunar campaign increases prior to the start of propellant delivery to cis-lunar space. It is the magnitude and duration of the human lunar campaign, to a greater degree than those of the corresponding Mars campaign, that drives the cost breakeven; indeed, unless high ISRU system lifetimes are achieved (exceeding five years), the longer and more ambitious the Mars campaign, the worse lunar propellant production looks compared to propellant delivery.

The scope of human campaigns that are better supported by ISRU than not (as measured by the range of the cumulative total cost ratio being less than one) depends on several system technical parameters. Comparing the results of the MREE and Duke models in any of the results shows that the order-of-magnitude increase in efficiency achieved by the Duke model corresponds with significant increase in the magnitude and quantity of breakeven cases; as concepts for lunar ISRU systems mature, their location relative to these points can serve to characterize how likely they are to trade favorably with propellant delivery from Earth. Similarly, as the ongoing work to develop a stable of vehicles that

can deliver payloads to the lunar surface continues, this research enables the identification of performance targets for those vehicles to achieve if lunar ISRU is intended to eventually support a combined human lunar and Mars campaign. For both ISRU systems and multi-functional landers, their reliability has a significant impact on the cost breakeven; if these systems require frequent replacement, then propellant production in unlikely to compete with propellant delivery. Finally, there are multiple technology assumptions (e.g. lossless propellant storage and transfer) inherent to this analysis that, if not realized, will impact the cost breakeven.

From the perspective of the human campaign planner, this research illustrates that the value of lunar ISRU to a campaign hinges both on technical performance parameters as well as the nature of the campaign. A short campaign at the Moon followed by a quick transition to Mars exploration is unlikely to realize the same cost savings from propellant production that would result from a longer, more ambitious lunar campaign. Further, all of this is contingent upon the choice to use vehicles in both the lunar and Mars campaigns that rely on oxygen and hydrogen propellant; if other considerations push the choice of propulsion technology in other directions, then lunar ISRU may not benefit either campaign. Finally, without a serious effort to prospect for abundant and accessible lunar ice and to subsequently develop the technologies to enable its use, any human exploration campaign cannot make lunar ice ISRU a foundational capability.

Further work analyzing the transportation architecture required for a propellant production or propellant delivery architecture could identify alternative approaches that impact the cost breakeven; the impact of the distribution of key functions such as cargo delivery and propellant transfer across multiple vehicles within a transportation architecture could have significant implications. Another topic for future research is whether there is benefit from taking a hybrid approach to providing propellant, where the quantity supplied from Earth and from the Moon is not fixed throughout the entire campaign. Finally, as understanding increases of both future human exploration plans and associated capabilities, this research can be revisited with a tightened scope to address more specific questions around the value of lunar ISRU for a specific scenario.

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