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Demand Drivers of the Lunar and Cislunar Economy

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Executive Summary

For the next several years, a return to the Moon is likely to be the preeminent goal of the U.S. human space endeavor, with an initial landing of U.S. astronauts expected in the 2020s. Subsequent to the initial landing, the National Aeronautics and Space Administration (NASA) plans to develop a lunar base for a longer-term sustainable presence on the surface of the Moon. Some in the space industry have argued that a return to the Moon may lead to the creation of a more commercially oriented lunar economy that involves mining operations, tourism, scientific exploration, and other activities, which would be funded by governments, individuals, and businesses. If such a commercially oriented lunar economy emerges, demands on NASA to support lunar activities would be reduced. However, if demand for lunar goods and services from households and businesses is insufficient to create economically viable lunar businesses, the U.S. Government will need to play a more active role in supporting research, development, and the initial operations of lunar businesses to increase their economic viability.

To ascertain whether private sector demand could support commercial lunar activities, NASA requested that the IDA Science and Technology Policy Institute (STPI) examine the present contours and future scale of demand drivers of lunar and cislunar activities through 2040, with a focus on non-NASA commercial demand. This report summarizes STPI's assessment of demand from civil and commercial sources for lunar and cislunar activities, including the factors that drive that demand. This study was performed between September 2019 and March 2020. We looked at but did not evaluate demand for lunar goods and services to enhance U.S. national security, due to the lack of information at an unclassified level. We identified goods and services that might generate sufficient non-government revenue to be commercially viable. We also highlighted other goods and services that will require enhanced support from the U.S. Government if they are to become economically viable.

Approach

We first compiled a database of organizations targeting the Moon, and identified those that either have produced or plan to produce goods or services related to lunar activities. We interviewed a subset of these organizations concerning their products, technologies, their estimates of the likely size of prospective markets, and their goals and perspectives on future market developments. In addition to these companies, we also interviewed other experts from space associations and government agencies.

We next estimated the prospective costs of major technology systems that will be needed for activities on the Moon, especially human lunar missions. We drew on the space engineering literature, publicly available prices and costs from companies and government space agencies, and other information to derive a set of cost models. The cost models permit the user to estimate costs of each technology system as a function of quantities supplied, factoring in the effects of increased production on reducing fixed costs per unit. We also identified a list of lunar or cislunar activities, goods, and services that are likely to be in demand. We divided the customer base for these goods and services into two groups: governments and philanthropists, and households and businesses. For each group we identified the activities, goods, and services that they might wish to acquire in the 2040 timeframe.

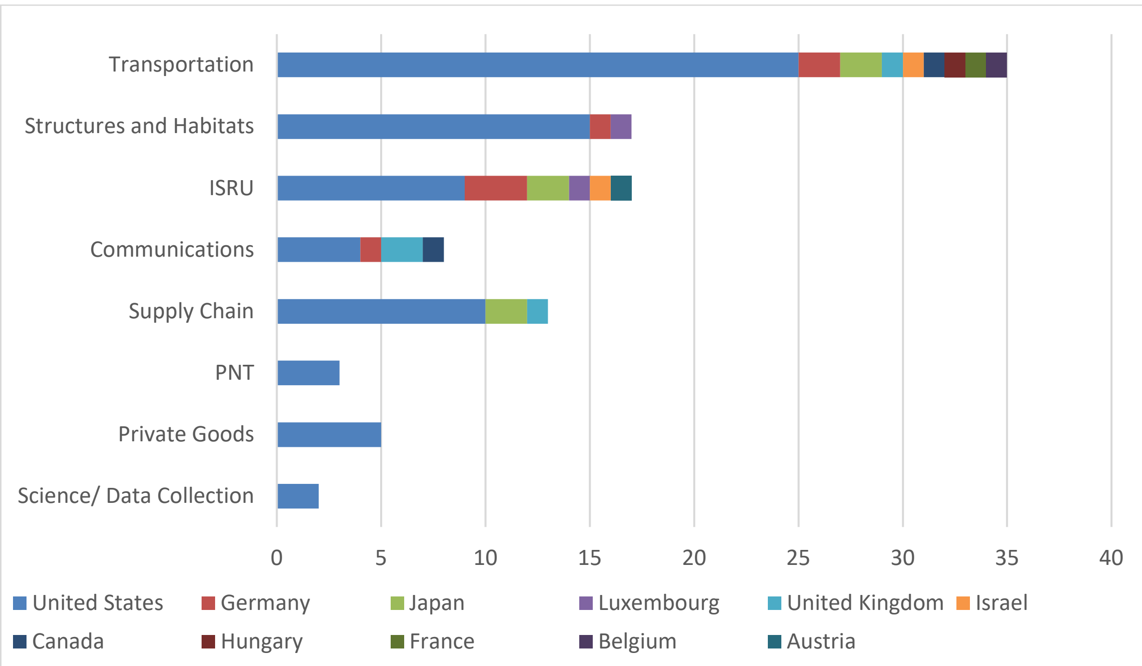
In the case of governments and philanthropists, we identified human lunar and robotic scientific missions as the primary activities or goods and services that they would wish to purchase. We then estimated prospective government funding levels to fund these activities. Employing the cost estimates for transportation and the costs of human missions to the Moon, we estimated the number of human lunar missions and scientific missions that might be feasible through 2040.

Building on the database analysis above as well as the interviews, we identified 12 goods and services that could be produced on the Moon or in cislunar space that households and businesses might purchase. For each of these prospective markets, we first estimated the cost of providing the good or service on the Moon. If the product could be produced on Earth for lower cost, we concluded that the product is not economically viable. In cases where products—such as lunar tourism or lunar burials—are in demand by consumers, we estimated likely sales using a combination of ability and interest to pay (in the case of lunar tourism) and industry estimates of potential interest and demand at our estimated price points (e.g., lunar burials).

Survey of Companies and Findings from Interviews

STPI found more than 80 organizations in 12 countries that offer or aspire to offer services and products on the Moon or in cislunar space. Most are U.S.-based. However, several allied countries are home to such organizations; in order of the numbers of organizations headquartered within them, these countries are Germany, the United Kingdom, Japan, and Luxembourg. Most of these organizations are commercially oriented, although two critical private stakeholders in developing the cislunar economy, SpaceX and Blue Origin, have less of a near-term focus than others: both are investing heavily in lowering the cost of transportation services to the Moon. Of the rest, only a quarter exclusively target the Moon (and more than a third of those are startups); for most other organizations in our database, the Moon is one component of their broader provision of space services. Eighty percent of the organizations are either established companies or have some flight heritage, venture funds, or a government contract. Most companies focus on transportation or structures and habitats, two areas of derived demand where there are likely to be stable long-term government contracts (Figure ES-1).

Interviews reinforced findings from the database: most organizations see their business cases tied to space-oriented agencies, especially NASA, and in particular the Artemis program and human activities on the Moon. Some interviewees noted, however, that if human exploration activities become common, demand for small lunar landers may weaken, as the per-kilogram costs for the larger human launch vehicles and landers are likely to be substantially less than for smaller launch vehicles and landers.



Source: STPI Database

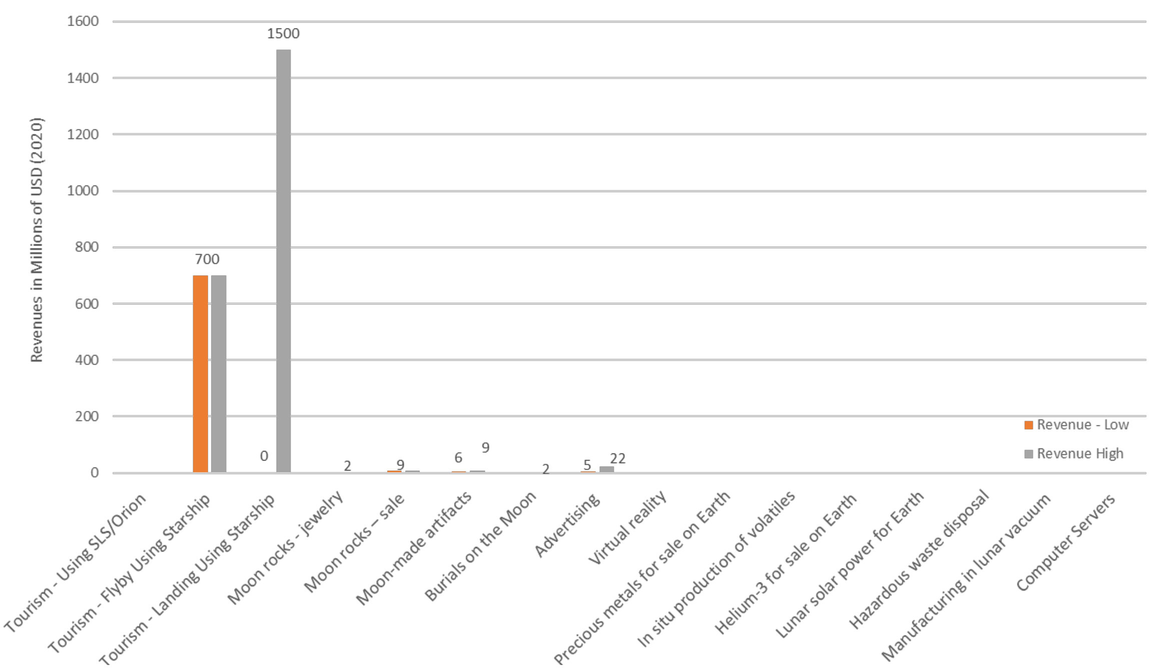
Figure ES-1. Lunar Companies by Country and Sector

A few interviewees argued that the Department of Defense's demand for goods and services in cislunar space, if and when it materializes, will be greater than that of NASA. However, none provided quantitative data on the nature of that demand to support their claims. While relatively few companies have plans independent of government space agencies that tie into their vision of settling the Moon, most companies count on funding from the government. A small minority have creative approaches that leverage terrestrial applications of their space offerings and vice versa. Issues of property rights and legal uncertainties, such as those related to mining on the surface of the Moon, were brought up in some discussions but did not seem to be central challenges to the business plans for these companies.

Market Analysis

STPI estimated that the budget available for government-funded human lunar missions could be about $63 billion over 17 years, from 2024–2040. In principle, if this were all that governments were willing to spend, this figure would cap the amount of money available to the private sector to support the lunar human exploration activities of NASA and partner governments. In light of our estimated cost of a human mission to the Moon ($2.6 billion at the low end, and $4.9 billion at the high end), under this budget cap, it would be feasible to launch at least one mission a year to the Moon under the low cost scenario, but no more than seven missions over a decade under the high cost scenario.

For products and services that may be demanded by households, we explored more than a dozen markets and found that only markets for lunar tourism, lunar rocks, burials on the Moon, and lunar artifacts exist or are likely to exist (See Figure ES-2). Other than advertising, we found no good or service purchased by businesses that was economically viable in the timeframe of interest. We also looked at derived demand for goods and services produced on the Moon to support other lunar activities. Mining lunar water to produce propellant could become economically viable under some conditions, but will need further analysis. Even our most optimistic estimate for the cost per kilogram of propellant on the lunar surface may be too high to enable the export of propellant to other destinations in cislunar space at an economically viable price.



Source: STPI Analysis

Figure ES-2. Revenue Range for Private Lunar Markets

All other activities are uneconomic, for one or more of four reasons: the underlying technology is underdeveloped; there are no likely buyers in the 2040 timeframe; the cost of providing the services exceeds revenues obtained from selling it; or the product is cheaper to produce terrestrially than to produce on the Moon. In general, private demand is insufficient to sustain a pure-play lunar company. Such companies, if they are to become economically viable, need to find ways to exploit existing proven markets, either terrestrially or in near-Earth space.

Our research shows there are two principal drivers of demand for lunar and cislunar goods and services: (1) government expenditures on Moon-related activities, which trigger a derived demand for transportation, capsules, landers, and other lunar goods and services, and (2) transportation costs, which drive the cost of producing and transporting goods on the Moon, but also drive costs of transporting goods from the Earth to cislunar space and the Moon. If launch costs fall as much as some predict, it may continue to be cheaper to transport water and propellant to the Moon rather than to produce them in situ. While private demand for lunar goods and services is not sufficient to sustain a pure-play lunar company, the government can still reduce its costs, accelerate its schedule, and build streams for emerging lunar capabilities by utilizing commercial acquisition practices to procure the services it needs for lunar exploration.

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1. Introduction

A. Background and Study Objectives

For the next several years, a return to the Moon is likely to be the preeminent goal of the U.S. human space endeavor, with an initial landing of U.S. astronauts expected in 2024 (Pence 2019; Davenport 2019). For a longer-term, more sustained presence on the surface of the Moon, the National Aeronautics and Space Administration (NASA) plans to launch a habitable platform to cislunar orbit by the early 2020s (NASA 2018; NASA 2019d; NASA 2020b). NASA's foreign partners have committed to providing significant support to this mission. Additionally, the U.S. aerospace industrial base, philanthropists, and commercial space companies are designing, building, and in some cases financing the required spacecraft, components, and services to return to the Moon, and on to Mars.

Some in the space industry have argued that a return to the Moon may lead to the creation of a more commercially-oriented lunar economy that involves mining operations, tourism, scientific exploration, and other activities, which would be funded by governments (U.S and foreign), individuals, and businesses (Hervieu 2019; Hickham 2020; Rincon n.d.; Zuniga 2017). If this were the case, NASA would not have to shoulder all the costs of developing rockets, landers, and other systems to get to the Moon and establish a human presence there. However, if demand for lunar goods and services from non-government sources is insufficient to create lunar businesses that are economically viable, the U.S. Government would need to play a more active role in supporting the research, development, and initial operations of lunar businesses to increase their economic viability.

To explore the realism of a commercial lunar economy, NASA requested that the IDA Science and Technology Policy Institute (STPI) examine the present contours and future scale of demand drivers of lunar and cislunar activities, with a focus on non-NASA commercial demand. This study was performed between September 2019 and March 2020.

B. Methodology

The sections below present our study questions and the assumptions, scope, analytic approach, and data sources used to address them.

1. Study Questions

To address the goals of the study, we organized the data collection and analysis around the following six study questions:

1. What are the goods and services that could be produced or used on or around the Moon?
2. Who is interested in purchasing these goods and services? How much money do they have available to purchase them?
3. Who wants to produce those goods and services, either on Earth or the Moon? What motivates them? What are their strategies, funding streams, business plans and timelines?
4. What are the technological options for producing these goods and services? What are their costs of production? How do those costs compare with terrestrial costs?
5. Given costs, what are the quantities demanded for lunar goods and services at various price points and under a variety of scenarios?
6. Ultimately, what factors are driving the demand for lunar and cislunar goods and services? How would changes in these drivers affect demand?[1]

2. Assumptions

a. Defining Commercial

The United States is increasingly looking towards commercialization as a means to achieving its national space policy goals. In referencing plans to send U.S. astronauts to the Moon by 2024, Vice President Mike Pence said "If commercial rockets are the only way to get American astronauts to the Moon in the next 5 years, then commercial rockets it will be" (Pence 2019). NASA documents prominently note that "commercial companies will play an increasing role in the space industry" (NASA n.d.), and Fred Kennedy in his role as the then Director of Department of Defense's Space Development Agency said that "how we do things in space has to change" and that now is the time to "take advantage of that synergy with the commercial sector" (Erwin 2019).

There is excitement in the space community about the prospects of commercial space transforming the space sector. However, what policy leaders mean when they use the term "commercialization" is ambiguous, and "commercial space" is often used as a magic bullet to solve all problems in the space sector (Lal and Wei 2019). A recent testimony in the U.S. House of Representatives noted that in the space community, the term "commercial space" may mean any one of at least three ideas: companies that are often, but not always, startups; commercial approaches, which are often fixed-price, milestone-based contracts;

[1] For the purposes of this study, cislunar space is defined as the volume of space that extends from geostationary orbit around Earth to encompass the Moon and orbits around it (NASA 2016).

and firms having primarily private customers, or customers other than the U.S. Government (Lal 2019).

Given the goal of the study to explore non-NASA demand, we use the most expansive definition of commercial, and include all three of the concepts above, plus philanthropic investments. To this end, we split lunar goods and services into two separate categories. Sales of lunar goods and services to households and businesses fall under the standard definition of commercial. This category includes expenditures by philanthropists on launch, landers, rovers, or habitats on the Moon as commercial expenditures. We also define some purchases of goods and services by government space agencies for lunar missions as commercial. As per the second definition above, we consider a procurement "commercial" if a space agency purchases repeated services or more than one of the items using fixed-price approaches; or if the lunar goods or services are purchased through competitive bidding, and the space agency leaves the design and manufacture of the product to the winning company. A key feature of this definition is that because the companies contribute to the development of the product of service and expect to market them to other customers, the space agency does not dictate the design or manufacturing processes used to manufacture the product.

b. Scope of Analysis

The timeframe for the analysis as per the NASA-requested scope of the project is through the year 2040. We believe that 20 years is the longest extent to which we can generate plausible observations about the likely shape of future demand for lunar goods and services. Using history as a guide, we assume that for a market for lunar goods and services to be fully developed by 2040, the underlying technologies have to be fully developed by 2030. This assumption precludes applications where the underlying technologies are in the early stages of development. For example, interest in in-situ resource utilization (ISRU) will concentrate on extracting water and other volatiles rather than regolith, precious metals or other materials.

We principally focus civil and commercial markets in cislunar space. National security in and from cislunar space (referred to as LULINT) is being discussed in space circles as a significant driver of activities in cislunar space. National security agencies may wish to track what other countries are doing on or around the Moon or in other parts of space from cislunar space, use the Moon as a location to test military space technologies, and purchase propellant for their space-based activities from ISRU facilities on the Moon, if that propellant is cheaper than if sourced from a terrestrial provider. However, these markets are not addressed in this report since we were not able to access quantitative data for national security related demand or applications.

3. Analytic Approach

Our approach to the analysis has three parts. First, we identified a set of goods and services that are considered as potential commercial markets enabled by lunar activities. Our set of goods and services may be incomplete, but it is sufficiently broad to illustrate the overall economic landscape for the Moon. An analysis that fully accounts for the interconnected nature of the goods and services is not possible within the scope of our study; thus, we have separated the provision of each good and service into separate markets that we analyze quasi-independently.

Next, for each market, we first defined the product and potential customers, and identified the companies and the technologies that they are attempting to develop to provide the product. We then estimated the costs of the most promising technologies and their terrestrial alternatives to identify those technologies that are most cost competitive using cost estimates from analogous systems or parametric cost estimates based on engineering data.

Lastly, drawing on these cost data, we assessed likely demand for the product at two or more price points, generating a rough demand curve, employing information on similar purchases, discussions of willingness to pay, and other data. We concluded with an assessment of the likely commercial markets that will be viable based on comparative costs and the potential size of the market.

4. Data Sources

We used a wide variety of information for this analysis. We drew on market and industry reports from the commercial press to identify and describe technologies, gather price information, and tap discussions of the strengths and weaknesses of comparative technologies. We also used this information to gather information on current sizes of markets of interest and on market prices. We used budgetary data from space programs from government sources and databases.

We identified 84 companies that offer or are planning to offer services and products on the Moon or in cislunar space for which we gathered information from websites, the commercial press, and annual reports. The complete database that summarizes company information is available as a companion excel file to this report. We also conducted 29 interviews with company representatives, 2 non-profits, 1 financial organization, 1 expert in relevant technologies, and 9 individuals from government organizations, professional associations, and other organizations that support lunar missions.

To ensure all entities had the opportunity to inform our analysis, we created an online data collection instrument, and sent to all 38 companies that did not respond to our request for interviews. Of these, nine companies responded.

C. Organization of the Report

After listing the study questions, methods, and sources in Chapter 1, in Chapter 2 we list the types of lunar products and services that each set of customers (households and businesses, and philanthropists and space agencies) may wish to purchase. Next, in Chapter 3, we present both quantitative and qualitative information about the organizations that have plans and aspirations to provide lunar goods and services.

Chapter 4 attempts to estimate the cost of technologies and systems that will likely be needed to provide these products and services. Building on this cost data, Chapter 5 presents our analysis of goods and services that government space agencies and philanthropists will need to purchase for their lunar missions. As part of this analysis, we project future budgets of space agencies for lunar missions through 2040 to provide a baseline for future expenditures on lunar missions. We analyze markets for heavy launch, lunar landers, rovers and hoppers, and habitats for human missions to the Moon and light launch and small landers for science missions. Chapter 6 summarizes the same analysis for goods and services that might be of interest to households and businesses, and ends the report with a summary of all markets. Chapter 7 summarizes our findings.

Appendices A–C provide the database of companies identified by the STPI team. Appendix D reproduces the questionnaire administered to the companies. Appendix E is a list of interviewees. The remaining appendices (F–H) provide the calculations underlying the analysis. The excel spreadsheet with the full analysis is provided as a companion to this report.

2. Potential Markets for Lunar Goods and Services

In this chapter, we first define who the potential customers for goods and services from the Moon are. We then discuss the goods and services that they would like to purchase and the derived demand for lunar services, such as launch and power, that are needed to provide these goods and services.

A. Final Demand for Cislunar Products and Services

Households will purchase goods and services from the Moon to satisfy their preferences for novelty and adventure. Businesses will purchase goods and services from the Moon because they are cheaper or provide a unique capability. Both sets of customers are sensitive to cost. Households will not purchase a trip to the Moon if they deem the price too high. Businesses will choose the lowest cost option for the provision of a good or service. For this customer base, in most cases, the existence of lower cost terrestrial options for delivery of an equivalent good or service will eliminate a technology option that involves the Moon.

Governments and most philanthropists, on the other hand, are motivated by factors beyond economics; they view space as an end, not a means. They are constrained in pursuing their visions for the Moon, such as lunar settlement, by the mismatch between the funds available (budget) and the cost of achieving those visions.

For each category of potential customers, in this section, we focus on final demand: lunar goods and services (such as scientific exploration or lunar trinkets) that these customers desire. In section B, we review derived demand: the required lunar goods and services (such as transportation and communication services) that make it possible to satisfy final demand for these customers.

Table 1 displays our list of demand for lunar goods services by these two customer categories. As can be seen, we identified three reasons why governments wish to go to the Moon: (1) as a location for human exploration of space, including human settlement and technology development for exploration of and beyond the Moon, such as to Mars; (2) as a site for science, or technology development related to science on the Moon, or for beyond the Moon, such as for Mars; and (3) as a location to signal geopolitical strength and enhance national security. Goods and services that households are motivated to purchase include activities that can only take place on the Moon, while businesses are pursuing methods for using the lunar environment or resources to create goods that may be in demand by the previously described customers.

Table 1. Lunar Goods and Services by Customer Category in the 2040 Timeframe

Governments and Philanthropists	Households and Businesses
Human exploration of space	*Households*
• Sustained human presence on the Moon or in cislunar space	• Lunar tourism (surface and cislunar)
	• Moon rocks
• Performance of humans in space	• Lunar artifacts (objects made on the Moon to be sold on Earth)
• Testing exploration- and settlement-relevant space technologies	• Lunar memorials (ashes to the Moon)
Space science	*Businesses*
• Lunar science	• Lunar advertising
• Astrophysics—the Moon as a site from where to observe the universe and solar system	• Virtual reality
	• Mining precious metals for sale on Earth
• Testing science-relevant space technologies	• Extracting Helium-3 for sale on Earth
	• Manufacturing in the lunar vacuum
Signaling Geopolitical Strength and National security	• Hazardous waste disposal
	• Supercomputing and data storage
• Lunar and cislunar Intelligence, Surveillance, Reconnaissance	
• Testing military space technologies	
• Permanent robotic outpost	

1. What Do Governments and Philanthropists Want from the Moon?

For governments and philanthropists pursuing human exploration of space, the Moon provides a site for temporary or permanent bases for people. It also provides a place for research on how humans respond to the rigors of space, such as extended periods of low gravity, high doses of solar and cosmic radiation, and extended periods of isolation from Earth in the company of a small group of people. Lastly, the Moon and cislunar space is considered a "proving ground" for deeper exploration of space, and many of the technologies required for deep space exploration can be expected to be tested in cislunar space or on the surface of the Moon (NASA 2016).

Planetary scientists would like to conduct research on the Moon to better understand lunar geology, the formation of the moon, and the origins of the solar system. The Moon provides a stable location for optical and radio telescopes to study the Sun, the solar system, the rest of the universe with minimal observational obstructions. The Moon also provides a site for testing space technologies relevant to science. A base on the Moon could, for example, facilitate a series of tests on the effects of radiation, vacuum, and extreme heat and cold on materials and equipment to be used to explore the solar system or even for use on Earth under harsh conditions.

As the space capabilities of some U.S. competitors have risen, officials responsible for U.S. national security have voiced increasing concerns about the potential of competitors to use the Moon as a location for interfering with U.S. reconnaissance and communications activities that play a critical role in U.S. defense and intelligence operations (AFRL 2019). Placing systems or satellites on or around the Moon to keep track of competitors' activities could enhance U.S. security.

2. What Might Households and Businesses Purchase in Cislunar Space?

As noted above, the time span of this study is limited to 2040. We argue that for a lunar product to be sold commercially by the end of the 2030s, the technology to produce it would have to have been developed by the 2030. Thus, our list does not include a comprehensive list of activities that are discussed within the space or science fiction communities.

In our survey of companies with lunar activities (discussed in Chapter 3), we identified three lunar products to be sold to terrestrial households: recreational trips to the Moon or cislunar space; artifacts incorporating materials from the Moon; and burying symbolic portions of one's ashes on the Moon. In each of these cases, at least one business had sold or was marketing the product.

We also included the following lunar products and services targeted at terrestrial businesses in our analysis: sales of sponsorships for advertising; extraction of precious metals; manufacturing in the lunar vacuum; supercomputing; hazardous waste disposal; and mining Helium-3 (See Table 1). Of these activities, only sales of advertising and sponsorships for lunar missions have actually occurred.

B. Derived Demand for Goods and Services Needed for the Moon

We consider the activities and products listed above as final demand. In each case, the product provides the outcome desired by the end user. However, to provide each of these activities or products, numerous supporting activities are needed: launch services to get to cislunar space; spacecraft to take cargo or crew to and from the surface of the Moon; rovers to move lunar tourists around; and electricity, air, and water to survive. The most immediate markets targeted by companies offering to provide these goods and services are government space agencies and philanthropists. Table 2 lists the goods and services that will be needed to support government and commercial activities on the Moon.

Space tourism and human exploration of the Moon require space transportation services to take crew and cargo to the Moon and back. Surface transportation, such as rovers, may also be necessary to support crewed or robotic operations on the lunar surface.

Surface operations may also require the use of a habitat for crew living and working quarters. Surface operations will also require power and communications services, which could potentially be provisioned as a commercial service.

Table 2. Goods and Services in Support of Lunar Activities

Heavy launch services	*Lunar habitats*
• Human	• Structures
• Cargo	• Life support
Capsules - human	• Power
Lunar landers for humans and heavy cargo	• Communications
Lunar rovers or hoppers	*ISRU*
Light launch	• Exploration technologies
• Scientific payloads	• Extraction equipment
• Other cargo	• Processing equipment
Lunar landers for light payloads	• Power
Satellites for space situational awareness	• Materials transport

Some scientific missions to the Moon will be able to be conducted robotically. These missions may only need lighter launch vehicles; scientific payloads and other cargo may be able to be transported within fairings and will not need specially designed capsules. They will need some mechanism, like light lunar landers, to deposit their payloads on the lunar surface.

For the purposes of this study, we assess a lunar habitat for a small number of astronauts that is inhabited intermittently for shorter periods of time, and a larger habitat that can host a relatively large number of people for longer periods of time. These habitats will need systems to provide life support, power, and communications.

Finally, there is a potential opportunity for lunar resources to be harvested and sold to support the operations listed above. NASA and other organizations are exploring ISRU as a means of reducing costs of lunar and other space missions by supplying products from the Moon rather than transporting them from the Earth. Interest in ISRU in our timeframe (out to 2040) has been concentrated on extracting water. Some of this water can be used to satisfy the needs of people visiting the Moon. However, most of the interest has been focused on extracting hydrogen and oxygen from the water to be used for propellant. Some have also suggested using regolith to build or insulate lunar bases. ISRU entails a large number of enabling activities and technologies: exploration, extraction, processing, and transport. All of these activities consume energy. We assess the costs and feasibility of lunar ISRU in Chapter 4.

Historically, space agencies have designed and closely supervised the construction of launch vehicles, capsules, and other equipment needed to explore space. By our definition, these activities are not commercial. The two most prominent philanthropists with goals for human exploration of space are building their own rockets and capsules rather than sourcing these products through bids from outside vendors. In the analysis that follows in Chapters 4 through 6, using our definition of commercial, we assess whether an enabling technology needed for lunar missions can be procured commercially: using fixed price contracts to make repeated purchases of the good or service.

3. Non-Governmental Organizations Involved in Creating a Lunar Economy

In this chapter, we summarize our understanding of organizations that are or could be involved in providing products and services either on the Moon, in cislunar space, or to get to one of these destinations. Section 1 summarizes the database of organizations, and section 2 synthesizes insights from interviews conducted with a subset of these organizations. While we subdivide companies based on their stage of development, in this chapter we do not offer an explicit assessment of the realism of their offering. The goal of this chapter is to provide the complete landscape of organizations in the lunar sector. Subsequent chapters provide STPI's assessment of how realistic company offerings are.

A. Descriptive Statistics

Our database of lunar organizations includes 87 organizations. Of these, 84 organizations, both for- and non-profit, offer or are planning to offer services and products on the Moon or in cislunar space.[2] These 84 organizations offering goods and services are the primary focus of this chapter. Three non-profit organizations—Cislunar Marketplace, For All Moonkind, and Open Lunar Foundation—do not offer a good or service targeting the Moon, but rather are advocacy organizations for lunar settlement and are therefore not included in the analysis. One non-profit organization, SpaceIL, is included in the list of 84 organizations analyzed because they are offering lunar transportation as a service. Appendix A lists the names and basic information about the 84 organizations. Appendix B provides more information about the products and services offered by the organizations.

1. Focus

Of the 84 companies in our database, 23 are exclusively targeting the Moon for their products or services (Figure 1). For 45 of these companies, lunar goods or services are one component of their broader space services.

Seven of the 84 companies are primarily terrestrial companies that are offering a lunar service or good as a "one-off" or a minor part of their business model. The remaining 9

[2] Three organizations not included in the analysis had at one point targeted the Moon through the Google Lunar XPRIZE, but since the conclusion of the competition have re-focused on other space products and services. These three companies—Artemis Space, Independence-X, and Valles Marineris—are not counted towards the 84 companies currently planning lunar services.

companies offered both space-based and terrestrial services, with at least one lunar offering, in their business model.

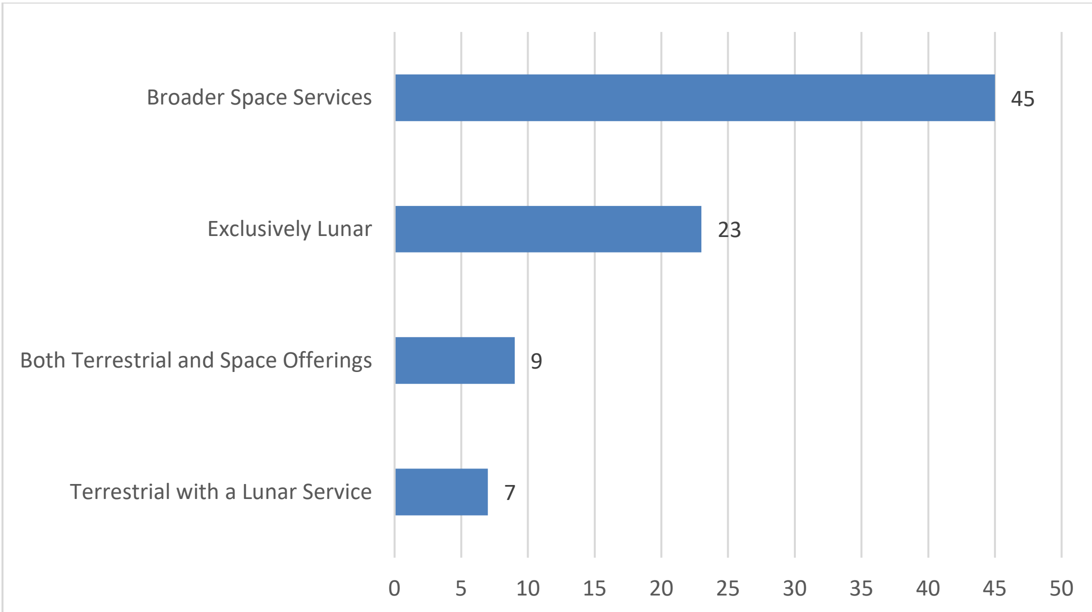

Figure 1. Companies with Lunar Goods and Services

2. Companies by Country

Of the 84 companies in our database, the vast majority—58, or about 69 percent—have their headquarters in the United States (Figure 2). Germany follows with six companies. Japan has five companies planning lunar activities. United Kingdom has four companies. Luxembourg, Israel, and Canada each have two companies. India, Hungary, France, Belgium, and Austria each have a single company planning to offer lunar services or goods. By continent, there are 60 companies headquartered in North America; 16 companies in Europe; 6 companies in Asia; and 2 in the Middle East. By far, there are more companies engaged in lunar activities in the United States than anywhere else. All three of the non-profits identified but not included in our database are based in the United States as well.

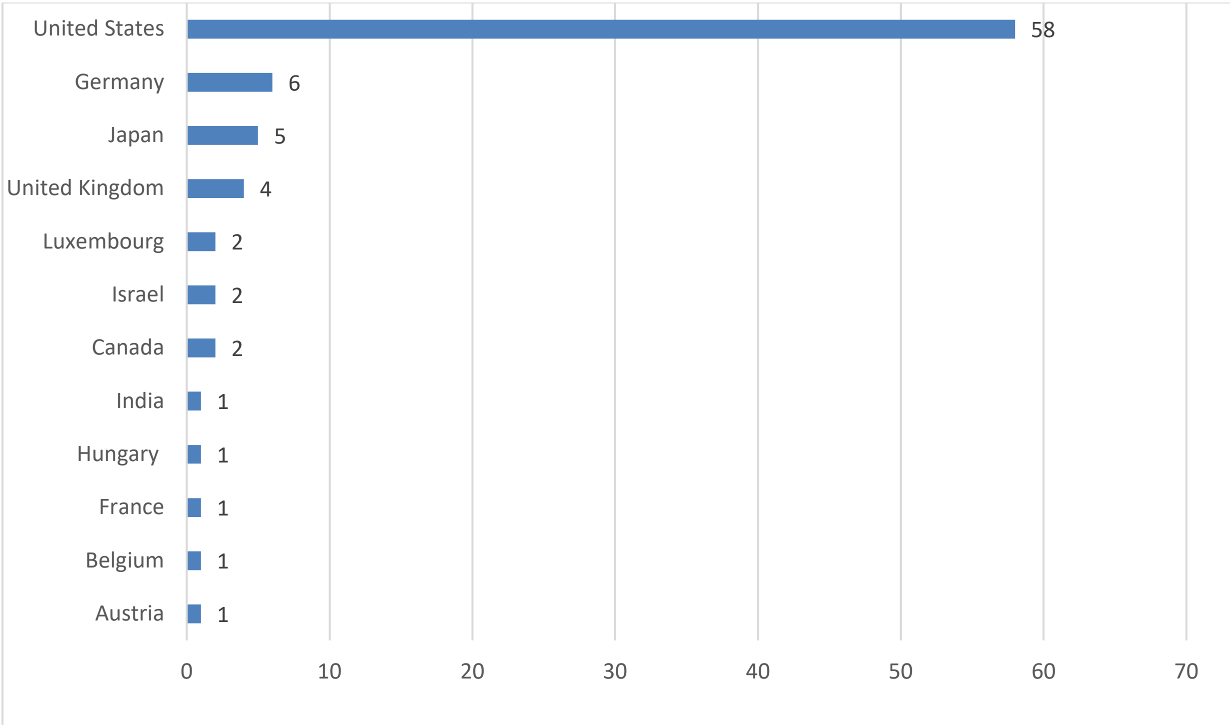

Figure 2. Lunar Companies by Country

3. Companies by Maturity

These companies were also evaluated based on how established they are to date, on a qualitative scale of one to three developed by STPI:

- Companies that are well established, and have been in operation for 10 years or more were rated as three (or most mature) on this scale.
- Those that have either flight heritage, a government contract, or had raised funds were rated as a two on this scale.
- Companies that are early stage startups were given a score of one (or least mature).

It is important to note that our rating does not pass judgment on the technical aspects of their products or services; rather, this scale provides a rough estimation of the business development of these companies. Sixteen out of the 84 total lunar companies, or about 19 percent, are stage one businesses or are nascent (Figure 3). Twenty-eight companies (about 33 percent) were rated at stage two, indicating that they had been in operation less than 10 years but had flight heritage, raised funds, or had a government contract of some sort. The remaining 40 companies (48 percent) were rated at stage three, indicating that they were well established and had been in operation for over 10 years.

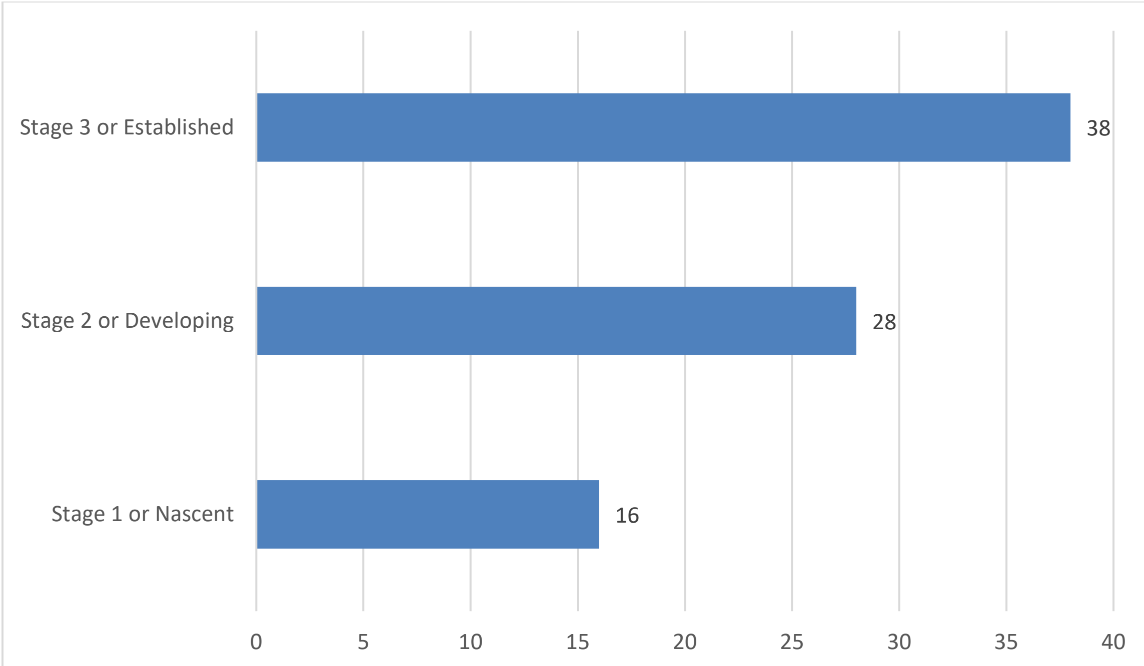

Figure 3. All Lunar Companies by STPI-Assessed Stage of Business Development

Out of the 23 companies for which lunar services are the primary focus of their business model (see Figure 1), nine were considered nascent or at a stage one (Figure 4). Eight were at a stage two, or had a government contract, flight heritage, or had raised funds. Six of the companies that were entirely lunar focused rated at stage three.

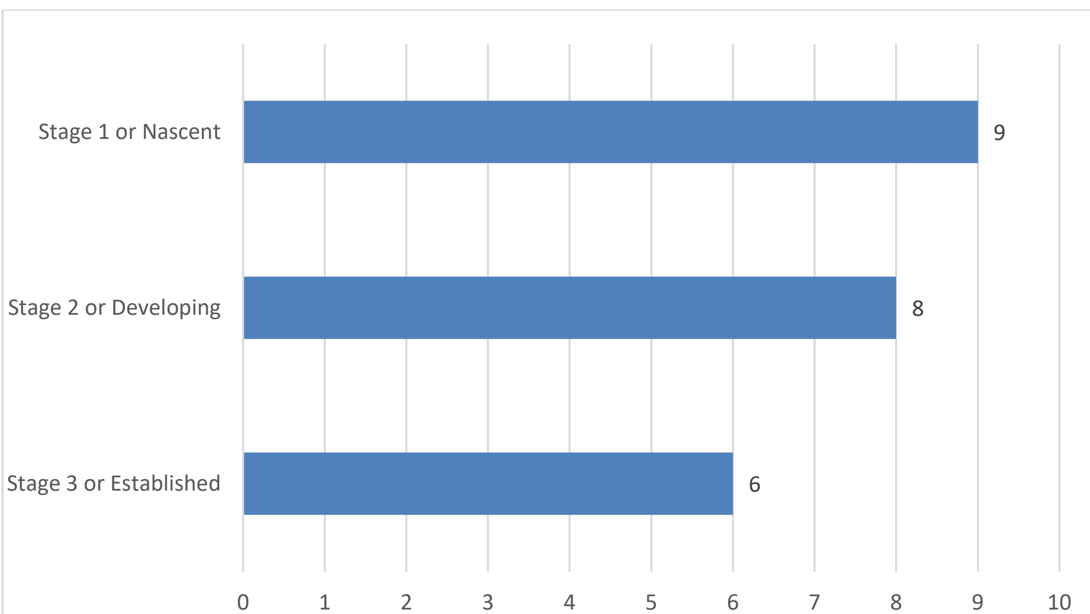

Figure 4. Exclusively Lunar Companies by STPI-Assessed Stage of Business Development (n=23)

4. Companies by Sector

We sorted these 84 lunar companies into seven sectors based on their intended offerings. These sectors were: Transportation; Structures or Habitats; ISRU; Communications; Position, Navigation and Timing (PNT) Services; Private Goods such as Tourism, Moon rocks, and Memorials; Supply Chain Manufacturers; and Science and Data Collection.

By far, the largest sector is Transportation, at 36 companies or 43 percent (Figure 5). The second largest sector is ISRU, with 18 companies or 21 percent. Structures and Habitats follow closely with 17 companies, or about 20 percent. There are 13 companies—about 15 percent—providing supply chain manufacturing in support of lunar operations. There are three companies planning to offer PNT services. Five companies are planning to offer private goods, and another two companies are providing science or data collection services. The Transportation sector is broken down further into Lunar Landers; Earth to Orbit Launch Vehicles; Earth to Lunar Surface Launch Vehicles; Orbit to Orbit Transfer Vehicle; Space Tethers; Space Elevators; and Lunar Rovers. The Structure and Habitat sector is divided into subsectors of In-Space Habitats, Surface Habitats, and Habitation Support. The In-Situ Resource Utilization sector is further divided into Prospecting, Mining or Processing, and Use or Output services. Description of the distribution of companies by subsector is available in Appendix C.

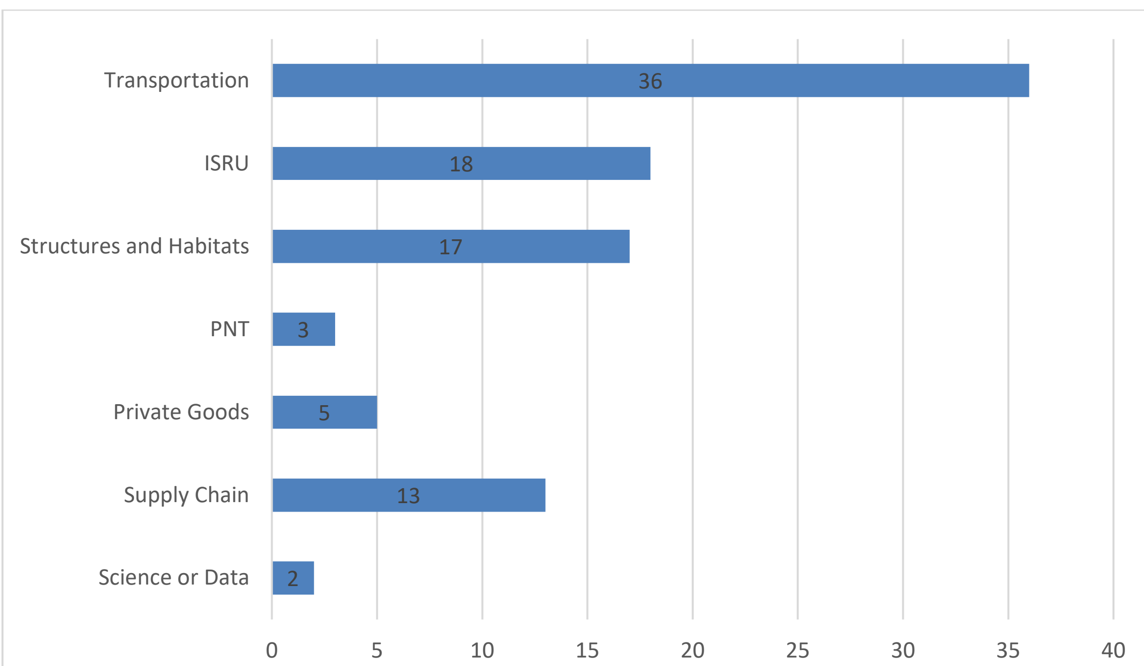

Figure 5. Lunar Companies by Sector

For all sectors, the United States has more companies than any other single country (Figure 6). For PNT services, Private Goods, and Science or Data Collection, all companies planning such services are based in the United States. For ISRU and Communications, the United States has about half of all companies interested in these activities. For Supply Chain, Structures or Habitats, and Transportation, the United States has the majority of the market share with 83 percent, 88 percent, and 69 percent, respectively.

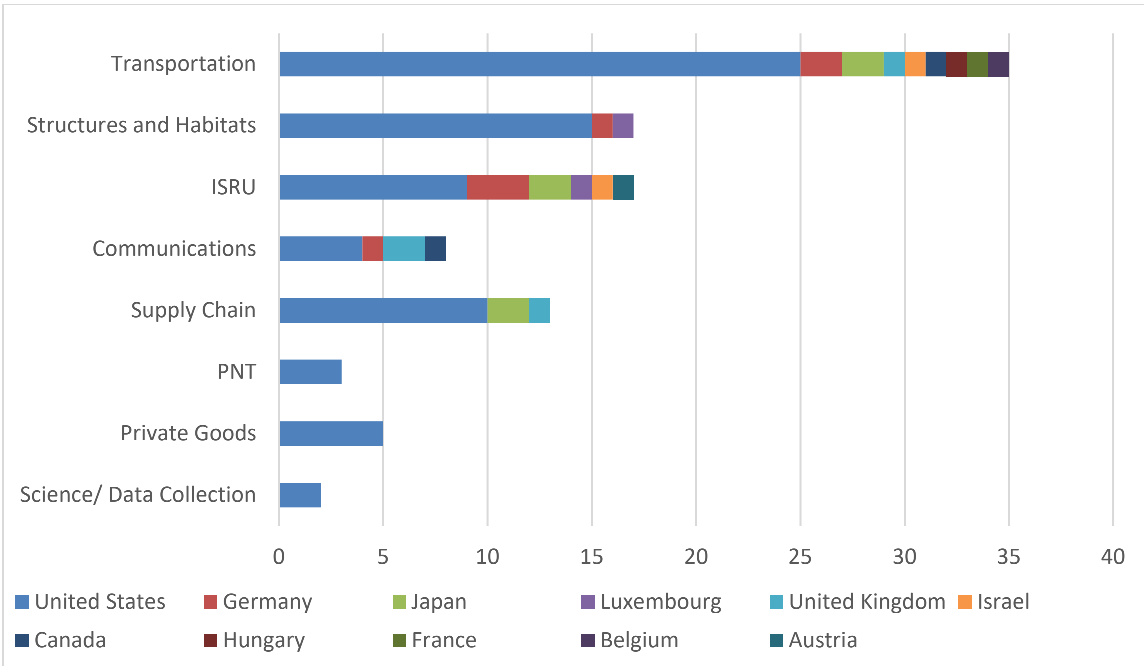

Figure 6. Lunar Companies by Country and Sector

B. Key Insights from Interviews

We conducted interviews with 29 companies, 1 financial organization, 2 non-profits, 9 experts in the space sector, and 1 expert in relevant technologies. We also asked companies that did not respond to our requests for interviews to complete an online questionnaire. This section summarizes viewpoints from the interviews and the questionnaire, with minimal STPI commentary. STPI's independent economic and technical analysis of these markets will be provided in Chapters 4 through 6. The protocol used for the interviews is included in this report as Appendix D.

Interviewee observations are divided into those regarding markets, divided by sector; motivations and strategies; funding; and finally, miscellaneous.

1. Markets

The majority of interviewees indicated that their business cases were tied to NASA or other government demand. Often such respondents noted that today, even the low-Earth orbit (LEO) economy is not yet mature, and, as such, there could be no expectation that the lunar economy could achieve what has not yet occurred in LEO. These interviewees indicated that with significant support, a viable market could form by supporting NASA operations, but they did not foresee a significant private demand in the timeframe of this study. Even as they plan to support government demand, these companies saw themselves as being commercial.

Some interviewees stated that technology driven and funded by NASA will be integral to future business cases. To this end, some interviewees noted that while there is adequate support for technology of a low-Technology Readiness Level (TRL), mid-TRL technologies will need more funding to increase the economic viability of lunar activities. Others went broader, and stated that NASA would need to set up the basic infrastructure before commerce could commence, although some noted that a billionaire-funded infrastructure project could achieve this as well. Either way, infrastructure and technology development support were often identified as key to any potential economic activities in the long-term.

Several respondents indicated that supporting human spaceflight development is either the only way to make a business case, or would increase the ways to do so. As some interviewees stated, there is an inflection point at which the number of humans on the lunar surface allows various business cases to become feasible, particularly—but not exclusively—ISRU.

Some respondents noted that marketing, advertising, and sponsorships will be a sizeable market. One such respondent noted that NASA would need to allow providers of services to NASA (such as those provided for the Commercial Lunar Payload Services [CLPS] program) to be more flexible with leveraging their own branding and imaging on these missions (NASA n.d.), as NASA is sponsoring payloads rather than the missions themselves. Conversely, some respondents have noted that a sponsorship and advertisement market may not be sustainable after the first successful landings.

Several respondents anticipate that the Department of Defense (DOD) will be a significant driver for lunar markets. One even anticipated that this demand would be larger than that of NASA. These respondents indicated that communications, PNT services, and ISRU would be the primary sectors of interest to DOD. It is important to note that not all respondents identified all three of these sectors as being of interest to DOD; communications and PNT were the most often identified sectors of interest. ISRU was only thought to be of use to DOD by a minority of interviewees. Out of all interviewees who identified DOD as a driver of lunar markets, none was able to articulate the expected size of DOD demand.

Many interviewees indicated that they anticipated that foreign space agencies would be a significant potential customer base. These interviewees generally identified the "traditional" space agencies—the Japan Aerospace Exploration Agency (JAXA), the European Space Agency (ESA), the Canadian Space Agency (CSA), and Roscosmos—as prospective customers. Often, India, the United Arab Emirates, and Israel were also noted as possible customers. These interviewees were mostly transportation service providers and mostly American, but not exclusively so.

a. Transportation Services

Many respondents indicated that successful commercial launches would further encourage the development of lunar markets. These interviewees noted that because the most recent lunar landing attempts have been unsuccessful, a successful commercial or non-governmental landing will be important to demonstrate that commercial providers can be effective. Until then, businesses and the public may be skeptical of their capabilities, these interviewees note. As such, establishing access will be important to encourage investment and use; further, access, they argue, will inspire new possible ways to utilize access to the Moon. Beyond establishing that commercial providers can actually access the Moon, some respondents noted the importance of making these services routine and affordable. Out of this group of respondents, some emphasized that routine access to the Moon is the key to market development, over cost. Their rationale was that companies would be more likely to invest in lunar systems or send things to the Moon if access were routine, because even the mission was unsuccessful, there would be other opportunities frequently enough that the risk could be weighed, rather than having a single chance. Others emphasized the importance of cost more than regularity of access. They argued that once access becomes cheaper, more use cases become feasible for a greater number of actors. However, both groups of respondents agree that ideally access would become both cheaper and more routine. Three respondents noted that space tugs would be an important part of this ecosystem and would provide an economical method to get from Earth orbits to lunar orbits.

Several interviewees noted that the number of CLPS providers—currently, 14—is unsustainable, in that it may be possible for two or so companies to profit and find a market niche, while the others will be forced to consolidate, drop-out, or cease to exist. In particular, some interviewees noted that the small lander market may be particularly short-lived. These individuals noted that as NASA and other space agencies focus increasingly on habitation and permanent presence, payload sizes will increase to accommodate the transportation of large equipment, systems, and humans, as compared to the early missions that will focus primarily on much smaller science and exploration payloads. As this shift occurs, the demand for small landers will decrease significantly. A few respondents noted that when this occurs, small landers could transition to "hoppers" or small vehicles that visit various locations on the Moon to accommodate science and exploration demands. One interviewee noted none of the CLPS providers or their international counterparts participated in any information sharing, leading them to "reinvent the wheel," in that they each separately invest in addressing the same technical challenges. Further, they argue, the large number of providers puts a strain on the finite and small amount of talent with pertinent skills.

b. Rovers

Most interviewees associated with companies building lunar rovers noted that their rovers are being offered as part of end-to-end services. That is, most rovers are being offered as an extension of their lunar landing services, all of which were small lunar landers. These respondents noted they foresaw that the customers for their landers would desire mobility options. They stated that science and exploration markets would value the ability to visit various locations on the lunar surface to collect data or place sensors.

c. Structures and Habitats

Several interviewees indicated that landing pads would be necessary for sustained surface operations, although they would not be necessary for initial science and exploration missions. These respondents noted that landing pads are important to protect nearby operations and heritage sites like the Apollo sites from the ejecta caused by landing on the lunar surface, as lunar regolith can damage machinery and disrupt its surroundings. In order to accommodate sustained human presence or regularly operate machinery on the lunar surface, a landing pad would need to be constructed such that large vehicles could land and not damage their surroundings. Alternatively, barriers could be constructed, or large vehicles could be forced to land a certain distance from other operations or key sites and then transport their cargo where it is needed.

d. In-Situ Resource Utilization

Many respondents noted the need for prospecting on the lunar surface to gain a better understanding of the resources available and their locations. There is an understanding of the composition of lunar regolith in broad terms; the amounts at various locations, however, are unknown. In order for ISRU operations to commence, there would need to be more knowledge on the composition of various lunar sites, to inform these missions. This would require prospecting missions; most respondents did not make a note of how many would be required, the methods by which to prospect, or who would conduct these operations. One respondent noted that this should be an undertaking of NASA through CLPS.

There were disagreements among interviewees as to the viability of a "water economy" or market based up the extraction and sale of lunar water for consumption and propellant. A majority of interviewees did not see this as a commercially viable market due to the affordability of terrestrially-sourced propellant and water, even if launched into orbit. Within the minority, some insisted that in the long-term, prices would be competitive as

ISRU operations become more efficient. One interviewee indicated that water propellant would be the first market, initially driven by NASA demand and provided by a commercial supplier. Two launch providers have indicated that their designs would be amenable to re-fueling with water propellant. Another stated that they would need significant evidence of success and affordability before it could be factored into their designs. One launch provider has made the offer to those interested in ISRU that they would purchase lunar-sourced propellant if it were price competitive with terrestrial propellant.

Two respondents believe that Helium-3 extraction could be a “killer app” for the Moon. These interviewees either noted the cost of Helium-3 in national security applications, or the potential for Helium-3 based fusion reactors on Earth. Both noted the relative scarcity of Helium-3 on the Earth. A vast majority of respondents, however, did not think Helium-3 was a viable market. Some interviewees noted that for the past 40 years, fusion has been thought to be 20 years away. Further, these interviewees noted that the lack of development of Helium-3 fusion systems on Earth is due to a lack of technical feasibility, not lack of supply of Helium-3.

Two different respondents noted that utilization of the lunar vacuum could allow for the manufacturing of different valuable materials. These interviewees noted that the lunar vacuum was stronger and cleaner than in LEO, which could improve the value of these manufactured materials. These interviewees noted that additionally, many of the raw materials needed for these operations (e.g., iron, silicon, aluminum) already exist on the lunar surface.

e. Communications

Several interviewees indicated that they believed communications services would be a significant market in cislunar space. Some interviewees noted that their landers—not all landers—offer communications to facilitate scientific missions, in that data could be sent back to Earth as it was collected. For such applications, communications services would be offered as part of end-to-end services. These respondents indicated that this could potentially serve as a competitive advantage compared to other providers.

Other interviewees thought that communications would be necessary to support both NASA and DOD operations on the Moon or in cislunar space, both for communication with other entities on the lunar surface and communication with Earth or mission control. Two interviewees noted that while supplying government with communications services could be lucrative, this niche would be filled by a small set of companies, perhaps even one.

2. Goods and Services for Households and Businesses

There was some disagreement among interviewees regarding the tourism market. One respondent anticipates that it will be the first lunar market to emerge. Another noted that it would be unsustainable after a few trips are completed, as the pool of individuals who could finance such missions is exhausted. Others noted that in the long-term it would be a viable market as transportation costs decreased or access became routine.

Many interviewees noted that they thought transporting lunar rocks back to Earth as trinkets could be a viable market, but they noted that there are no companies planning to do so, at least publicly. The lack of companies planning to bring back Moon rocks was a point of confusion among many such interviewees. They mused that perhaps it is either too early for such plans; prohibitively expensive to bring lunar regolith back using current vehicles; return mass is being utilized for scientific instruments and samples; or there could be legal regulations or uncertainty around such activities.

3. Science or Data-Collection

A few respondents noted that science and exploration will be the primary markets for small landers. These interviewees indicated that science and exploration missions value the mobility and flexibility in landing sites that small landers can offer, as well as the more frequent launch cadence such landers can accommodate. These interviewees report that large landers have less flexibility on landing sites due to size; will be launched less frequently, hindering iterative experiments valued by scientists; and will not allow scientists to choose landing sites as scientific payloads will fly as secondary payloads or "ride-shares" on large missions.

Several respondents noted that there would be a market for testing technologies or technology maturation on the lunar surface, for both space and terrestrial technologies. These respondents indicated that the extreme environmental conditions would be helpful in testing space technologies for future missions into Deep Space, or for terrestrial technologies that will in turn be used in extreme locations on Earth. Further, such respondents indicated that testing terrestrial technologies on the Moon would be helpful in advertising. That is, these companies could advertise that their product is "Moon-tested." Some respondents indicated that mobility would be valued in a testbed designed to test space technologies. One out of this subset indicated that lunar technology testing would be preferable to the International Space Station (ISS) due to the increased flexibility in testing that the Moon would allow, while NASA places severe restrictions on activities on the ISS due to safety concerns.

4. Motivations and Strategies

For motivations, interviewees generally fell into two categories. The largest are those who shifted their focus on the Moon to match NASA's Artemis program and to anticipate potential NASA needs. The other category is those who have a vision of human settlement throughout space, regardless of NASA's ambitions. Within this group, some view Mars as their ultimate destination and the Moon as a temporary stop or proving ground for pertinent technologies. Others are not necessarily "destination-specific," but interested in space settlement as a whole. For these companies with interplanetary visions, they anticipate using their services to their own ends, not simply providing services to customers.

For organizations that have targeted the Moon as a reflection of NASA's priorities, in most cases the corresponding strategy is to bid for NASA contracts and grants, either to provide services or to develop technologies. Most of these organizations fall into two classes—traditional air and space contractors, and younger, smaller companies. For the contractors, these companies already offer other space goods or services. As such, they consider lunar missions to be a reasonable extension of their capabilities. That is, the services or goods they provide for other space missions can be adapted to lunar applications, perhaps with some technical obstacles but not insurmountably so. Further, few of these larger contractors expect to or could support private customers in the future; most only anticipate serving NASA demand for the timeline of this study. These contractors are almost entirely transportation companies, although sometimes they operate in other sectors.

The younger, smaller companies intend to leverage NASA funding and support to develop their capabilities. For many of these companies, their technologies are not yet operational, and they anticipate relying on NASA—in both funding at early and mid-TRL levels—to bring these technologies to market. Many of these companies are either lunar or space specific, and as such do not anticipate being able to raise private funding to support themselves at this stage; often they do anticipate having private customers, however, and as such expect to be able to either raise funding in the future or use sales as support instead of NASA.

As mentioned above, there were a minority of companies targeting the Moon because of their own institutional vision for humankind's future in space. These companies view the Moon as the first stop or a proving ground for space technologies. One of these companies has a significant source of private funding to pursue this vision. Some are attempting to support this vision by selling terrestrial versions of their goods or services to fund the development of their vision for space. Another sells services in Earth orbits in order to fund the development of technologies for deep space applications. One foreign company, while not focused on human settlement throughout space, is similarly aligned in a motivation to democratize space access, and funds their lunar activities through corporate sponsorships and advertisements, which are largely driven by national interest.

5. Funding

Some of our interviewees are funding their lunar technologies by repurposing this same technology for similar terrestrial markets. One such company is eventually interested in ISRU and mining on the lunar surface, and in order to develop and fund this technology, they are marketing their services and systems to terrestrial mining companies. Similarly, another such company building lunar habitats identified a niche in the housing and tourism market. Given that their technologies are recyclable and use in-situ materials, they have been able to appeal to eco-tourists with their terrestrial prototype, as well as potentially selling versions of their habitat to eco-conscious communities. For companies in this group, revenues generated from terrestrial activities will be leveraged to further their lunar ambitions.

Many interviewees intend to fund or are funding their development with NASA support. A majority of this group intend to eventually sustain themselves through private customers, using NASA funds for the initial development of their technologies until a non-governmental market builds up. A few interviewees already have private customers with which to support their company; these companies sell consumer goods—such as memorials or lunar trinkets—and are by a far a minority amongst interviewees.

6. Other Notable Comments

There were disagreements amongst interviewees regarding whether Antarctica is a good analog for lunar development. A few noted that Antarctica is a suitable analog because there would likely only be a few humans there at a time conducting science and research, with some tourists visiting on occasion over the years. These interviewees stressed the hostility of both environments, seeing value primarily for research and tourism. However, others contested this analog, stating that if commercial utilization of Antarctica had been allowed, many companies and countries would have been interested in exploiting the resources available there. This group of interviewees instead emphasized the vast resources they saw in both places, and therefore they believe that if transportation can provide reliable access, and legal rights of usage could be established, utilization of lunar resources could occur in significant levels.

Some interviewees indicated that they would feel more comfortable with a clearer legal regime for resource utilization. They worried that without legal certainty, investment is more difficult to procure. Other interviewees believe that the lack of current regulations on lunar development are a benefit, in that they have leeway to act how they would please or they believe it is too nascent of a market to develop regulations. Others would like the certainty of regulations establishing their right to utilize lunar resources. One even indicated the desire for a "one-stop-shop," similar to what has been proposed for activities in LEO.

Some respondents noted that national interest and pride will be a significant driver of the lunar market. As more countries become spacefaring, they will view lunar missions as points of national pride. To accomplish this, foreign companies and governments are more willing to fund or otherwise support their home country's lunar ambitions. Many interviewees noted SpaceIL as an example of such national support driving lunar missions.

4. Costs of Relevant Technologies

In this chapter, we estimate the costs of key lunar technologies and systems, principally the cost of transporting humans and cargo between Earth and the Moon, and the costs of activities such as transportation, power, habitats, communication, and ISRU on the surface of the Moon. The costs of these systems are necessary inputs to estimating the economic feasibility and potential demand for lunar goods and services in Chapters 5 and 6.

A. Methodology

Our methodology for estimating the costs of the transportation, habitat, power, and space resource mining systems is illustrated in Table 3. We begin by partitioning each proposed system into its constituent elements. For instance, the elements of a lunar mining system may include a rover for resource prospecting, a robot that excavates lunar rock, a rover to collect and haul the material to a processing plant, and various processing plants to produce water, propellant, or other end products from the material. For each element of a system, we estimate the development costs needed to build the first unit, unit costs for each subsequent unit produced, and costs associated with the launch, operations, and maintenance of the elements. For each technology system (e.g., transportation, lunar mining), we model the output of the system, based on the performance parameters of the technological elements, as a function of the demand for the goods and services that the technology system produces. For example, given a specified demand for tons of lunar cryogenic propellant per year, our model will estimate the number of excavators, haulers, processing plants, etc. that are required to meet that level of demand. The number of elements required to meet the specified demand can then be combined with their associated costs to estimate the total capital expenditure required to meet the demand. Finally, we divide the total cost by the output (i.e., the demand) over a decade to estimate the annualized cost of providing the good or service.

Where possible, we have drawn on analyses in the literature or public statements by companies to estimate the development or unit costs. Where no such estimate exists or where estimates vary widely, we use our engineering judgement to pick a value or to provide a low and high estimate. *For most technologies, we have assumed that the cost to produce the n-th unit is less than or equal to one-third of the development cost; this is a variable that can be adjusted within the model.* For low rates of production, we believe this ratio is reasonable and it appears to be congruous with cost estimates produced by Lavoie and Spudis (2010; 2011; 2016), upon which we have also based many of our cost estimates.

Units with higher rates of production, such as the small autonomous rovers in the water mining architecture, are assigned a more favorable ratio.

Table 3. Template of STPI's Methodology for Estimating the Cost of a Good or Service

Input Parameters			
Input 1: Launch Cost ($M/kg)	LaunchCost		
…			
Input N: …			
Demand for Product	AnnualOutput		
	System Element 1	…	System Element N
Costs ($M)			
Development	DevCost		
Unit Fabrication Cost	UnitCost		
O&M Cost / Unit-Year	OMCost		
Tech Specs			
Param 1: Mass of Unit [kg]	Mass		
…			
Param N: …			
Calculation 1: …	Inputs & Params used here		
…			
Calculation N: …			
Units in Operation	Units		
Annual Input	Input	…	Out_N-1
Annual Output	Out_1	…	AnnualOutput
Over the Decade 2031-2040			
Units Launched [#]	Units		
Total Mass to Launch [kg]	MassToLaunch = Mass*Units		
Total Dev and Unit Cost [$M]	DevCost + (Units-1)*UnitCost		
Total O&M Cost [$M]	OMCost*Units*10		
Cost of Launch [$M]	MassToLaunch*LaunchCost		
CAPEX Per Element [$M]	CAPEX_1 = Sum of costs above	…	CAPEX_N
Total Costs for System			

Total CAPEX	CAPEX = CAPEX_1 +…+ CAPEX_N
Annualized Cost over Decade	CAPEX / (10 * AnnualOutput)

Note: Orange cells are input parameters. The green cell is the input parameter along which the total costs are parametrized. Light grey cells are calculations that utilize the various input parameters. The dark grey cells are intermediate and final outputs.

In general, we have chosen our development and unit costs using the assumption that technologies are developed competitively and commercially, as opposed to using cost-plus contracts with government oversight requirements. In other words, the company pays the full development costs, which are passed on to the customer within the price of providing the good or service. We amortize the development and unit costs over a decade.

B. Cost of Space Transportation

The cost of access to the lunar surface is a driving factor for the cost of lunar products and services. Access to the lunar surface can be analyzed in approximately four segments: ascent to orbit from the surface of Earth or the Moon; orbital maneuvers that transfer spacecraft between Earth and lunar orbits; descent from an orbit to the surface of Earth or the Moon; and lunar surface-to-surface operations that allow crew and cargo to be distributed to points of interest. In this section we estimate the costs of sending small payloads to the lunar surface, a two-stage lunar descent and ascent element for cargo and crew inspired by the Human Landing System (HLS), a hypothetical sample return mission, crewed missions to the lunar surface using the Space Launch System (SLS) and HLS, and missions to the lunar surface using the SpaceX Starship. For all of these missions, the propellant required is assumed to be terrestrially produced.

1. Two Stage Human Landing System

The HLS is the spacecraft that NASA intends to use for round trips of crew between the lunar Gateway and the lunar surface. As specified in its broad agency announcement (NASA 2020b), the HLS needs to support the landing of four people and to be able to survive a portion of the lunar night with the use of pre-placed surface assets. Most concepts for the HLS appear to be comprised of separate stages for the descent and ascent; thus, a rough comparison with the Apollo Lunar Excursion Module (LEM) is reasonable, noting that the HLS has a larger crew capacity and surface duration time than the LEM. The non-recurring development cost for the LEM was $14.7 billion in FY 2017 dollars, while the unit costs were about $0.7 billion in FY 2017 dollars (Zapata 2017). As the LEM was not reusable and the unit costs are so high, we will ignore operations and maintenance costs. The costs associated with the LEM will be used to produce a high cost estimate for a two-stage HLS.

For a lower cost estimate, we assume that a modern commercial company will be able to develop its human landing system at approximately one-fourth of the cost of the LEM, i.e., $3 billion. Similarly, the unit costs are assumed to be $0.18 billion, one fourth of the LEM unit costs. We do not claim that this represents a likely cost for such a system, but that it is in the realm of the possible for a commercially developed system where the company bears most of the development costs on its own. Further, while the LEM had to be self-sufficient for the entire period of its 3-day lunar surface operation, the HLS can leverage pre-placed assets; thus, easing the burden on the landed mass requirements, Environmental Control and Life Support Systems (ECLSS), and overall cost of the HLS. We have used our engineering judgement to distribute the development and unit costs across the descent and ascent stages at a ratio of 1:2. The ascent stage is assumed to be used solely for crewed missions, while the descent stage can be used for both crewed and cargo missions.

We do not know the anticipated level of reusability for the ascent stage; regardless, we assume that each ascent stage can be used three times. We note that maintenance and reuse would be challenging given that, per the HLS Concept of Operations, the spacecraft would need to detach from the Gateway after its use, then loiter in space until the next mission, which might be 1–2 years away, possibly being refurbished in lunar orbit, before finally mating to a new expendable descent stage prior to its next use. We have chosen $30 million as the maintenance cost per re-use of the ascent element; however, we have no firm basis for this cost. We assume the descent stage is not reusable and has no associated maintenance costs.

The HLS would be launched, uncrewed, from Earth to rendezvous with the Gateway in lunar orbit. We use the Blue Moon lander concept as a point of reference to estimate the mass that must be launched. Its descent stage is planned to eventually be capable of transporting 6.5 metric tons to the lunar surface (Bezos 2019); we assume this is the mass of the crewed ascent stage. The dry mass and propellant mass of the descent stage are approximately 3 and 12 metric tons, respectively (Bezos 2019). Thus, the total stack mass of the HLS would be approximately 21.5 metric tons. The HLS Concept of Operations (NASA 2019) states that the HLS will be launched into trans-lunar injection (TLI) using a commercial launch provider. For a general HLS with this stack mass (i.e., not the Blue Moon concept), we make the simplifying assumption that the cost of launching an integrated HLS can be approximated by using the cost of a Falcon Heavy launch. The Falcon Heavy may be capable of sending about this much mass to TLI; for reference, it can send 27 metric tons to GTO and 17 metric tons to Mars (SpaceX website n.d.). For the launch of an integrated HLS lander, we assign a single Falcon Heavy. To reuse an ascent stage, we again assign a single Falcon Heavy launch that carries a new descent stage along with the propellant and materials needed to refuel and refurbish the ascent stage. The cost of an expendable Falcon Heavy launch is approximately $150 million.

Table 4. Low and High Cost Estimates for Each Use of the HLS to Deliver Cargo (One Way) or Crew to the Lunar Surface

	Low Cost HLS ($M)		High Cost HLS ($M)	
Uses Per Decade	Cargo	Crewed	Cargo	Crewed
1	710	1457	2900	13400
2	460	843	1650	7150
3	377	639	1233	5067
4	335	552	1025	4025
5	310	487	900	3400
6	293	444	817	2983
7	281	422	757	2686
8	273	398	713	2463
9	266	380	678	2289
10	260	371	650	2150
11	255	358	627	2036
12	252	347	608	1942
13	248	343	592	1862
14	246	335	579	1793
15	243	328	567	1733
16	241	325	556	1681
17	239	320	547	1635
18	238	315	539	1594
19	236	314	532	1558
20	235	309	525	1525

Source: STPI calculations

Note. The costs are a function of the total number of uses per decade. Each use of a crew mission is assumed to also require a cargo mission; thus, the uses per decade apply to both cargo and crew missions simultaneously. For example, one use per decade means there is one cargo mission and one crew mission in a decade, which implies that 2 descent stages and 1 ascent stage were flown. Note that the crew costs do not include the cost of transporting the crew between Earth and the lunar Gateway.

The costs per use we have calculated for the HLS are shown in Table 4 as a function of the number of uses required over the course of a decade. A complete breakdown of the cost calculations, per the methodology described earlier, is found in Table F-4 and Table F-5 in Appendix F. The cost of the crewed mission given does not include the cost of transporting the crew to the lunar Gateway; it is only for the HLS operations. We assume the HLS can deliver 6.5 metric tons of cargo to the lunar surface, if no crew is present. Alternatively, the ascent stage is assumed to hold a crew of four. Assuming 10 cargo and crew HLS uses over a decade, we illustrate representative costs per kilogram of cargo and costs per crew in Table 5. For example, the representative low cost for a cargo mission is found by taking the total cost per use of $260 million from Table 4 and dividing by 6.5

metric tons, i.e., $40,000 per kg. Similar calculations were done for the high cost for cargo, and the low and high costs for crew.

Table 5. Representative Costs for the Operation of HLS

	Cargo	Crew
Low Cost	$40,000/kg	$93,000,000/person
High Cost	$100,000/kg	$538,000,000/person

Note that the crew costs do not include the cost of transporting the crew between Earth and the lunar Gateway. The low and high costs provided here are for a 10 mission per decade flight rate.

2. Crewed Missions using SLS and Orion

To estimate a high cost crewed mission to the lunar surface, we use SLS for launch from Earth; the Orion capsule for orbital transfer through cislunar space and for Earth reentry; Gateway as a lunar rendezvous point; and HLS to transfer crew between Gateway and the lunar surface. We provide only cost estimates for the manufacture and operation of SLS and Orion, excluding development costs. This represents the marginal cost to NASA or potential private customers for the use of SLS and Orion. We also note that use of the Gateway is not necessarily required, as described in the HLS announcement (NASA 2019), so a private customer would likely attempt to avoid this cost if possible. Other costs not considered here, such as those associated with Gateway and ground support services, will be discussed in Chapter 5 as part of the discussion of government demand for human exploration.

In a previous study, we estimated that SLS would cost $1 billion per launch in FY2017 dollars (Linck et al. 2019). Orion capsules will cost NASA approximately $1 billion new and $0.65 billion per refurbishment (Linck et al. 2019). NASA claims the per-launch cost of Orion will be $0.4 billion to $0.65 billion. We believe both of these cost estimates are exclusive of ESA's contribution to Orion, the European Service Module, which provides power and propulsion. If ESA did not provide the service module, it would cost NASA approximately $0.24 billion to construct it (Linck et al. 2019). In total, assuming limited reuse of the Orion vehicle, we estimated approximately $0.85 billion per Orion launch in our previous work.

A cost estimate for a human mission to the lunar surface is obtained by adding the costs of SLS ($1 billion) and Orion ($0.85 billion) to the cost of HLS for a given number of missions per decade from Table 4. Assuming that 10 crew missions per decade is a representative mission cadence leads to HLS costs of $371 million and $2,150 million for low and high cost missions, respectively. Thus, representative low and high costs for a crewed SLS/Orion/HLS mission to the lunar surface are $2.2 billion and $4 billion, respectively.

3. Starship

A large reduction in the cost of space access could drive demand for lunar goods and services. The architecture proposed by SpaceX—formerly known as the BFR System, currently referred to as Starship—was frequently mentioned as an architecture that could lead to such a reduction in costs. The cost reduction would come from the combination of a reduced cost per kilogram for payloads delivered to LEO, and the use of on-orbit refueling to provide a space vehicle with a large delta-v capability for taking humans and cargo to the Moon, Mars, and beyond.

The proposed BFR System is composed of at least three elements: a booster, a ship, and a tanker (Musk 2016). The first element is the booster, currently named *Super Heavy*, upon which the tanker or the ship will launch. Super Heavy is to be designed to be capable of lifting 100 metric tons to LEO initially, with plans to expand its payload capacity to 150 metric tons in the future. The ship—known as Starship—is designed to hold either cargo, at the capacities previously stated, or a crew of up to 100 to LEO. In interviews, Musk has clarified that there will likely be fewer crew per Starship on trips to the Moon or Mars, because crew will desire more living space for extended duration trips. For trips beyond LEO, Starship will generally require at least one refueling in-orbit prior to departure. The final element of the BFR System is a tanker—which we will refer to as Super Tanker—that will carry fuel to orbit to provide to a Starship. The names and designs for these elements have evolved since Elon Musk began discussing them publicly in 2012. For the purposes of gathering cost information, we consider the Interplanetary Transport System, the BFR System, and Starship plus Super Heavy as iterations of the same system.

In a presentation from 2016 at the International Astronautical Congress, Musk estimated unit, maintenance, launch site, and propellant costs for each BFR element (Musk 2016). While these numbers are for a previous BFR design that had a 300 metric ton payload to LEO capacity—about 2 to 3 times the most recent design—they are the only publicly available unit costs of which we are aware. In the 2016 presentation, SpaceX claims the cost to the company to launch a single Starship to Mars will be $62 million. The SpaceX cost estimate appears to include amortization of the unit's fabrication across vehicle reuses; however, it does not appear to include an amortization of the vehicle's development costs. Further, it assumes a flight rate and level of reusability that we did not find credible within our timeframe of interest. Therefore, we have provided a more realistic cost estimate.

Elon Musk has publicly estimated that development costs will range between $2 to $10 billion dollars to develop the BFR system (Musk 2018). More recently, Musk estimates the cost being "probably closer to a 2 or 3 [billion] than it is to 10" (Wattles 2019), which may be a product of the transition to stainless steel instead of carbon composite. We take these estimates to be for the development of all three BFR elements combined, and assign them a full development cost of approximately $5 billion. We apportion the development costs to the Super Heavy, Super Tanker, and Starship in the ratio of 1:1:3.

To compute the average cost of a mission over our notional decade, we must first calculate the number of launches required to complete all of the projected missions. In addition to the one cargo and one crew mission per year, we also assume that SpaceX will launch its cargo Starship once per month to LEO or geosynchronous Earth orbit (GEO) as it retires the Falcon vehicles and transitions to Starship for all space missions. For the missions to the Moon, we also calculate the number of refueling flights required to support lunar operations. This is important because the number of refuelings contributes to the number of Super Heavy and Super Tanker vehicles that must be built, the total number of launches over which development costs will be spread, and the operations and maintenance costs of each mission. To compute the costs of cargo missions, we make the simplifying assumption that Super Tanker will be used to deliver non-crewed missions. This is reasonable because the substantial extra cost of a crew-rated vehicle is unnecessary when no crew is present.

We model the orbital dynamics of two variants of the BFR system, which we call Version 1 and Version N. Version 1 is the first iteration of the system currently under development by SpaceX, and proposed to be ready for its first orbital flight in 2020 (Henry 2019). Version N is a future iteration of Starship that approximates its final intended performance. The specifications that we use to model each iteration of the vehicle are described in Table 6 and were inferred primarily from two public statements by Musk (Musk 2019a; Musk 2019b). One additional specification, which will be necessary for the discussion on ISRU, is that the raptor engines that power both vehicles burn methane and liquid oxygen (LOX) at a ratio of 1:3.8. We base our estimate of the Starship Version N masses on Musk's desired dry mass of Starship and apply a modest reduction to the dry mass of Super Heavy. Our assumed reduction to the Super Heavy's dry mass is reasonable because its resulting dry mass fraction (dry mass divided by propellant mass) is still larger than the dry mass fraction for the first stage of the Falcon Heavy. Holding the total stack mass constant at 5,030 metric tons leads to an extra 100 metric tons of mass available to distribute among the payload and the upper stage propellant mass. We have chosen to hold payload capacity constant at 100 metric tons, instead of increasing it to 150 metric tons as Musk has stated, to ensure that sufficient propellant is available on orbit for lunar missions. Thus, the propellant capacity for Starship has been increased to 1,300 metric tons. Further, we assume that Super Tanker carries no payload other than propellant, so its propellant tanks are further increased to 1,400 metric tons total.

Table 6. Assumed Specifications of Starship Based on Public Statements by Elon Musk

	Version 1			Version N		
	Super Heavy	Super Tanker	Crewed Starship	Super Heavy	Super Tanker	Crewed Starship
Dry Mass [MT]	230	200	200	200	130	130
Propellant Mass [MT]	3300	1300	1200	3300	1400	1300
Max Payload to LEO [MT]	0	0	100	0	0	100
Specific Impulse [s]	320[a] - 354[b]	380[c]	380	320[a] - 354[b]	380	380

a. Sea-level ISP is used for retro-propulsive landings

b. We infer from simulations of Falcon 9 that the average specific impulse (ISP) over the course of an ascent is approximately 10.5 percent higher than sea-level

c. Musk 2019a

We find that the Version 1 vehicle may be capable of some interesting missions; however, we do not see a pathway for lunar sample returns using the Version 1. We find that a reusable tanker could launch approximately 90 tons of propellant into LEO, available for transfer to a crewed or cargo Starship, before it returns to the surface of the Earth. Assuming that a moon-bound Starship is refueled 13 times in LEO, it could deliver about 90 tons of cargo to the lunar surface if it landed with its propellant tanks empty. Despite this high number of launches for a single mission—14 total—we estimate that the cost per kilogram for delivery of 90 metric tons to the lunar surface would be approximately $7,000 ($45 million per launch of Super Heavy and Super Tanker, times 14 launches, divided by 90 metric tons). A breakdown of the costs associated with the Version 1 are given in Table F.3 of Appendix F. Alternatively, a lunar flyby mission could be accomplished using only two refuelings in LEO. We believe that the Version 1 capabilities are not sufficiently close to the future capabilities of SpaceX; thus, we will not analyze them further.

For the remainder of our analysis, we focus on the Version N system, as it is more representative of the technology in its potential final state. We stress that these calculations, which use the Tsiolkovsky rocket equation, reported delta-v's for each leg of the journey, and assumptions about the specifications of the Version N system, *are rough*. Similarly, we did not perform an optimization or explore the mission trade space in depth. Further, for the BFR system to be successful within our timeframe of interest would require large advances in vehicle reusability, on-orbit refueling operations, and launch schedule management. Failure to achieve any of these large advances may preclude the architecture from becoming successful. The following performance estimates are meant to be illustrative of future operations and cost reductions that might be associated with an architecture like the one proposed for the BFR system. *We make no claim about the likelihood that they will come to fruition within our timeframe of interest.*

For the total Starship mass and propellant fraction, we find that a fully fueled Starship does not have sufficient performance to execute a round trip mission to the lunar surface if it leaves from a circular orbit in LEO (200km). Instead, we have chosen a staging orbit that is attained by an impulsive burn of 1 km/s from LEO (200km circular) to raise its apogee only; circularizing the staging orbit would be a waste of propellant. This orbit was not chosen via optimization and is not an optimal staging orbit; however, it makes all lunar return missions of interest feasible and is meant for illustrative purposes. Using this orbit, we find that a Starship would require approximately 12 refueling trips, with each Super Tanker able to deliver 100 metric tons of propellant, to achieve a fully fueled Starship. As shown in Table F-4, this number of refuelings per mission is used to determine the total number of launches over the course of a decade, which is then used to calculate the cost of launch for each vehicle (Super Heavy, Super Tanker, and Crewed Starship), with a specified level of reusability. Larger numbers of launches affect average costs by disbursing development costs over larger number of units. The per-launch costs for each vehicle are then rolled up to full mission costs (Table 7).

With a full tank, departing from the staging orbit, we estimate the payload masses for two kinds of round trip cargo missions: pure cargo delivery and pure sample return. For the first mission, we estimate that Starship can deliver 84 metric tons to the surface of the Moon if it returns to Earth carrying zero payload mass. Alternatively, if Starship travels to the surface of the Moon with zero payload mass, it can return 44 metric tons of mass to the surface of Earth. Constraining the outbound and return payload masses to be equal, Starship can carry 29 metric tons. To estimate the crew size for a mission to the lunar surface, we roughly estimate the amount of mass that can be traded for a single crew member. The intended crew capacity of Starship is 100 people or 100 metric tons to LEO, which is a ratio of 1 metric ton to one person. For the multi-day trip to the lunar surface, passengers would require more space to move around than for a short trip to LEO. We assume a mass-to-crew ratio of 2 metric tons for trips to the lunar surface—double the ratio for LEO.

Table 7. Estimated Total Cost for BFR System Missions to Lunar Surface[a]

	Round Trip ($M)[b]		One Way ($M)[c]
Missions Per Decade	Cargo	Crew	Cargo
1	458	3,683	321
2	420	2,026	313
3	391	1,459	306
4	383	1,182	300
5	372	1,008	296
6	356	925	292
7	353	839	289

Missions Per Decade	Round Trip ($M)[b] Cargo	Round Trip ($M)[b] Crew	One Way ($M)[c] Cargo
8	341	766	286
9	336	712	283
10	327	665	279
11	326	655	277
12	319	620	276
13	316	593	274
14	317	573	273
15	311	550	272
16	305	544	271
17	309	533	270
18	305	516	269
19	300	500	268
20	296	486	263

Source: STPI calculations

a. Assumes that Super Heavy and Super Tanker are each reusable 20 times, while Starship is reusable 5 times. While this level of reuse is optimistic, it is also orders of magnitude less than SpaceX is targeting.

b. One mission per decade means that there is one crew mission and one supporting cargo mission.

c. The one-way cargo mission does not attempt to recover the landed spacecraft. It also supports a crewed mission in a 1:1 ratio, as with the round trip. The associated cost of the crewed round trip missions increase slightly due to a decreased flight rate for the Super Heavy and Super Tanker but are not shown here. There are no assumed cargo round-trip missions embedded in the one-way cargo cost.

As with the HLS cost estimates, we assume that 10 missions over the course of a decade is approximately a representative level of use; the costs associated with this level of use can be divided by the estimated payload amounts to calculate representative costs per kilogram. For cargo missions, a single cargo Starship is required, which we have assumed to be the same cost as the Super Tanker. Further, 12 refueling missions using the Super Tanker are required to fill the propellant tanks of the cargo ship in the chosen staging orbit. To deliver 84 metric tons and recover the empty cargo Starship would cost $3,900 per kilogram ($327 million divided by 84 metric tons). Likewise, to travel to the lunar surface with no payload, it would cost $7,400 per kilogram to return 44 metric tons. Finally, a crewed mission would require 13 Super Heavy launches, 12 Super Tanker launches, and a single crewed Starship, for a total cost of $665 million.

The fully reusable BFR system is not the cheapest method of delivering mass to the surface of the Moon. The cost to manufacture a single Super Tanker (and thus cargo Starship) is approximately $130 million. Insisting that this cargo vehicle be returned to Earth reduces the amount of mass that can be delivered to the lunar surface and forces a higher staging orbit to be used, which also increases the number of refueling flights required to fill its propellant tanks. Alternatively, a new cargo Starship Version N can land 100 metric tons of payload on the lunar surface, leaving from LEO with only five refuelings, if the cargo Starship does not carry with it the propellant needed for a return trip to Earth. Note that this is seven fewer launches of a Super Heavy and Super Tanker stack—a combined expense greater than the unit cost of a new cargo Starship. The full cost per one-way mission is shown in Table 7 as a function of launch cadence. Using 10 missions over a decade as a representative number of uses, the cost per kilogram for a one-way delivery to the Moon is $2,800/kg ($279 million divided by 100 MT).

Table 8. Estimated Total Cost for BFR System Crewed Lunar Flyby Missions

Missions Per Decade	Scenario 1	Scenario 2
1	3,324	408
2	1,703	379
3	1,162	355
4	891	336
5	727	318
6	658	317
7	578	301
8	515	288
9	465	276
10	426	265
11	416	269
12	387	260
13	363	251
14	344	243
15	326	235
16	324	238
17	309	233
18	295	226
19	283	220
20	271	215

Note. Scenario 1 assumes that, over the course of a decade, Starship is not used for any crewed lunar landings. This means that the full development and unit costs of the crewed Starship must be covered by the customers of the flyby missions. Scenario 2 assumes that 10 crewed lunar landing missions over the decade in addition to any crewed flyby missions. For both scenarios, the reusability assumptions are the same as Table 7 and 10 cargo missions to the lunar surface are assumed.

Finally, we investigate the scenario of a lunar flyby using a crewed Starship. Such a launch would only require two refueling in LEO to provide sufficient fuel for the journey.

The cost of such a mission varies widely depending on whether the crewed Starship is also flying missions to the lunar surface (Table 8). We note that this mission would allow for the full 100 metric tons to travel on the lunar flyby; however, it is unclear what a reasonable number of passengers may be for such a flight. The passengers will spend the duration of their weeklong journey in the ship and will require at least as much habitable volume as was assumed for the lunar surface passengers. Thus, the maximum number of passengers is 50; however, this is optimistic.

4. Small Cargo Missions to the Lunar Surface

Delivery of small payloads to the lunar surface is based on currently proposed CLPS capabilities. Astrobotic, one of the CLPS providers, has published their price per kilogram to lunar orbit ($0.3 million), the lunar surface ($1.2 million), and delivery of a payload on their rover ($4.5 million) using their Peregrine lander (Astrobotic 2019). Based on the price per kilogram cited above and a payload capability of 200 kilograms, the price of a Peregrine mission is about $240 million (200 kilograms times $1.2 million/kg). We will accept these prices as credible, noting that they may also change in the future.

5. Hypothetical Sample Return Missions

We are unclear as to the intended sample return capabilities of a crewed HLS and thus we did not model it. Instead, we provide two rough estimates for the cost of sample return. Our high cost estimate is based on the small cargo landers associated with CLPS. No CLPS companies appear to have plans for a sample return mission; so, we have extrapolated from the proposed mission plan for China's Chang'e 5 sample return mission.

The total wet mass of Chang'e 5 is reported to be 3,780 kilograms (Gunter's Space Page n.d.), which is about three times more massive than the Astrobotic Peregrine at 1,300 kilograms (Astrobotic 2019b). Chang'e 5 will only bring back approximately 2 kilograms (Jones 2017). Charitably assuming that Peregrine could also bring back 2 kilograms yields an optimistic estimate of $120 million per kilogram ($240 million divided by 2 kilograms) for this class of mission. This cost is likely prohibitive.

We produce a lower cost estimate that may be more amenable to scientific sample return missions and other commercial ventures. Our lower cost estimate uses a hypothetical architecture that is for illustrative purposes only. The architecture modeled uses a Falcon Heavy to launch a lunar single-stage-to-orbit (SSTO) vehicle and a space tug into TLI. The combined mass of the SSTO and tug equal 22 metric tons, the approximate mass that Falcon Heavy could boost to TLI. The tug inserts the SSTO and itself into low lunar orbit (LLO). The SSTO then descends with no payload to the lunar surface, returns to LLO with a full payload, and transfers the payload to the tug. The tug then returns from LLO to LEO, using aerobraking to reduce the amount of propellant needed. To return the sample to the surface of the Earth, a Falcon 9 launches a Dragon v1 capsule to LEO, where the capsule takes the payload and returns to Earth. We note that the use of a SSTO lunar vehicle and aerobraking at Earth results in an extremely optimistic architecture and cost. What follows is a lower bound on the cost of sample return for scenarios where Starship does not exist.

We assume the ratio of structural mass to propellant mass (called dry mass fraction or DMF) of a lunar SSTO vehicle is approximately 0.5, which is in line with others from the literature (Lavoie 2016; Cichan 2018). The DMF of the in-space tug is assumed to be 0.2, based on a modified Dragon trunk for Trans Earth Injection (Miller 2015). The SSTO and tug are both assumed to use a LOX/LH2 propulsion system with a specific impulse of 450 seconds. The container of the payload is assigned a mass of 0.5 metric tons. With these parameters specified, we solve for the masses of the tug (dry: 0.9 metric tons, propellant: 4.5 metric tons), SSTO (dry: 5.4 metric tons, propellant: 10.7 metric tons), and payload returned to LEO (2.3 metric tons). The payload mass fits inside a single Dragon capsule. Using rough estimates for the cost of an expendable Falcon Heavy ($150 million), the tug ($100 million), the cargo SSTO ($100 million), and the Falcon 9 with Dragon v1 ($80 million), we find a total mission cost of $430 million. This equates to a cost of approximately $190,000 per kilogram of sample returned. This does not include the cost associated with gathering the lunar cargo or placing it in the cargo vehicle on the surface of the Moon. Our estimates for the costs did not follow the methodology used for the HLS or Starship because this architecture is sufficiently hypothetical and optimistic that its purpose is only to provide a rough order of magnitude.

C. Cost of Lunar Surface Transportation

For lunar surface operations, we estimate the costs of pressurized and unpressurized rovers. The cost of the unpressurized rover is modeled after the Lunar Roving Vehicle (LRV) used during the Apollo missions. The total cost of the four rovers was $38 million (Williams 2016); we do not have a year-by-year breakdown of those costs, so we will assume they are all in 1971 dollars, which is the year of the Apollo 15 mission—the first time that a rover was used. To convert to 2018 dollars, we use the U.S. GDP deflator (BEA n.d.) to find that the 1971 dollars need be multiplied by a factor of 4.8. Thus, the total cost of the LRVs is about $180 million in 2018 dollars. For this cost, four rovers were built.

Using our standard heuristic that the n-th unit cost is one-third the cost of the first unit, we get development and unit costs of approximately $90 million and $30 million, respectively. These costs for the LRV represent our high cost estimate of an unpressurized rover. For the low cost estimate, we have reduced the LRV costs by a factor of 3 ($30 million and $10 million for development and unit costs). This is not tied to an identified commercial unpressurized rover concept, but we note that the LRV technology is relatively simple and should be able to be produced cheaply. The mass of the LRV was 210 kilograms, which we have retained for the low cost model as well. We assume that the unpressurized rovers will have much better performance characteristics (e.g., range and cargo capacity) than the LRV; however, we do not attempt to model or specify them. The costs for reusable unpressurized rovers are given in Table 9. Reusable rovers are appropriate for missions where the crew will return to the same location on every mission. Alternatively, some missions may call for a single visit, in which case the rover will be expendable—used only once. We estimate the costs of expendable unpressurized rovers in Table 10.

Table 9. Annual Cost per Rover of Reusable Unpressurized Rovers

Units in Decade	Low Cost ($M)	High Cost ($M)
1	3.6	12.6
2	2.6	9.6
3	2.3	8.6
4	2.1	8.1
5	2.0	7.8
6	1.9	7.6
7	1.9	7.5
8	1.9	7.4
9	1.8	7.3
10	1.8	7.2

Note. Annual costs assume that all development, unit, launch, and operations and maintenance (O&M) costs are amortized over a decade of rover use. The low cost is calculated from the low cost rover model and the low cost launch vehicle (Starship at $2,800/kg). The high cost is calculated from the high cost rover model and the high cost launch vehicle (HLS at $40,000/kg).

Table 10. Cost Per Use of a Disposable Unpressurized Rover

Units in Decade	Low Cost ($M)	High Cost ($M)
1	30.6	98.4
2	20.6	68.4
3	17.3	58.4
4	15.6	53.4
5	14.6	50.4
6	13.9	48.4
7	13.4	47.0
8	13.1	45.9
9	12.8	45.1
10	12.6	44.4

Note. Costs per use assume that the development costs are amortized over a decade. For each use, the user must bear the full unit and launch costs; there are effectively no O&M costs as the unit is disposable. The low cost is calculated from the low cost rover model and the low cost launch vehicle (Starship at $2,800/kg). The high cost is calculated from the high cost rover model and the high cost launch vehicle (HLS at $40,000/kg).

We envision a pressurized rover would only need to accommodate a crew of 2–4 people. Designs such as the Pressurized Lunar Rover or the Arno rover (Zakrajsek 2005) are likely appropriate. They both have a mass of 6 metric tons and can accommodate a crew of at least three people for sorties of at least 6 days. Spudis and Lavoie (2011) provide a development cost of $2,000 million for a pressurized rover that has similar technical characteristics, called a "Personnel Transfer Vehicle" in 2011 and later a "Surface Utility Vehicle" (Lavoie and Spudis 2016). We use this development cost for our low cost estimate and apply the standard factor of one-third of the development cost to estimate an n-th unit cost of $670 million. For a high cost estimate, we assign the same kind of rover a development cost of $4,000 million and unit cost of $1,300 million. This development cost is roughly in line with Germain's (2007) pressurized rover cost of $3,000 million in 2007 dollars, which is approximately $3,600 million in 2018 dollars. The annual costs per unit, amortized over a decade of use, are given in Table 11.

Table 11. Annual Cost per Rover of Reusable Pressurized Rovers

Units in Decade	Low Cost ($M)	High Cost ($M)
1	205	463
2	138	329
3	116	285
4	105	263
5	98	249
6	93	240
7	90	234
8	88	229
9	86	225
10	85	223

Note. Annual costs assume that all development, unit, launch, and O&M costs are amortized over a decade of rover use. The low cost is calculated from the low cost rover model and the low cost launch vehicle (Starship at $2,800/kg). The high cost is calculated from the high cost rover model and the high cost launch vehicle (HLS at $40,000/kg).

D. Cost of the Gateway

We estimate the costs of the cislunar Gateway under the assumption that it will consist of eight modules: a power and propulsion element; the European ESPRIT, a communications and connecting module; the associated U.S. utilization module; an airlock; an international partner habitat; a U.S. habitat; a logistics package; and a robotic arm built by Canada.

We based our estimates of the development and construction costs of Gateway on a recent STPI report (Linck et al. 2019). The study estimates that U.S. costs for Gateway will be $5,732 million 2017 dollars, or $5,872 million 2018 dollars. We add to that number the costs of Canada's contribution, its robotic arm. We assume that Canada's entire budget for the Moon through 2024, $797 million Canadian dollars or $540 million 2018 U.S. dollars, is used to fund the construction of the robotic arm (Boucher 2019).

We estimate the costs of the European ESPRIT communications and connecting module and the international partner habitat at $615 million and $2,466 million 2018 dollars, based on estimates of the costs of the U.S. utilization module and the U.S. habitat module, respectively (Linck et al. 2019). Summing the U.S., Canadian, and ESA contributions yields a total estimate of $9,491 million 2018 dollars for Gateway.

E. Cost of Power

1. Solar Power on the Surface of Moon

We estimate the cost of electricity on the Moon from solar panels and from nuclear reactors. For the solar panel estimate, we use the modular power production element from the Lavoie and Spudis architecture, capable of producing 25 kilowatts (kW) per module. Each module weighs 1.1 metric tons. The modules have a development cost of $200 million and—although the original element had a unit cost of $50 million—we assign a unit cost of $25 million, one-eighth of the development cost, in anticipation of a higher rate of production than used in the original study. To estimate the cost, we provide the value assuming 80 percent utilization of the installed power capacity, which is an optimistic but reasonable value for certain areas of the lunar polar region. The cost per kilowatt-hour (kWh) provided in Table 12 can be easily scaled to any utilization rate X by multiplying by 0.8 and dividing by X. As per Table 12, a 1 MW solar system may cost about $20 to $40 per kilowatt-hour.

Table 12. Estimated Cost of Electricity on the Moon from a Modular Solar Power System

	Cost per kWh at 80% Utilization	
Power Capacity (kW)	**High Cost**	**Low Cost**
25	139	116
100	64	41
200	52	29
1,000	42	19
2,000	41	17
5,000	40	17
10,000	40	16
100,000	39	16
1,000,000	39	16

Note. The high and low costs differ based only on the cost of launching the modules. The low cost launch vehicle is Starship at $2,800/kg and the high cost launch vehicle is HLS at $40,000/kg. The development and unit costs of the power modules are amortized over a decade. The figures above do not include operations and maintenance costs. Annual energy production (kWh) is calculated assuming an 80 percent utilization of the total power capacity. For a fixed usage rate, the cost per kWh hour drops as capacity increases because there are more kilowatt-hours over which to distribute the development costs of the system.

2. Nuclear Power on the Surface of the Moon

The cost of a nuclear fission system for generating electricity on the Moon includes the cost of developing the system; cost of launch; and the costs of operating, repairing and decommissioning. Working with experts in the space nuclear community, we costed out a 100 kWe hypothetical system that uses low-enriched uranium, has a moderated core, uses the Brayton cycle, and has an estimated mass of 4.5 metric tons (NASA 2019; interviewees). No reliable cost information is available for a 1 MWe system on the surface of the Moon, so we use the upper end of a 100 kW system as the basis for costing a 1 MW system. Such a system is expected to weigh about 18 metric tons. All numbers in this section are based on discussions with experts at the Department of Energy (DOE), NASA and from the private sector.

For the purpose of this section, we assume that cost of development, launch, and fuel replacement will dominate total cost (the heuristic of n-th unit being one-third of the cost of the first is not used here because by 2040, an insufficient number of systems will likely have been built). Operating costs other than fuel replacement are expected to be minimal, although after its operating life the entire reactor will likely need to be replaced. Other than replacing fuel in the larger system, these reactors are expected to operate autonomously, and to operate for at least 10 years. The reactor would require refueling, which can be assumed to cost $100 million per year. Using these assumptions, Table 13 shows the cost of a 1 MW nuclear power plant on the surface of the Moon as about $4 to $6 billion. For reference, a 60 MWe next-generation nuclear power plant on Earth is expected to cost about $3 billion (Conca 2018). Converted on a kilowatt-hour basis, the cost is about $50–80 per kilowatt-hour. This assumes 90 percent capacity utilization.

Table 13. Estimated Cost of a 1 MW Nuclear Power System on the Surface of the Moon

	Low ($)	High ($)
Cost of developing 1 MWe LEU system ($)	3,000,000,000	5,000,000,000
Weight of I MW system(kg)	18,000	18,000
Cost of launching I MW system ($) assuming $2,800 per kg for launch to the lunar surface	50,400,000	50,400,000
Fuel replacement including launch (100M per year for 10 years) ($)	1,000,000,000	1,000,000,000
Total cost of 1 MW system ($)	4,050,400,000	6,050,400,000

	Low ($)	High ($)
Annual Cost per kWh (assuming 10-year operation at 90% capacity factor)	51	77

Source: STPI calculations based on discussions with experts

F. Cost of Extracting Resources on the Moon

NASA and commercial companies have expressed interest in mining resources on the Moon. Some representative types of materials include: lunar material for construction of structures on the lunar surface or in cislunar space; export of platinum group metals and rare Earth elements to terrestrial markets; and the production of propellant for delivery to users in cislunar space. In this section, we estimate the cost of extraction and production. The discussion on the availability of volatiles and metals is included in Appendix G. We do not attempt to estimate the cost of using lunar material for construction because we assess that the technology will not be mature enough for NASA to introduce into the critical path of its human exploration plans. Lunar construction may be a driver of demand for commercial companies if a purely private market for lunar construction materials exists; however, we do not analyze this case. Other simpler uses of lunar materials, such as for radiation shielding or construction of landing pads, are likely feasible within our timeframe; however, these are likely to be one-time purchases. To constrain scope, our cost estimates focus on the dominant potential drivers of demand for lunar resources: metals and volatiles. We estimate the availability of these resources in Appendix G: Lunar Resources.

1. Volatiles

We first estimate the cost of mining water in the permanently shadowed regions (PSRs) of the Moon to produce LOX and liquid hydrogen (LH_2). Before any mining operation can begin, the presence, form, and accessibility of water in the specific PSR of interest must be characterized, which can only be determined by in-situ measurements. We assume that a mining company will send a series of surveying missions that use a rover roughly similar to NASA's Volatiles Investigating Polar Exploration Rover (VIPER). Details on VIPER are scarce; however, it is reported to cost approximately $250 million (Foust 2020). We assume that the rover's mass will be around 350 kilograms, so that it can be carried on CLPS providers in the early 2020s. We assume that a mining operation will send four VIPER-class missions to gather in-situ measurements at locations where water concentrations are thought to be favorable; thus, reducing economic risks associated with uncertain water concentrations and other environmental properties.

Architectures for extracting water from the ice or regolith use some form of heat, followed by the use of a cold trap to condense and gather the water vapor into liquid water. Initial research indicates that methods of heating and cooling the water vapor can only be done effectively in a closed chamber (Zacny 2019). For this reason, we will not investigate lunar water mining architectures that use open chambers, such as heated dome-shaped tents (Kornuta et al. 2018), because the lunar regolith itself acts as a more effective cold trap than the ISRU mining equipment. That leaves two architectures for mining water that we have identified as the most promising: the swarm of robots proposed by OffWorld and Planetary Volatiles Extractor (PVEX) proposed by Honeybee Robotics.

We estimate the cost of a mining architecture that is loosely inspired by the Offworld architecture and other architecture studies published by Lavoie and Spudis. Our model architecture uses tens to hundreds of small robots that excavate lunar material and haul it to a central processing plant. There are two classes of robots: excavators and haulers. The processing plant extracts water from the regolith and optionally electrolyzes the water into cryogenic LH_2 and LOX. The smallest proposed rovers of which we are aware for similar tasks are those proposed by the company OffWorld.

The OffWorld master plan lists their robots as having a mass of 50 kilograms with 13.5 kWh batteries (OffWorld n.d.). These little robots have a planned excavation rate of 390 kilograms per hour. We assume that the drills and saws used to perform the excavation take approximately 3 kW of power—in line with terrestrial stone saws. For an excavator robot, we allocate about 1.5 kWh for traverses, leaving 4 hours ((13.5-1.5 kWh)/3kW) of continuous excavation per battery charge. We assume that the excavating robots will be recharged and used three times daily. The hauler is a companion rover that will scoop and haul the excavated lunar material to a central processing plant. We make the simplifying assumption that the daily excavation rate of the excavating robot is equal to the daily hauling capacity of a single transport rover. Thus, the exactor and hauler robots are needed in a ratio of 1:1. The robots are assumed to be effectively autonomous.

To produce a cost estimate for such a small rover, we use previous NASA rovers as a point of reference. Sojourner (11 kilograms) cost $25 million in then-year dollars (NASA n.d.), which we assume corresponds to the launch year of 1996; this is equivalent to $37.5 million in 2018 dollars and leads to a development cost of $3.4 million per kilogram. Alternatively, Spirit and Opportunity (both 185 kilograms) each cost approximately $400 million (Associated Press 2007) to develop, with an operations cost of approximately $10 million per rover. These costs are assumed to be in 2003 dollars, which we have inflated to $540 million and $13 million for development and operations costs in 2018 dollars, respectively. Thus, Spirit and Opportunity had a development cost of approximately $2.9 million per kilogram in 2018 dollars.

We assign the excavating rover a mass of 60 kilograms and assume that it will cost $2 million per kilogram to develop, cheaper than NASA's historical development costs per kilogram, for a total development cost of $120 million. This is likely a fair estimate because a commercial company should be able to design a rover more cheaply than NASA, and the excavation robots will be more capable and rugged than Sojourner or Spirit. The transportation robot will have significant overlapping hardware with the excavator, but is assumed to be less costly due to its simpler mission; we assign this 60-kilogram rover a development cost of $100 million. While the mining rovers for our analysis are assumed to be 60 kilograms, in line with the stated proposal of at least one lunar mining company, we do not claim that rovers with the needed capability can be built at this mass point. For instance, the mass of a 13.5 kWh battery, capable of producing 3 kW of power, would likely exceed the rover's mass budget. Instead, fuel cells would be required to achieve the necessary energy and power density. We do not analyze this further, but note that 60-kilogram rovers at this power and energy density seem optimistic.

We estimate the cost to extract water from the excavated lunar material and for electrolysis of the water into cryogenic propellant. For both of these functions, we use the estimates given by Lavoie and Spudis (2011; 2016). They estimate that a facility for extracting water from lunar material would have a mass of 1.2 metric tons, a development cost of $375 million, a unit cost of $125 million, and each unit could produce 48 metric tons of water annually with a 25 kW power supply. Similarly, the facility to electrolyze water and store cryogenic propellant would have a mass of 1.2 tons, a development cost of $525 million, a unit cost of $175 million, and could produce 32 metric tons of LH_2 and LOX (at a ratio of 1:5) with a 25 kW power supply.

Annual O&M costs for each unit are assumed to be 20 percent of the associated unit cost. This leads to annual costs of $3 million per excavator rover. As a point of comparison, the operations costs (there were no maintenance costs) of Spirit and Opportunity were approximately $13 million per rover. All else being equal, we anticipate that the commercial operation of the autonomous excavator and hauler rovers will produce reduced operations costs compared to NASA's operations costs. However, the mining rovers will be operating in a more challenging environment and will require regular repairs. Similarly, the two processing plants will have annual O&M costs in the $25 to $35 million range per unit. We do not have a point of reference for these costs; however, we note that these units will be more difficult to repair than the rovers. This is partially due to the likelihood that the parts in need of repair or replacement will require substantial disassembly to access. Such parts are likely to experience abrasion from the processing of lunar materials and corrosion from the acids produced by heating lunar volatiles in solution with lunar water.

We assume that all of the equipment will operate during the lunar day and conserve energy during the lunar night. Due to substantially reduced costs per kWh associated with modular solar panels compared to nuclear power, we chose solar power for providing energy to recharge the rovers and run the processing plants. We recognize that some polar locations have solar illumination between 80 to 90 percent of the time (NASA n.d.); however, we did not analyze the effect of the low incidence angle of the sunlight and the associated shadows that each solar panel may cast on the solar panels behind it. Thus, we simply assume an average solar illumination equivalent to equatorial locations (50 percent). For a fixed production rate of water or propellant, we find that varying the solar illumination percentage between 50 and 80 percent produces only minor changes to the overall cost. This is because, for a fixed production rate, the same number of processing units is required and these dominate the overall costs.

Costs are shown in Table 14 for the production of water, cryogenic propellant at a ratio of 1:5, and LOX only on the lunar surface. The costs assume that the equipment necessary for the mining operation is launched on an HLS at its representative cost. All costs also assume that the regolith being mined is 5 percent water by mass—in line with the average LCROSS result, discussed in Appendix G below. For the cost of cryogenic propellant, it is assumed that the excess oxygen is not sold to a customer because the LOX is far less valuable if not used as a propellant. Similarly, we estimate costs for production of just LOX, with the excess hydrogen not sold to a customer. Note that for both LOX:LH2 and pure LOX production, the costs per kilogram will be lower if a buyer is found for the "waste" products. In the absence of lunar methane production, the cost of LOX production is required to analyze potential use of lunar resources by the SpaceX Starship. The Starship could theoretically carry with it all of the methane needed for a return journey but only enough oxygen for a one-way trip to the Moon; after arriving at the Moon, it could potentially refuel with sufficient lunar LOX to return to Earth.

Table 14. Costs per Kilogram of Lunar Water or Propellant with High Launch Costs

Annual Production (MT)	Water ($/kg)	LOX:LH2 ($/kg)	LOX ($/kg)
25	5,852	8,507	8,169
50	2,997	5,302	4,448
100	1,815	3,441	2,846
200	1,260	2,640	2,280
500	898	2,282	1,781
1,000	798	2,081	1,588
2,000	739	2,025	1,535
10,000	688	1,957	1,469
20,000	682	1,947	1,463
100,000	677	1,941	1,456

Note. For each lunar product, the cost reported assumes that it is the *only* lunar product being produced and sold. For example, the cost of LOX:LH_2 propellant assumes that there are no buyers for water or LOX without the LH_2. The cost per kilogram for a product is a function of the average annual production rate over a decade. For example, to achieve a cost of $898/kg for water, the mining operation must produce 500 metric tons of water annually for a decade. All costs are for production on the lunar surface; the costs will be higher if the products are being transported off the lunar surface. The cost to launch the mining equipment from Earth to the lunar surface is $40,000/kg using the HLS.

We find that the costs of propellant are not very sensitive to an order of magnitude reduction in the cost of launch from Earth (Table 15). This is because the launch costs associated with using HLS are nearly one-tenth of the sum of the development, unit, and O&M costs of the mining operation. The economies of scale also taper off rapidly as demand increases. This is due to the modular approach taken whereby the production of more water or propellant requires the manufacture and deployment of more rovers and processors, which also increases operating costs.

Table 15. Costs per Kilogram of Lunar Water or Propellant with Low Launch Costs

Annual Production (MT)	Water ($/kg)	LOX:LH2 ($/kg)	LOX ($/kg)
25	5,284	7,587	7,420
50	2,704	4,568	3,900
100	1,574	2,808	2,391
200	1,025	2,054	1,807
500	683	1,681	1,332
1,000	583	1,499	1,153
2,000	527	1,440	1,096
10,000	479	1,376	1,033
20,000	474	1,367	1,027
100,000	469	1,361	1,021

Note. Except for the cost to launch the mining equipment, the assumptions underlying these costs are identical to those of Table 14. The launch vehicle used here is the Starship at a cost of $2,800/kg.

We have previously noted that our cost estimates for the water mining architecture are very optimistic and the associated costs are likely a low cost estimate at any given annual rate of production. The only lower estimate of which we are aware comes from the Commercial Lunar Propellant Architecture (CLPA) study (Kornuta et al. 2018); the CLPA study attempted to design a mining architecture that could produce propellant at a cost less than $500/kg on the lunar surface. At this cost point, they assumed an annual production of 1,640 metric tons of lunar propellant.[3] Above this cost point, they did not believe that customers would buy lunar propellant in cislunar space. Their launch cost from Earth to the lunar surface is given as $36,000 per kilogram, which is in approximate agreement with our high cost launch scenario. For an annual production rate of 1,640 metric tons of propellant, Tables 14 and 15 show that our estimated cost is approximately $1,500–$2,000 per kilogram. Thus, even our optimistic architecture does not appear to reach the threshold for economic viability specified by the CLPA study.

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[3] Kornuta estimated that annual cislunar customers would demand about 450 MT per year. This is congruous with previous work by the authors on asteroid mining (Colvin et al. 2019) that estimated annual demand for propellant between 300 MT and 500 MT. To provide 450 MT of propellant to customers throughout cislunar space would require the production of 1,640 MT of propellant on the lunar surface, two-thirds of which is burned during delivery to the cislunar customers.

For a high cost estimate of lunar water or propellant, we note that Charania (2007) and Jones (2019) both investigated lunar propellant to satisfy an assumed government demand of 60–70 metric tons per year. Charania estimated a cost of $27,000 per kilogram in 2007, which would be approximately $32,000 per kilogram in 2018. We note that the Charania study assumed that water made up only 1 percent of the lunar regolith by mass, while we have assumed that it is 5 percent. Jones (2019) did not explicitly state the cost of lunar propellant on the lunar surface, but implied that it is in a range of approximately $8,000 to $16,000 per kilogram. Jones concluded that they could not find a scenario where lunar propellant could beat the cost of propellant transported from Earth. Both Charania and Jones use a substantially more expensive launch vehicle to deliver their mining equipment, Ares V and SLS, respectively. While we found the cost of lunar propellant production is relatively insensitive to the high and low costs of launch from Earth that we investigated, substantial increases in launch costs above our high cost of launch scenario may have a more significant on the cost of water and propellant.

According to the logic of the Kornuta study, if lunar-derived propellant costs above $500 per kilogram on the lunar surface, near-Earth users that are performing LEO-to-GEO-tugging services would not purchase the lunar propellant. The LEO-to-GEO tug market is approximately half of the total demand for in-space propellant. Deprived of this market, a lunar propellant operation would need to produce less annual propellant and the cost per kilogram would increase. We note that it is unclear whether lunar propellant or terrestrially delivered propellant is more economical for this reduced market and do not analyze the economics of cislunar propellant markets further.

Similarly, the economic viability of using lunar water or propellant for surface operations is unclear. If SpaceX were to refuel their Starship missions to the lunar surface with lunar oxygen—assuming the Starship lands with sufficient liquid methane—the Starship could potentially return to Earth with a full 100 metric tons of payload, instead of only approximately 29 metric tons as we previously estimated. On the one hand, Starship alone may be capable of providing a sufficient market for lunar production of liquid oxygen. On the other hand, if SpaceX does not refuel with lunar oxygen, then Starship may be able to deliver water and propellant to the lunar surface more cheaply than those substances could be produced in situ. Specifically, one-way cargo deliveries on Starship have a lower cost per kilogram than lunar water or propellant if annual production of those resources is less than 50–100 metric tons, which may be the case. As before, we note the economic feasibility is unclear in this instance and we do not analyze this situation further.

2. Metals

To roughly estimate the cost of mining metals, we use the same excavator and rover robots from the mining architecture and disregard the prospecting and processing elements. As discussed in Appendix G, the best potential source of platinum group metals on the

Moon is likely the remains of metal (m-type) asteroids. To get 1 metric ton of platinum group metals (PGMs) in a year, from ores with a concentration of approximately 33 parts per million (ppm) by mass as in m-type asteroids (see Table G-1), would require the excavation of 30,000 metric tons of material (1 metric ton divided by 33 parts per million). Coincidentally, this falls within the mass range of recoverable asteroid material associated with a crater diameter of one kilometer on the Moon (discussed in Appendix G). Table 16 shows the cost per kilogram to excavate and haul the raw materials to a processing plant. The cost of the rovers alone, to excavate and haul such mass, pushes the cost per kilogram of any resulting PGMs above the terrestrial price of PGMs by a wide margin. For example, Rhodium is the most expensive PGM at nearly $78,000 per kilogram in terrestrial markets (Appendix G). We do not develop the cost of a metal mining architecture further, as it appears to be economically infeasible as a primary business objective. For this analysis, we do not investigate the possible value of lunar PGMs, other metals, or other byproducts (e.g., bulk material for making concrete) from lunar volatile extraction and processing. Sale of such byproducts may provide a secondary revenue stream to a company producing water or propellant on the lunar surface, thereby reducing the effective cost per kilogram of the water or propellant.

Table 16. Cost to Excavate and Haul Raw PGM-bearing Material

Annual Quantity of PGMs Excavated and Hauled (Metric Tons)	Cost Associated with Rovers Alone ($/kg)
1	132,198
10	114,873
100	113,141

Note. The costs above amortize the development, unit, and launch costs of the required excavator and hauler robots over a decade. One metric ton of PGMs corresponds to about 30,000 metric tons of asteroid material, most of which is iron and nickel. The costs per kilogram *do not include* the processing of the PGMs from this raw material.

G. Cost of Lunar Habitat

We provide a high cost and low cost estimate for a human lunar habitat. The high cost habitat is based on the four-person habitat described by Lavoie and Spudis (2011; 2016). The development cost is $3,000 million and the unit cost is $600 million. They do not state the habitable volume, but we assume that it is around 20 cubic meters. The mass is 10 metric tons and it is designed for operation near the lunar poles. Annual costs for this type of habitat are shown in the high cost scenario in Table 17.

Our model for the cost and size of a low cost lunar habitat is based on parameters for the maximum number of simultaneous crew and the number of crew-years that are to be spent in the habitat annually. The habitat is assumed to be pressurized and modular, so that it is easy to scale with the number of crew. The habitat element is modeled after the BA-

330, developed by Bigelow Aerospace, which is the successor to the TransHab technology developed by NASA. We chose the BA-330 because it is relatively mature, adaptable to the lunar surface, and is modular. It has been reported that, upon full inflation, the structure will be as hard as concrete (Latrell 2015). TransHab—the precursor to Bigelow's technology—was tested to withstand ballistic projectiles fired at 7 km/s or more (Seedhouse 2015). If true, this habitat could be partially buried or covered with regolith to provide necessary radiation shielding. We note that Bigelow Aerospace laid off its entire workforce on March 23, 2020, partially in response to the COVID-19 pandemic. Even if Bigelow Aerospace does not return to operations, the intellectual property associated with Bigelow's improvements to the TransHab technology may still be available for purchase or license by a future company that wishes to build space habitats. In this case, our following analysis is still effectively applicable.

The BA-330 is reported to have a pressurized volume of 330 cubic meters (Bigelow Aerospace n.d.) and be capable of housing approximately six people (Miller 2015). We believe that the module has sufficient habitable volume to house far more than that with an appropriate upgrade to its ECLSS system; however, for this analysis, we will accept its capacity as six people per habitat module.

Table 17. Annual Cost to Operate a Lunar Habitat for a Decade

Units in Decade	Low Cost Per Year ($M)	High Cost Per Year ($M)
1	169	392
2	133	272
3	121	232
4	115	212
5	112	200
6	109	192
7	107	186
8	106	182
9	105	179
10	104	176

Note. Cost varies based on the number of modules delivered over the course of a decade and the cost per kilogram used to launch the habitat and its resupply mass. The high cost scenario uses the Lavoie and Spudis habitat, launched on the HLS, capable of housing up to 4 people. The low cost scenario uses a variant of the BA-330, launched on a Starship, theoretically capable of housing 6 or more people. The numbers above do not include the cost of crew resupply as that cost depends on the number of crew and their average duration of stay.

To estimate the development and unit costs of the habitat, we use two points of reference. Our first point of reference is Seedhouse (2015), who estimates that the unit cost of an orbital version of the BA-330 would be $125 million, and does not specify a development cost. He does not provide a reference for this cost nor is it clear that he has first-hand access to the Gate Reports 1 and 2, which Bigelow Aerospace delivered to NASA as part of their Space Act Agreement for the development of a space habitat, though he refers to them elsewhere. Our second point of reference is the high cost habitat we have already described. By taking the midpoint between these two widely varying points of reference, we estimate the unit cost of the habitat to be $360 million. Applying our standard ratio of 1/3 for unit to development costs for units with a low rate of production, we estimate a development cost of approximately $1,000 million. We note that it is unclear how much Bigelow will actually need to spend on development costs, as the company acquired a substantial portion of the needed intellectual property from NASA's TransHab program.

For operations and maintenance costs, we follow Seedhouse (2015), who lists a cost of $50 million as annual "operation support costs." This is separate from the three annual cargo resupply costs, which he estimates as $100 million per flight. It is likely that his launch cost is for a Falcon Heavy, the same vehicle that he assumes will launch the B330 to LEO. A Falcon Heavy can lift 60 metric tons to LEO, while the habitat can hold six people. Over the course of a year, that results in 180 metric tons (3 times 60 metric tons) of payload needed for 6 crew-years—or, 45 metric tons of resupply mass per crew-year. As it is not clear what level of insight Seedhouse has into the B330 architecture, we do not use his cargo resupply numbers. NASA estimated that a single crew member uses about 4 kilograms per day of consumables (Linck et al. 2019), which would be 1,460 kilograms per crew year (4 kilograms per day times 365 days). A brief investigation of the cargo manifests for the first few SpaceX commercial resupply flights shows that the ratio of crew consumables to other cargo mass may range from 1:1 to 1:6. We choose a ratio of 1:2 consumables to other cargo mass. This may be on the low side, but we anticipate that the financial incentive to save mass delivered to the Moon will drive toward a low ratio. We assume that the other mass scales with the number of habitats and not with the number of people on board. This results in 2,920 kilograms per unit (2 times 1,460 kilograms) of extra resupply mass to be delivered annually. Appendix F shows a full accounting of the development, unit, and various operations costs, amortized over a decade.

The cost of ECLSS is assumed to be contained in the cost of both habitats. Eckart (1997) demonstrates that an ECLSS system for a representative lunar base can decrease its annual resupply mass by a factor of approximately five by closing the water loop. Once the water loop is closed, decreases in annual resupply mass for closing the atmosphere and waste loops are relatively negligible, while appreciably increasing the landed mass of the habitat under some circumstances. Current ECLSS systems, for instance on the ISS, are already nearly completely closed loop for water. For these reasons, we assume that the habitats we model have closed the water loop and that resupply masses due to atmosphere and waste management are effectively zero.

There are some important costs that we have not modeled. For instance, we do not model the non-recurring cost of providing radiation shielding by burying the modules or covering them with regolith. The BA330 is designed for a crew of four to six people and the costs of its power and ECLSS systems are assumed to cover that many people. We have not modeled the costs associated with providing extra power and a larger ECLSS system to accommodate crew levels above the designed amount. For now, we assume that these extra costs will not inflate the ultimate cost by more than a few percent; however, future models should incorporate these aspects.

H. Cost of Lunar Space Suit

A space suit is required for lunar surface activities; however, its cost is relatively small compared to other associated costs. Thus, we only roughly estimate the cost of a suit. For the Constellation Program, NASA awarded a $745 million contract to Oceaneering to develop and build 109 space suits (Associated Press 2008). Inflating this contract value to 2018 dollars ($872 million) and dividing by 109 units, we estimate a suit will cost around $8 million. For simplicity, we assume that astronauts will not share or reuse suits.

5. Demand for Lunar Goods and Services by Governments

In this chapter, we estimate demand for lunar goods and services by NASA and its partner space agencies for human exploration activities and for science on the Moon through 2040. As discussed in Chapter 1, demand for defense and national security-related activities are not included in the scope of this report.

A. Demand for Human Exploration

1. Product

Space agencies and philanthropists have plans to send humans back to the Moon for exploration. The current interest in sending people back to the Moon stems from philosophical desires for a sustained human presence on the Moon; to study the performance of humans in a low gravity, high radiation environment so as to better understand the challenges of sending humans to Mars and beyond; and as a location to test technologies like habitats and rovers that will be needed for future missions to potentially establish a permanent settlement on the Moon or for a mission for a human landing on Mars (Table 1). In addition, while on the Moon, astronauts will collect scientific data and run scientific experiments.

2. Technologies

A NASA report released in April 2020 describes its vision for long-term human lunar exploration (NASA 2020b). NASA plans to begin landing lunar base elements in approximately 2028 that will enable "longer surface expeditions" with a crew of four (Berger 2019; NASA 2020b). Based on NASA documents, we assume that by 2028, NASA will have landed sufficient resources to allow a crew of four to survive for 2 weeks, i.e., the daylight portion of a single lunar day. For comparison, astronauts aboard Apollo 17 spent 3 days on the lunar surface (NASA n.d.).

We use publicly available NASA documents to estimate the Artemis architecture in its sustainable phase. SLS will launch four astronauts on Orion from Earth to Gateway. At Gateway, the astronauts will transfer into the HLS, which was previously launched on one or more commercial heavy-lift launch vehicles. The HLS will transport all four astronauts to the lunar surface where they will stay for up to 45 days. On the surface, astronauts will make use of a small lunar habitat (roughly 20 cubic meters of habitable volume) and a small pressurized rover (e.g., the Space Exploration Vehicle). They will also use one or more unpressurized rovers. Commercial launch providers will land these elements, including all other necessary supplies, on the lunar surface prior to the arrival of the astronauts. To decrease cost, we assume that the astronauts will return to the same landing site for every mission; this allows reuse of the habitat and pressurized rover, which may both be costly. At the end of their stay, the astronauts will return to Gateway using HLS, where they will transfer to Orion for the journey back to the surface of Earth.

We assume that government astronauts will complete a full lunar mission no more than once per year. We base this assumption on NASA's estimated procurement of HLS transport services once per year for 10 years starting in 2028 (HLS BAA p.10). NASA and its partners may find that they cannot afford this launch cadence, in which case they will engage in fewer missions. It is less likely that NASA will be able to afford a significantly increased launch cadence. During our timeframe of interest, we assume that NASA will not replace SLS and Orion with a crewed Starship; thus, we do not analyze the possibility.

3. Costs

Drawing on the high and low cost estimates for each architecture element (Chapter 4), we estimate the annualized cost of a lunar mission in Table 18. In general, the costs of crewed launch depend upon the flight rate over a decade. For simplicity, we do not account for such dependence in Table 18; instead, the costs are for a nominal SLS flight rate and one HLS use per year. The annualized costs for the habitat and rovers include the cost of delivering them to the lunar surface. As discussed in Chapter 4, we amortize development and other investment costs over 10 years. Because the costs below assume a single use per year for all the elements, the annualized cost is also the average per-mission cost.

Table 18. Annualized Cost of a Lunar Mission

Element	Units	Low Cost Per Trip ($M)	High Cost Per Trip ($M)
SLS/Orion	1	1,850	1,850
Crewed HLS[a]	1	370	2,150
Habitat	1	170	390
Pressurized Rover	1	200	460
Unpressurized Rover	1	4	13
Space Suits	4	8	8
		Low Total Cost ($M)	**High Total Cost ($M)**
All		2,626	4,895

Source: STPI calculations. See Chapter 4 for all costs.
a. Cost numbers for HLS assume a flight rate of once per year (i.e., 10 times per decade)

4. Demand Assessment

The number of human missions to the Moon will depend on available funding. In this section, we first estimate potential spending on human space exploration missions by NASA and its partners. Based on other human space exploration programs, most notably, Mars, we then estimate the amount of funding that is likely to be available for human missions to the Moon. Using the cost figures above, we then determine whether the posited number of trips in the two low and high cost scenarios above fall under space agency budget constraints.

a. Potential funding available for human space missions

During the course of our interviews and our review of the potential demand by households and businesses for lunar goods and services, we concluded that in the course of the next two decades, most of the demand for technologies enabling human missions to the Moon is likely to be from space agencies. Accordingly, space agency budgets will determine most of the funding available for human missions to the Moon. In this section, we project the potential size of future space agency budgets of NASA and its international partners for human missions to the Moon. We also discuss potential funding for lunar missions from other countries and from philanthropists.

1) NASA

Our projections for future NASA expenditures are based on the FY 2020 enacted budget and budget projections through 2024 (NASA 2019a). (We only show budgets after 2020 in the figures below because the budget is fully allocated through 2024.) We create top line annual estimates of potential expenditures on human exploration by summing NASA budgeted expenditures on Deep Space Exploration Systems and Exploration Technology. We convert these budget numbers into constant prices of 2018 using projections by the Office of Management and Budget (OMB) for future increases in inflation in the GDP price deflator through 2024 (OMB 2019). After 2024, we assume that NASA expenditures in these categories stay flat in constant prices through 2028. After 2028, we add NASA expenditures on operating costs for the ISS to this total under the assumption that NASA will no longer support the ISS after that year (OIG 2019).[4]

We assume expenditures on space and flight support remain constant throughout the forecast period. Expenditures on space flight support are assumed to shift from the ISS to lunar and Mars missions over time. Under this assumption, this category neither adds nor subtracts from our topline.

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4 Prior to 2019, NASA had planned on operating the ISS through 2028. The Administration changed this date to 2024 in 2019 (OIG 2019). In light of the complexities of shifting the ISS to a private entity or deorbiting it, we assume that the 2028 date is more realistic.

To calculate how much of these budgets may be available for lunar human exploration missions, we subtracted from these totals STPI projections of expenditures on human exploration missions to Mars generated for a previous NASA study, and construction expenditures on Gateway and SLS and Orion (Linck et al. 2019). We deduct these expenditures on Gateway and SLS and Orion under the assumptions that these programs are going ahead under all circumstances.[5]

We considered using the Administration's budget request for FY 2021 as a starting point for our projections rather than budget numbers for FY 2020. The Presidential Budget Request includes a large increase in spending on Human Exploration and Operations for the Moon-to-Mars campaign: 74 percent for Deep Space Exploration Systems and 56 percent for Exploration Technology (NASA 2020a). Most of the early spending would go to missions to the Moon. Because it is not clear that Congress will pass this budget, we have chosen to use the FY 2020 appropriated numbers and projections for this analysis.

2) Partner countries

ESA, CSA, JAXA, and the Russian space agency, Roscosmos, all collaborated with NASA to build and operate the ISS. All of these agencies have expressed interest in working with NASA on lunar missions.

ESA is teaming up with its international partners to return humans to the Moon (ESA 2019b). It has four major exploration programs. In partnership with Roscosmos, the Luna Resurs-Orbiter program will carry European technology to land precisely and safely on the Moon (PILOT) and to extract and analyze samples of the lunar terrain (PROSPECT). ESA is also providing the service modules for Orion that will provide propulsion, life support, power, air and water, and control the temperature in the crew module. It is also supporting a mission to explore lunar resources after 2025. The goal of that mission is to produce drinkable water or breathable oxygen on the Moon. Its Heracles mission is scheduled for 2028; it is designed to gain knowledge on human-robotic interaction while landing a spacecraft on the Moon, collecting samples with a rover operated from the Lunar Gateway and sending samples back to Earth (ESA 2019c).

As per ESA 2019c, ESA's total budget for 2020 is 6.68 billion euro, or \$7.48 billion. Of this, 645.2 million euro (\$722 million) is dedicated to Human and Robotic Exploration. We assume that in constant prices, ESA's budgets for Human and Robotic Exploration remain static through 2040. We assume that Human and Robotic Exploration funds are available for lunar missions as of 2020.

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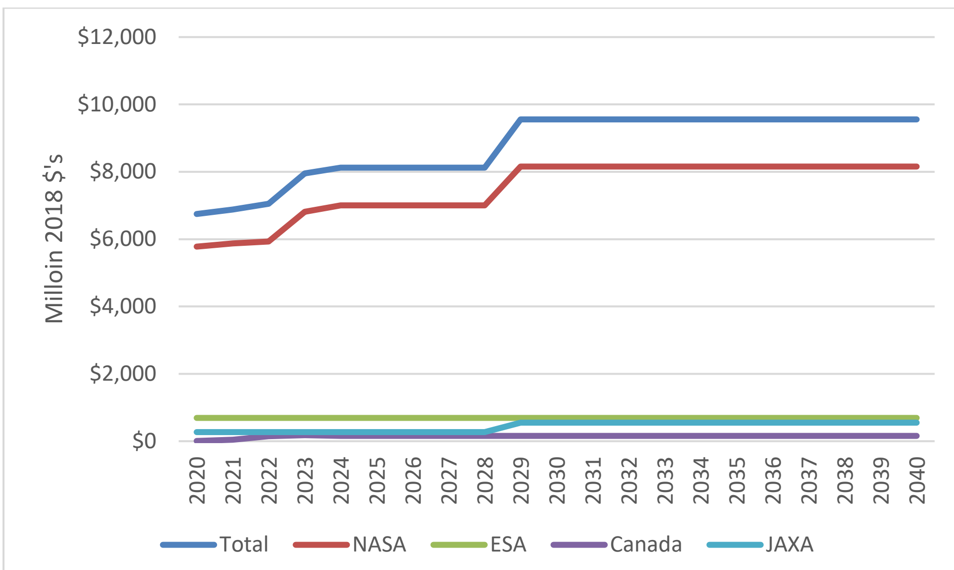
[5] Costs of SLS, Orion, HLS, and the Gateway were estimated in Chapter 4. We deduct these costs from human lunar exploration budgets by spreading them over the 2020 to 2027 timeframe.

In 2019, the Canadian Space Agency committed to work on the NASA-led Lunar Gateway, including Canadarm3 but also through the new Lunar Exploration Accelerator Program (Bains 2019). Canada's "Canada Reaches for the Moon and Beyond" program will increase spending on lunar and associated programs from $10 million Canadian ($8 million) in 2019–2020 to $265 million Canadian ($199 million) in 2023–2024 (Boucher 2019). We use this series for Canadian expenditures on lunar missions through 2025 after which time we assume expenditures stay constant at the 2024–2025 figure of $240 million Canadian ($181 million 2018 U.S. dollars) through 2040.

JAXA is also budgeting for the Moon. For 2019, it budgeted 31.2 billion yen ($286.2 million) for the ISS, 15.7 billion yen ($144.0 million) for space science and exploration, and 14.4 billion yen ($132.1 million) for space technology and aeronautics. We include all these budgetary categories but the budget for the ISS, for a total of 30.1 billion yen ($270.2 million 2018 dollars) for 2019 (Toukaku 2019) in our estimate of potential Japanese expenditures on human missions to the Moon through 2028. We assume these expenditures will remain the same in constant dollar terms through 2028, after which the 31.2 billion yen spent on the ISS is added to the human space flight program for a total of 61.3 billion yen ($562.3 million 2018 dollars). We assume that Japan continues to spend this amount on human space programs through 2040.



Source: National space agency budgets; STPI projections

Figure 7. Projected Spending on Human Space Exploration by NASA, ESA, Canada, and JAXA

Russia has participated actively in the ISS, but in recent years it has been charging other countries' astronauts for launch to the ISS. During this period, it is not clear whether Roscosmos has been a net contributor to the ISS or whether payments for launch services have covered its ISS costs. In 2015, Roscosmos budget was reduced 30 percent. In constant ruble terms, the cumulative budget between 2016 and 2025 was reduced from 2 trillion rubles to 1.4 trillion rubles, or to 140 billion rubles ($2.3 billion) per year (Reuters 2016). Because of the uncertainty and opacity surrounding the Russian space budget, we have refrained from projecting future Russian spending on lunar missions in collaboration with NASA and other participants in the ISS project.

Figure 7 shows our projections of government budgets allocated to human space exploration by year. Aggregate spending on human space exploration by NASA and its partners runs $8.1 billion 2018 dollars from 2025 until 2028, after which it rises to $9.6 billion 2018 dollars per year through 2040.

3) Other countries

Several other countries have lunar programs. Since details about their programs through 2040 are lacking, they are not included in the estimates. However, lunar aspirations of three countries—India, South Korea, and Israel—are listed below principally because they have the potential to add to U.S.-led efforts or compete with U.S. companies.

India has a comparatively small but thriving lunar program. The Indian Lunar Exploration Program (Chandrayaan) is an ongoing series of outer space missions by the Indian Space Research Organisation (ISRO) to build and launch lunar orbiters, impactors, soft landers, and rovers (ISRO 2020). As of October 2019, ISRO has not committed to working on the Artemis program with NASA (Singh n.d.). The recently announced lander and rover, Chandrayaan-3, to be launched in 2021, is estimated to cost under $90 million (Foust 2020a, Wall 2020). In its next phase in 2024, ISRO is planning a joint mission with JAXA to explore the South Pole of the Moon, with JAXA providing the rover and ISRO the lander (UNOOSA 2019). Indian lunar plans beyond 2024 are unknown, but it appears India is interested in a long-term presence on the Moon.

The Korea Aerospace Research Institute (KARI), the South Korean space agency, is pursuing the Korean Lunar Exploration Project; KARI is coordinating research on a rover, a lunar probe, payloads, and a deep space Earth station (KARI n.d.). The Korea Pathfinder Lunar Orbiter, which is budgeted at less than $200 million, has been delayed several times and is now expected to launch on a SpaceX rocket in 2022 (Clark 2019). It will map natural resources including water, uranium, Helium-3 and others from lunar orbit, and includes an instrument from NASA (Ju n.d.). Phase 2 plans include a lander and a rover on a Korean rocket. Details are unavailable on Korea's long-term plans in space, but KARI's website shows South Korea's interest in exploring and utilizing the Moon.

Several other countries have plans related to the Moon, but not all these countries have government agencies leading these plans. In Israel for example, a private non-profit called SpaceIL plans to land a probe on the Moon (Keyser 2020). Its previous lander entered Moon’s orbit but was unable to soft-land. It was estimated to have cost $100 million, though all but about $10 million was raised privately.

4) Philanthropists

We define philanthropic giving for lunar missions as funds provided in the form of grants or in-kind services. After reviewing mission statements and public pronouncements by the two most prominent space entrepreneurs, Elon Musk of SpaceX and Jeff Bezos of Blue Origin, it is not clear whether either would classify as a philanthropist. We concluded that the two entrepreneurs are pursuing their visions for the Moon through investment projects within their two companies rather than donating funds to lunar missions. As discussed in Chapter 4, SpaceX is building a rocket, called Starship, to go to the Moon and back. However, it intends to sell Starship launch services commercially with hopes of recouping its investment.

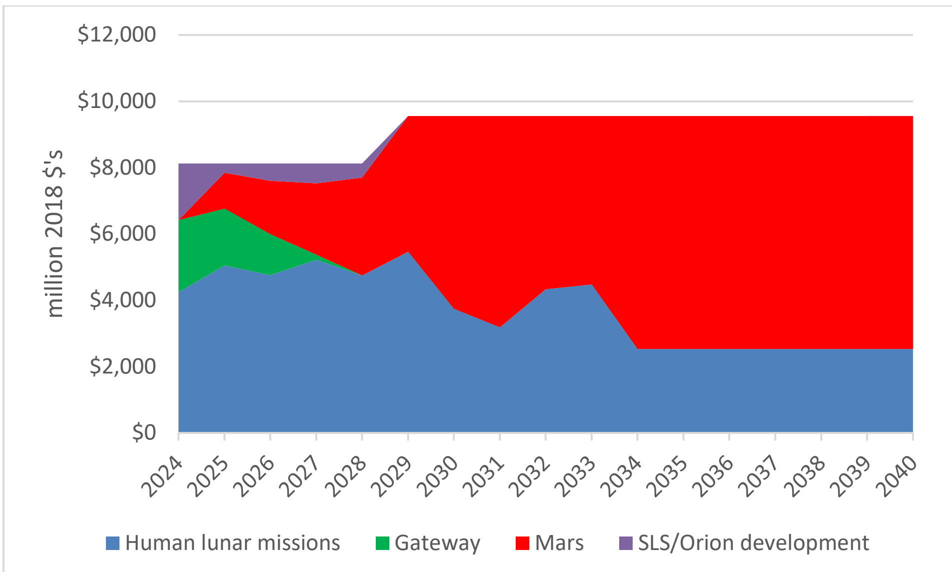
Blue Origin Chief Executive Officer, Bob Smith, has stated that Jeff Bezos, the owner of Blue Origin, believes that “a permanent human presence on the moon was essential to his long-term vision of millions of people living and working in space.” Blue Origin has also committed to partnering with NASA; as of 2017, it was internally funding the development of a lander for the Moon (Aviation Week 2017; Foust 2018). The level of internal investment is unknown but Bezos has noted publicly that the company will “do it alone if necessary.” In late 2019, Blue Origin announced that it will work with Lockheed Martin, Northrop Grumman, and Draper Laboratory to develop a human-rated lander for NASA's Artemis program (Grush 2019).

We have not attempted to estimate the value of these in-kind investments, especially as both companies would like to recoup these investments through sales of launch and other space services.

5. Potential Expenditures on Lunar Missions

We incorporate development and investment costs into annualized cost estimates for particular components of lunar missions, such as launch, because it better corresponds to a commercial approach to procuring goods and services. The commercial provider funds the upfront costs of developing the technology and then recoups the investment through subsequent charges. However, for the case of Gateway and SLS/Orion development costs, which we assume will not be procured through a commercial fixed price contract, we deduct development and construction costs from the total funds available for human space missions. In addition, not all of the projected spending on human space exploration will go to lunar missions. As per NASA documents, by 2025, expenditures on human missions to Mars will begin (Linck et al. 2018). These expenditures are also deducted from the total.

Figure 8 shows our projections of potential human lunar exploration budgets based on these estimates. As can be seen, potential budgets run from $4.2 billion to $5.2 billion 2018 dollars annually between 2024 and 2028. In 2029, potential budgets rise to $5.5 billion 2018 dollars because we assume that support for the ISS ends based on past statements by NASA. Despite the additional funds from the assumed end of the ISS mission, money for lunar missions falls after 2029 as expenditures on human exploration missions to Mars rise. By 2034, we project that the money available for lunar missions would run $2.5 billion per year in 2018 dollars.



Source: STPI projections of human space exploration budgets (Linck et al. 2019). While we use these budget estimates for the purpose of this analysis, we make no assessment about the ability of NASA to accomplish its lunar and Mars exploration goal within these budgets. For simplicity in this analysis, we have assumed that the expenditures on Moon and Mars exploration can be clearly delineated, which is not generally possible.

Figure 8. Potential Lunar Human Exploration Space Budgets

As the sections above explain, the budget available for human lunar missions is about $63 billion over 17 years, from 2024–2040; this is roughly $3.7 billion on an annualized basis. This would enable 14 lunar missions per decade (or at least one per year) when lower costs are assumed ($37 billion over a decade divided by $2.6 billion per mission), and seven per decade when higher costs are assumed ($37 billion over a decade divided by $4.9 billion per mission), as discussed in Table 18. However, from 2034 to 2040, the annual aggregate budgets would be inadequate to fund one flight a year; flights would require a cadence of once every 13 months to fit within our projected budgets.

B. Demand for Science

1. Product

As noted above, there are three categories of science activities on the Moon, which the United States and its partners are likely to pursue: lunar science, which could include lunar geology; astrophysics, using the Moon as a site to observe the universe and the solar system; and testing space technologies for science applications.

2. Technologies

Research on lunar technologies will entail obtaining a large number of samples of lunar regolith from a wide range of sites. These samples can be collected by robotic means, by humans, or a combination of the two. It will entail landings at a variety of sites followed by the use of rovers that can range over many collection sites.

Using the Moon as a site for telescopes and other instruments to collect information about the solar system and the cosmos will likely entail one or more sites where telescopes and other sensors are placed. Although not constantly tended by humans, the sites will need electricity or some other source of energy to mitigate changes in temperature, computing capabilities, and communications. Testing facilities would likely be placed in proximity to habitats.

We surmise that some of the geology, most of the testing, and other lunar science will involve astronauts. Their costs and some of the research and transportation costs will likely be subsumed under the lunar human exploration budget, as instruments are transported to the Moon along with human exploration missions. However, in some instances, we expect that space agencies will transport and land robotic automated research experiments on small launchers and landers.

3. Costs

The cost of a launch and landing a small scientific payload under the CLPS contract is expected to be about $240 million. We use this figure as our estimate of the cost of robotic landings for lunar science missions.

4. Demand Assessment

NASA has funded lunar science through its Lunar Discovery and Exploration program. The President's Budget Request for this program was $218 million in 2019 and remains at that nominal level through 2023 (NASA 2018). In constant price dollars of 2018, the value of those expenditures would be $195.4 million in 2023. This program accounts for 7.9 percent of NASA's budget for planetary science. We assume that this figure will reflect NASA budgets for lunar science from 2023 to 2040.

ESA's 2020 budget for Science is 538 million euro ($602 million) (ESA 2019c). We assume that in constant prices, ESA's science budget remains static through 2040. Drawing on the NASA analogy above, we assume that 7.9 percent of ESA's total science budget will be spent on lunar science, which implies annual expenditures on lunar science by ESA of 43 million euro ($48 million). We assume this figure remains constant in constant dollar terms from 2020 through 2040.

Adding the two estimated lunar science budgets yields funding from NASA and ESA for lunar science missions of $237 million in 2018 dollars. We assume that this annual figure stays constant through 2040.

These funds are sufficient for roughly one launch and landing per year using a CLPS contract referenced in Section 3 above. We assume that purchases of scientific equipment and sensors are covered within this category.

These budgets are insufficient to cover all planned lunar science activities. We assume that lunar science experiments and equipment are likely to be incorporated into heavy launches, including human missions to the Moon. In fact, most of these services may eventually be provided by heavy launchers and landers that serve human missions rather than small launchers and landers because the per kilogram cost of the heavy launchers will be so much cheaper.

C. Cumulative Derived Demand for Lunar Missions Funded by Governments

As discussed in Chapter 2, for government-financed human space exploration and lunar science to proceed, many supporting activities are needed. We define demand for launch services, cargo and crew landing services, human habits, space suits, rovers, and lunar water as derived demand; demand for these products and services is driven by demand for government space exploration missions and space science missions. Using numbers from the sections above, available funds for human missions add up to about $3.7B a year, and $240M a year for science missions. Given the cost of a human mission ($2.6B in the low cost scenario, and $4.9B in the high cost scenario), NASA will be able to launch at least one mission a year (14 per decade) in the low cost scenario, and seven per decade in the high cost scenario). Given the cost of a small science mission, NASA will be able to launch a science mission annually as well.

6. Demand for Lunar Goods and Services by Households and Businesses

While most of the commercial companies discussed in Chapter 3 focus on obtaining funds from NASA and other government agencies to produce goods and services for lunar missions, some plan to provide goods and services for households and businesses that are not ultimately serving government customers. In this chapter, we draw on the cost estimates from Chapter 4 to assess the commercial feasibility of a number of lunar goods and services that have been proposed for sale to households and business. We project potential demand and estimate potential revenues for the activities that appear commercially feasible.

A. Household Demand

1. Lunar Tourism

a. Product

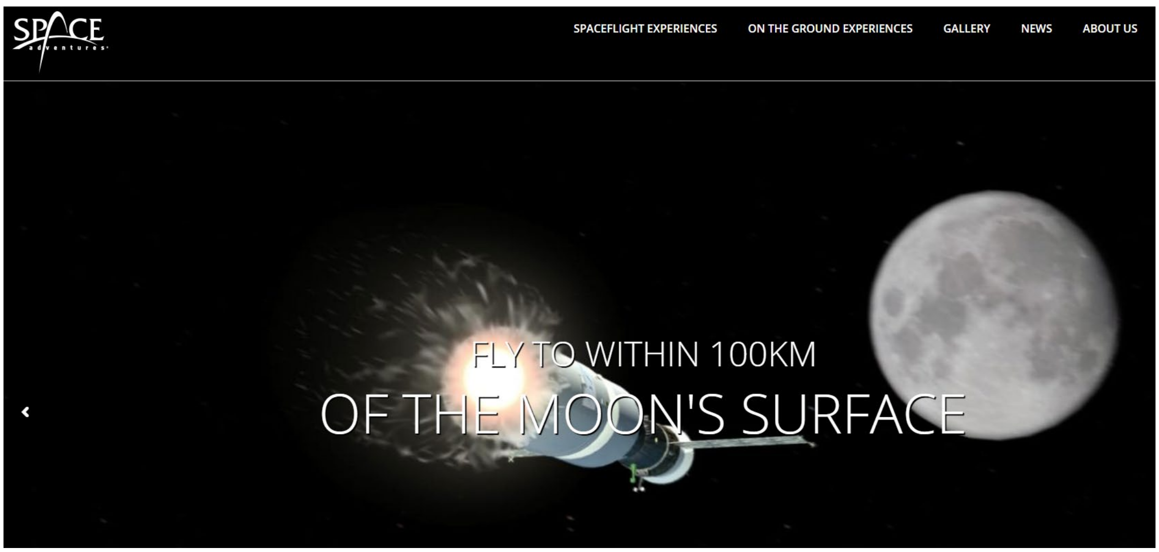
Several entrepreneurs and visionaries have entertained the idea of making money from lunar tourism. Tourists could either land on the surface of the Moon or fly by it without landing. In the former scenario, the lunar tourist would sleep in a lunar habitat and periodically venture out for lunar walks or drive in a lunar rover. Under the latter scenario, a lunar tourist would purchase a ticket to orbit the Moon, foregoing the lunar landing and stay.

A private lunar flyby is not a new concept: in 2012, Space Adventures advertised a $150-million seat on a lunar flyby mission on a Russian launch vehicle that was intended to launch in 2017, but never did (Masunaga 2018; Foust 2019). Space Adventures continues to advertise circumlunar missions (a 6-day journey around the Moon after 10 days on the ISS for adaptation to life in space) on its website (Space Adventures n.d.).

b. Business

Our envisioned trip to the surface of the Moon would entail launch, landing, a stay in a habitat, several Moon walks, potentially a trip on a rover, ascent from the lunar surface, and return to Earth. As elsewhere in this report, we have examined two launch options: SLS/Orion and Starship. The first option involves a launch on SLS using the Orion capsule. Once Orion reaches lunar orbit, it docks with Gateway from where the lunar tourists transfer to a human-rated lander. The lander would land close to a lunar habitat. The tourists would walk from the landing craft and travel to the habitat. After the end of their stay, the tourists would re-embark on an ascent vehicle, and return to Gateway from where they would take Orion back to the Earth. Orion has a capacity of four passengers.

In the case of Starship, the passengers would fly to Earth orbit, where the Starship would be refueled, then fly to lunar orbit, and land close to a habitat. The passengers would disembark and travel to the habitat for their visit. After their stay, the passengers would re-embark on Starship and return to Earth. As opposed to Orion, which exists, Starship is still in the construction phase, so assumptions on the number of passengers that could be carried are based on statements by SpaceX and our own analyses.



Source: Space Adventures n.d.

Figure 9. Advertisement by Space Adventures for a Trip around the Moon

In both instances, we assume that the tourists would be attended to at all times, constraining the number of slots per launch for tourists to total capacity minus support staff. In the case of Orion, we assume one pilot/captain for the mission and one medical staffer who would also provide other support, so the total number of tourists per launch would be limited to two. All four would descend to the surface of the Moon. In the case of Starship, for a trip to the Moon, especially one ferrying passengers and carrying supplies, as explained in Chapter 4, we estimate that Starship's capacity will be limited to 14 occupants due to volume constraints. We assume that 4 of the 14 would be support staff: the captain/pilot, a medical officer, a mechanic who would provide support for all the systems, and a host who would attend to the needs of the tourists. In this case, the total number of tourists per launch would be 10.

We assume that tourists paying millions of dollars to go to the Moon will wish to have adequate space, so based on our habitat designs, only the low cost habitat would be used and each habitat would only house six people. Under this assumption, only one habitat would be needed for the Orion contingent, but three would be necessary for the Starship group. We assume that each unpressurized rover is designed to carry four people, the driver, plus three tourists. We assume that the rover can only be driven by one of the support staff. In the case of Orion, this implies only one rover is necessary. In the case of Starship, we assume two rovers would be adequate, as the tourists would take turns going out on the rovers. In each case, we assume that a spare rover is available. We assume that each tourist receives a custom-fit lunar space suit that the tourist takes home at the end of the trip as a souvenir.

a. Costs

We provide the cost of three alternatives for lunar tourism: a high and low cost for lunar surface tourism and the cost of a lunar flyby using Starship. The high cost option uses SLS, Orion, and HLS for crew transportation, which we estimated would cost at least $2.2 billion in Chapter 4. This mission will fly two paying customers per year, use a single low cost habitat over a decade, and a single low cost unpressurized rover over a decade.[6] For a single unit of each over a decade, Chapter 4 provides the annualized cost of the habitat ($169 million) and the rover ($3.6 million). Each tourist also requires a space suit that costs $8 million. The sum of the transportation, habitat, rover, and space suit costs is about $2.4 billion. We assume that the tourists pay all costs of the trip. With two paying customers per year, **the cost per ticket is about $1.2 billion if the SLS is used for transportation of the tourists**.

A low cost option for lunar tourism uses the SpaceX Starship for all crew and cargo. The low cost habitats and unpressurized rovers are also used. To keep ticket prices relatively low, we assume that a lunar tourism mission will not include a pressurized rover. The per person costs for this mission drop significantly as the number of annual tourists increases. The annual number of Starship launches and the total number of habitats and rovers needed as a function of potential tourist demand are shown in Table 19. For a low flight rate, such as only two paying tourists per year, the number of launches, habitats, and rovers is the same as for the high cost mission for surface tourism, though the ticket price is about $420 million—roughly one-third of the high cost mission. For greater flight rates, the number of needed launches, habitats, and rovers increases, while the unit costs of each decrease. To satisfy 20 tourists per year, two flights of Starship would be required; recall that our model for Starship can hold 14 people, four of which will be non-paying support staff. Three habitats and three rovers are needed to support each flight of 10 tourists and four support staff; it is assumed the two tourist missions do not overlap in time, so that each

[6] The low cost options for rovers and habitats provided in Chapter 4 assumed the use of Starship for cargo delivery. Without Starship, the high cost option we calculate for lunar tourism would be even higher.

batch of tourists may share the same three habitats and rovers. **Each of the 20 tourists would pay approximately $75 million for a ticket.**

Table 19. Cost to Tourist of a Trip to the Surface of the Moon Using Starship

	Units			Annualized Unit Costs ($M)			Total Cost ($M)	
Tourists Per Year	Starship Per Year	Habitat[a]	Rover[a]	Starship	Habitat	Rover	Per Year[b]	Per Person
1	1	1	1	665	169	3.6	846	846
2	1	1	1	665	169	3.6	854	427
3	1	1	1	665	169	3.6	862	287
4	1	1	1	665	169	3.6	870	217
5	1	2	1	665	133	3.6	975	195
6	1	2	2	665	133	2.6	984	164
7	1	2	2	665	133	2.6	992	142
8	1	2	2	665	133	2.6	1000	125
9	1	2	3	665	133	2.3	1010	112
10	1	3	3	665	121	2.3	1115	111
11	2	3	3	486	121	2.3	1430	130
12	2	3	3	486	121	2.3	1438	120
13	2	3	3	486	121	2.3	1446	111
14	2	3	3	486	121	2.3	1454	104
15	2	3	3	486	121	2.3	1462	97
16	2	3	3	486	121	2.3	1470	92
17	2	3	3	486	121	2.3	1478	87
18	2	3	3	486	121	2.3	1486	83
19	2	3	3	486	121	2.3	1494	79
20	2	3	3	486	121	2.3	1502	75

Source: STPI calculations

a. Units per decade

b. Includes the cost of an $8 million space suit for each tourist, not shown in table

A lunar flyby does not require a habitat or a rover; thus, those costs are eliminated. We retain the cost of the space suits for each tourist. Using the SLS, the total cost and the ticket price are relatively unchanged between a crewed lunar landing and the flyby. For a flyby using Starship, however, two changes reduce the cost. Most significantly, fewer launches are required to refuel the Starship, thus bringing down the unit cost of a Starship mission. Additionally, each Starship can now hold potentially more people (i.e., payload mass), since it no longer needs to budget fuel for the lunar landing and ascent. For conservatism, we will continue to assume there are no more than 10 paying tourists per flight. Table 20 provides estimates of the ticket costs for a lunar flyby mission. These costs range from $430 million to $35 million per person, depending on the flight rate.

Table 20. Cost to a Tourist of a Flyby around the Moon Using Starship

	Units	Unit Costs ($M)	Total Cost ($M)	
Tourists Per Year	Starship Per Year	Starship[a]	Per Year[b]	Per Person
1	1	426	434	434
2	1	426	442	221
3	1	426	450	150
4	1	426	458	115
5	1	426	466	93
6	1	426	474	79
7	1	426	482	69
8	1	426	490	61
9	1	426	498	55
10	1	426	506	51
11	2	271	630	57
12	2	271	638	53
13	2	271	646	50
14	2	271	654	47
15	2	271	662	44
16	2	271	670	42
17	2	271	678	40
18	2	271	686	38
19	2	271	694	37
20	2	271	702	35

Source: STPI calculations

a. The costs provided assume that crewed Starship is used exclusively for lunar flybys; i.e., no governments are using Starship for crewed lunar surface operations and no tourists are paying for tourism trips to the lunar surface or low Earth orbit. If other users of crewed Starships exist, these costs would be lower.

b. Includes the cost of an $8 million space suit for each tourist, not shown in table

c. Demand Assessment

A market for space tourists exists, although to this point it has been small. Between 2001 and 2009, Space Adventures, Ltd. arranged eight flights for seven people (one person, Charles Simonyi, went twice) on Russia's Soyuz spacecraft to go to the ISS; Space Adventures paid Roscosmos for the service. On average, these space tourists paid $25.5 million for the combined cost of launch and the stay in the Russian section of the ISS (NASA 2011; 2015). In 2019, Axiom Space announced that it would charge a space tourist

$55 million (including launch) for a roundtrip to visit its module attached to the ISS (Corbett 2020). Space Adventures announced on February 18, 2020 that it has an agreement with SpaceX that would allow Space Adventures to fly four space tourists to a relatively high Earth orbit on a dedicated Crew Dragon mission (Foust 2020b). Training would take place in the United States, rather than Russia, and require just a few weeks compared to up to 6 months of training for the flights on Soyuz. Space Adventures has not yet disclosed the ticket price, although it has said it will be in the range of other orbital space flights. For sake of comparison, in June 2019, Bigelow Aerospace announced it would sell seats for $52 million on flights to the ISS for space tourists to stay in its module attached to the ISS (Foust 2020b). The first customer for a trip to cislunar space is a Japanese billionaire, Yusaku Maezawa. In 2017, he agreed to pay an undisclosed amount for a multi-person trip around the Moon on one of the early flights of SpaceX's Starship (Yuhas 2017).

How much would people be willing to pay to go to the Moon? When we compared ticket prices to the net worth of four of the seven individuals that paid to go to the ISS, we found that on average they paid 3.2 percent of their net worth—with a high of 6 percent and a low of 1.2 percent—for the trips. Futron (2002) estimated that based on the ticket prices paid by individuals that purchased tickets to ISS, the ratio between the cost of the flight and the net worth of two of the space tourists, and the vacation and discretionary income spending habits of a survey Futron conducted with Zogby, customers would be unlikely to spend more than 10 percent of their net worth for a ticket.

For reasons of health, age, and interest, not everyone who has the wherewithal will wish to go to the Moon or around it. Historical demand for trips to the ISS has been much lower than the number of people who could afford to go based on our criteria of the net assets needed for such a trip. At the $25.5 million average price tag to the ISS, and assuming that people would be unwilling to spend more than 3.2 percent of their net worth to go to the ISS, individuals would have needed $790 million in net assets to fall into the prospective pool of space tourists. Well over 2,100 people had this level of net assets, yet only 7 people went to ISS; another person ordered a trip, but then was unable to go. In other words, only 8 people out of more than 2,100 eligible customers went to ISS or attempted to purchase a ticket, less than 0.4 percent of the eligible pool.

The requisite financial resources and willingness to go to the Moon are not the only factors that affected the number of space tourists who tried to go to the ISS. To visit the ISS on Soyuz, tourists had to travel to Russia for a rigorous 6-month training program and an intensive course in Russian (Kryuchkov 2015). ISS tourists underwent stringent health inspections, eliminating some candidates. While on the ISS, tourists were expected to perform scientific experiments or tasks as requested by the flight program (Kryuchkov 2015). One of our interviewees noted that NASA actively discouraged such recreational visits. These demands would not apply or might be relaxed for lunar tourism, although the physical health requirements may remain.

Other indicators suggest that a large number of people might be interested in a trip to space. Virgin Galactic has reported significant interest in its suborbital tourism service. In February 2020, it reported 8,000 online reservations, double what it had reported at the end of September 2019 (Hebden 2020). These online reservations require a refundable deposit of $1,000, but the full price of the flight is $250,000 (Virgin Galactic n.d.).

To estimate potential demand for trips to and around the Moon, we must estimate the tourists' willingness to pay as a function of ticket price. Starting with a data set of the net worth of global billionaires (Forbes 2019), we define two scenarios for the willingness to pay of the billionaires. The low and high scenarios assume that potential customers will not spend more than 3.2 percent or 10 percent, respectively, of their net wealth on a lunar tourism ticket. Further, in both scenarios, it is assumed that only 10 percent of those with sufficient net wealth will actually purchase a ticket over the course of a decade. For example, if 200 people have sufficient net worth to purchase a ticket at price X, then we assume only 20 people will actually purchase a ticket over the course of a decade, which leads to only 2 tourists per year on average.

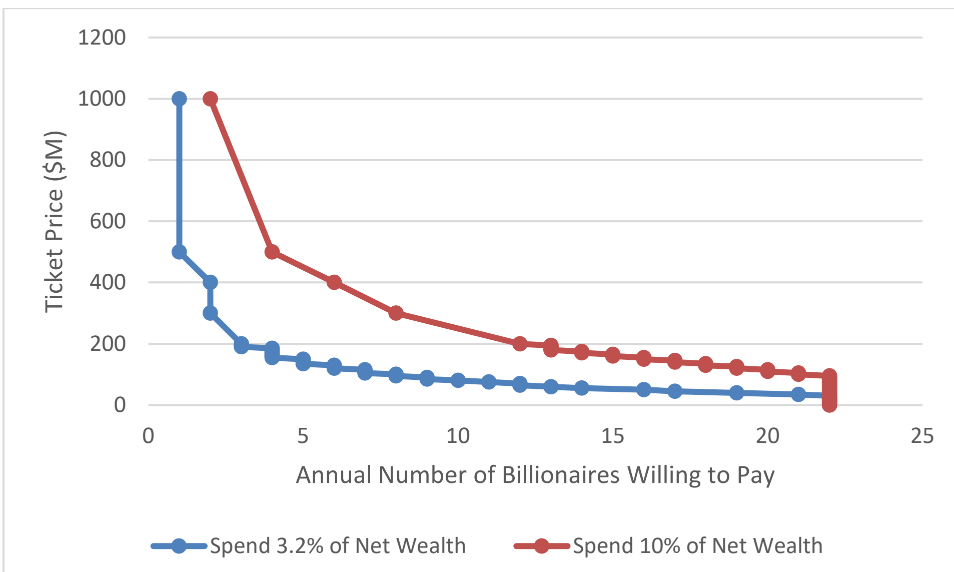


Figure 10. Willingness of Billionaires to Pay for a Lunar Tourism Trip

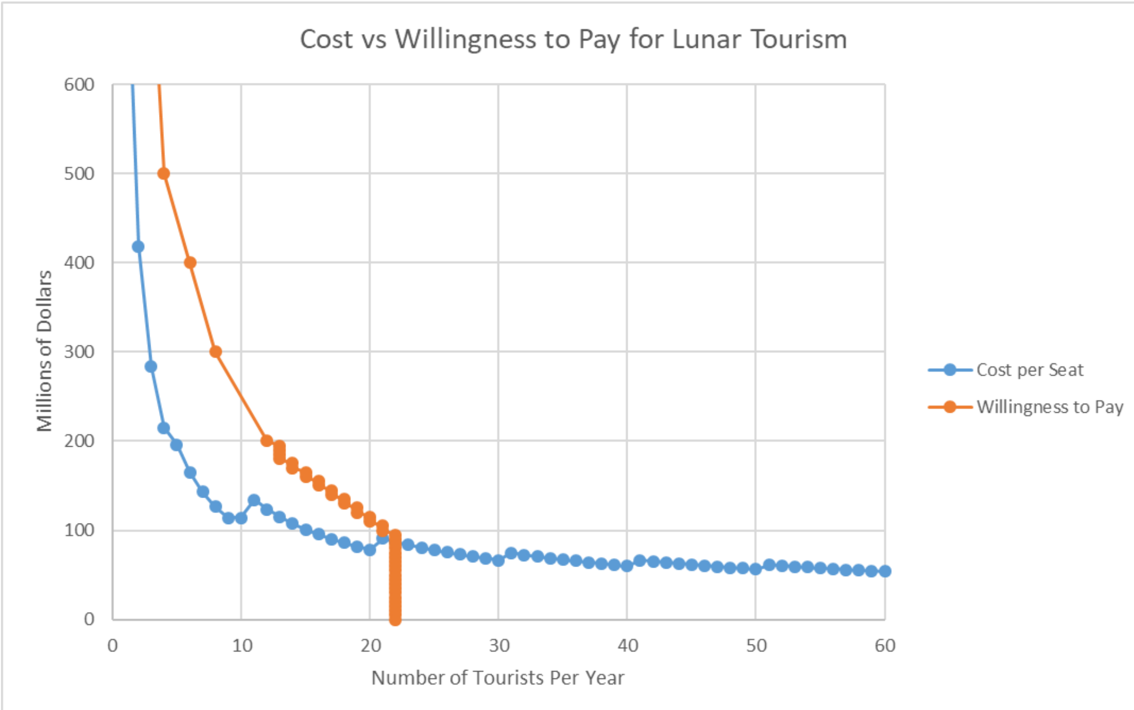
Our estimates for the willingness to pay of billionaires for lunar tourism are given in Figure 10. The information in this figure can be combined with our three previously estimated costs of lunar tourism to assess the economic feasibility of each. At a given annual number of tourists, if the cost of the ticket exceeds the price that billionaires will pay, then the activity is not feasible. The demand for lunar tourism is the point at which the cost and willingness to pay curves intersect. Using the billionaire dataset with the assumptions above, the lowest prices for which we can estimate demand are about $32 million ($1 billion times 3.2 percent) and $100 million ($1 billion times 10 percent) for the low and high demand scenarios, respectively. In order to investigate demand at prices below these levels would require data on individuals with net worth in the hundreds of millions of dollars, which we do not have. We find that the $32 million and $100 million price points both correspond to about 20 tourists per year; thus, we are unable to analyze demand for more than 20 tourists per year.

We previously defined two cost scenarios for landing on the Moon and one scenario for fly-by. The annual number of people who might be willing to pay for a lunar tourism flight for each cost scenario and willingness to pay option is shown in Table 21. For the scenarios where cost is less than willingness to pay out to 20 tourists per year—the limits of our billionaire dataset—we denote the maximum number of tourists as "20+."

Table 21. Annualized Costs and Number of Tourists to the Moon

Trip	Cost per tourist (millions)	# passengers willing to spend 10% of net worth	# of passengers willing to spend 3.2% of net worth
SLS/Orion/HLS	$1,200	0	0
Starship to surface	$75	20	0
Starship flyby	$35	20+	20+

A lunar flyby on Starship is economically feasible; under both scenarios for willingness to pay, the cost is less than the willingness to pay out to the limits of our billionaire data. A trip to the lunar surface on Starship is only economically feasible for the set of billionaires willing to spend up to 10 percent of their net worth; Figure 10 shows the cost and willingness to pay curves for this scenario. Using the willingness to pay scenario with a 3.2 percent threshold, cost generally exceeds willingness to pay by about $30 million; while our model shows this scenario is not economically feasible, its feasibility is likely within the margin of error for our models. Under the SLS/Orion/HLS option, no one is willing to pay the high cost of going to the Moon. Cost and demand curves for each feasible option are shown in Appendix H.



Source: STPI Calculations. See Table 19 and Figure 10 for the cost and willingness to pay data.

Figure 11. Economic Feasibility of a Trip to the Lunar Surface on Starship assuming Willingness-to-Pay of 10% of Total Assets

2. Moon Rocks

a. Product

Many people have collected rocks from the Moon, primarily from lunar meteorites. Some companies make a business out of incorporating bits of meteorites from the Moon into jewelry (Figure 12). Rocks from lunar missions, pieces of lunar regolith brought back to Earth, are much more coveted. To date, almost all Moon rocks brought back from lunar missions have been used for research or as diplomatic gifts. Some collectors, however, have managed to purchase some of these rocks from astronauts.

Because of the proven demand for rocks from lunar missions or from lunar meteorites, companies are already interested in purchasing rocks from the Moon for sale to the public. We split this demand into two markets: sales of lunar rocks from which pieces of about 10 milligrams are chipped and incorporated into "Moon jewelry,"[7] and fist-size or smaller rocks that collectors would display on a coffee table or in a display case.

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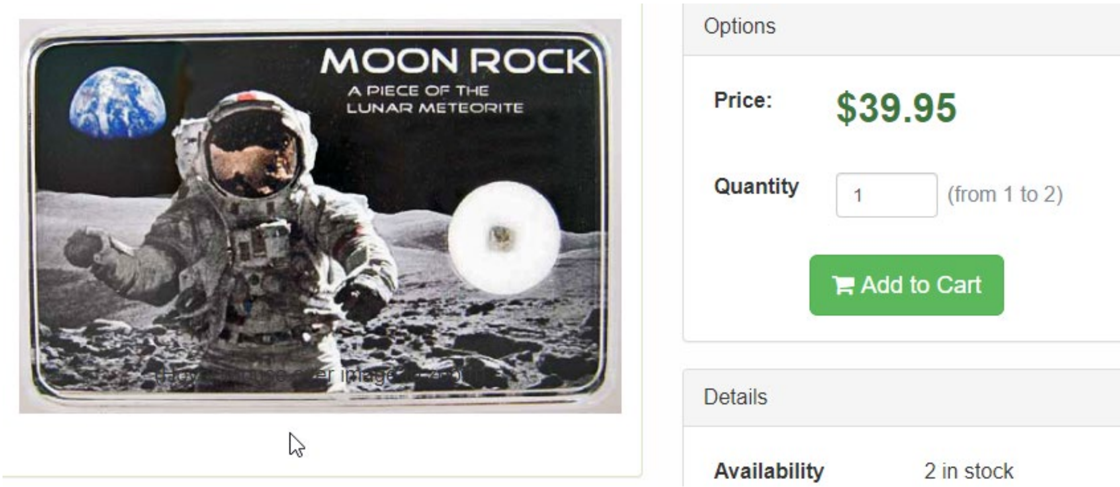
[7] Jewelers who take chips from lunar meteorites to insert into lunar jewelry use roughly this amount (Interview data).



Source: Meteorites for Sale n.d.

Figure 12. Advertisement for Rocks from Meteorite from the Moon

b. Business

Collecting and shipping Moon rocks back to Earth could entail using an autonomous rover to excavate rocks and put them into an autonomous hopper to bring them to an ascent vehicle. The rocks would then be robotically loaded into the ascent vehicle that would carry them to cislunar orbit and transfer them into a capsule that would bring them to Earth or be launched directly to Earth.

As discussed in Chapter 4, a small excavator and hauler robot together can generate 390 kilograms of lunar material per hour. Given the assumed battery capacity and power consumption, the excavator could operate for 4 hours per charge and, we assume, discharge its battery three times per terrestrial day. That would produce 4,680 kilograms per terrestrial day of lunar material. We assume that a company gathering rocks for sample return would use a similar robot if it existed. We assume that it would not be required to survive the lunar night, so the robot would operate for approximately 12 of the 14 terrestrial days in a lunar daylight period, producing up to 56.16 metric tons of rocks. The total mass to launch the equipment is approximately 120 kilograms. Alternatively, astronauts could collect small quantities of rocks by hand using a pick.

c. Cost

We estimate that a company collecting lunar rocks would only need to employ one excavator and one hauler at a total capital cost of $224 million. If the equipment is operated at full capacity, collecting about 56 tons of rocks (4,680 kilograms times 12 terrestrial days) in the course of a lunar day, the cost per kilogram of collected rock would be roughly $4,000 ($224 million divided by 56.16 tons). Our estimates of the costs of transportation to the Earth range from $7,400 per kilogram with Starship to $190,000 per kilogram with a hypothetical lunar SSTO; thus, the total cost per kilogram is $11,400 to $194,000, or $11.40 to $194 per gram (Table 22).

Table 22. Costs of Collecting Rocks from the Moon

Item	Low Cost	High Cost
Cost of Mining equipment	$224 million	$224 million
Capacity	56,160 kilograms	56,160 kilograms
Cost of mined rock on lunar surface per kilogram	$4,000	$4,000
Cost of transportation to Earth per kilogram	$7,400	$190,000
Total cost per kilogram	**$11,400**	**$194,000**

Source: STPI estimates of capacity and cost of extraction from Chapter 4

d. Demand Assessment

The vast majority of samples taken from the lunar surface are in the possession of the governments of the United States and Russia. The United States collected around 381 kilograms of lunar samples over the course of the Apollo program (CBS News 2012). Small pieces from rock collected during Apollo 17 were given to 135 countries around the world and all 50 States as tokens of American goodwill; these rocks are referred to as the "Goodwill Moon Rocks;" each weighs about 1 gram (Lefkow 2019; Bosworth 2012). The rest of the Moon rocks from Apollo are Federal Government property. Individuals found in possession of these rocks can be prosecuted for theft of government property. Such cases are investigated by the NASA Office of the Inspector General (Pearlman 2011).

The only lunar samples to ever be legally sold were collected by the Soviet Union's Luna 16 mission. Three fragments of lunar rocks—weighing approximately 200 milligrams—were given to Nina Ivanovna Koroleva, the widow of Sergei Pavlovich Korolev (Smith 2018). These samples have been sold twice; once in 1993 for $442,500, and again in 2018 for $855,000, both times at Sotheby's to unlisted buyers (Smith 2018). Using the most recent price of $855,000 for 200 milligrams, the price for those lunar samples was $4,275,000 per gram, or $4,275,000,000 per kilogram. For comparison, a colorless, 1-carat diamond costs around $65,000 per gram (Oyedele 2014).

There is a black market for Moon rocks. In 1998, a man attempted to sell a Goodwill Moon Rock weighing 1.142 grams, originally given to Honduras, for $5 million (Bosworth 2012). In 2002, four NASA interns stole about 101 grams of lunar samples and a Martian meteorite (CBS News 2012). They attempted to sell these rocks for about $8,000 per gram before they were arrested (Cho 2002). During the ensuing Federal trial, however, the court estimated that the value of these rocks was about $50,800 per gram in 1973 dollars, based on the cost of retrieval (Ingraham 2018). In 2020 dollars, that would be around $224,000 per gram, or $224,000,000 per kilogram.

In contrast to diamonds, the Moon rocks collected to date are not extraordinarily beautiful or vastly different from each other. The history of the Apollo and Soviet rocks—as well as their rarity—drives their costs. Once companies have access to lunar rocks through commercial launches, the rarity value will dissipate. Over time, prices should fall to the cost of collection plus a normal profit because anyone willing to pay the costs of collecting rocks will be able to enter the market; the supply of lunar rocks is essentially infinite. In short, the market price should fall to the cost of procuring the rocks, or $11,400–$194,000 a kilogram, or $11.40 to $194 per gram, as computed in Table 22.

At these prices, what quantity would the market demand? A jewelry company called Once a Moon creates necklaces incorporating 5 to 10 milligrams of lunar meteorite into each necklace, or 7.5 milligrams on average, which it sells for $130 to $220 per necklace (data from interview and website). The company sources these pieces from a meteorite weighing 233 grams. Once a Moon was only started in 2018, but the owners see prospective demand of 10,000 to 15,000 pieces of jewelry per year; at the high end, this translates into demand for 0.1 kilograms a year. The company notes they could increase the price of their necklaces somewhat if the lunar material were mined on the Moon.

In our interview, Once a Moon provided the maximum price they are willing to pay for lunar rocks, which exceeds our high estimate of the costs per kilogram of procuring rock from the Moon; bringing lunar rock back for sale on Earth should be profitable. However, as noted above, the quantity demanded is very small: 0.1 kilogram a year. So, although the cost of acquisition is favorable, the quantity demanded is very low. Although other jewelers could also make novelty necklaces, even if jewelers sold 1 million necklaces a year, total demand for lunar rocks would be just 7.5 kilograms a year, assuming that the other jewelers would use similar amounts of lunar material (5 to 10 milligrams per piece of jewelry).

The market for lunar rocks for display may be more favorable for sales of larger quantities of rock. As described above, currently there is no "market" for rocks returned from the Moon. The availability and legality of procuring these rocks is so restricted that the few prices available on willingness to pay for these rocks are unlikely to be a guide for prices of rock brought back from the Moon for commercial sale. There is a market for meteorites from the Moon, however. According to the Meteoritical Society—an international organization dedicated to the promotion of research and education in planetary science with emphasis on the studies of meteorites and other extraterrestrial materials—of the 404 identified lunar meteorites, 364, weighing cumulatively around 350 kilograms, can be bought and sold (Meteoritical Society 2020). NWA 11798, the largest lunar meteorite sold to date at 5.5 kilograms, was sold for $612,500 in 2017 (Schlosser 2018). A private seller of meteorites, Aerolite, sells a variety of lunar meteorites at per gram prices between $100 and $400, or $100,000 to $400,000 per kilogram, or an average of $250,000 per kilogram (Lunar Meteorites n.d.). The market for such materials is space enthusiasts; high net-worth individuals, such as Steven Spielberg, Elon Musk, Nicolas Cage, and Yo-Yo Ma are noted meteorite collectors (Schlosser 2018).

At these prices, lunar rocks could be profitably brought back to Earth. However, not in the quantities that the excavator would yield. We assume that the current market consists of the 350 kilograms of lunar meteorites that can be bought and sold and that the market price is $250,000 a kilogram for a total market of $87,500,000. We assume this market has a price elasticity of demand of -1, meaning as the quantity available for sale shifts, prices adjust so that revenues remain constant. The addition of 56,160 kilograms—the capacity of the mining equipment described above—to the market would expand supply by 160 times. To sell this quantity of Moon rocks, prices would have to fall to $1,560 per kilogram, below the cost of transporting the rock from the Moon. In other words, it seems unlikely that market demand for lunar rocks would be such that 56,160 kilograms could be sold at a price that exceeds the cost of transporting them to Earth.

What might be the demand for lunar rocks from jewelers and collectors? As noted above, the current stock of rocks from lunar meteorites is 350 kilograms. If the price were to fall to $7,400 per kilogram, high enough to cover our low estimate of excavation and transportation costs, and the price elasticity of demand were -1, the quantity demanded would run 11,820 kilograms. Theoretically, a lunar mining company could sell 11,820 kilograms annually and still cover its costs, assuming collectors do not resell lunar rocks, once acquired. However, because lunar rocks are not consumed but kept by collectors, a rock that has been sold can return to the market. Assuming the potential for resale, we think it more realistic to assume gradual increases in the supply of Moon rocks over time so as not to collapse the price. If astronauts were to bring back 1,180 kilograms a year for 10 years, expanding the total stock to 11,800 kilograms, prices might stay high enough to exceed our $7,400 estimate of the costs of shipping back rocks from the Moon. However, if return costs from the Moon run $150,000 per kilogram, astronauts would only be able to bring back 29 kilograms per year for 10 years for a total of 580 kilograms over the decade to keep prices from dropping below the cost of transportation. Based on both these calculations, the annual market could be $8.75 million per year.

In short, a novelty market for lunar rocks already exists; customers have shown a willingness to pay at both the low end (necklaces costing $130 to $220) and at the high end ($612,500 for a 5.5-kilogram lunar asteroid). However, 56,160 kilograms of lunar rocks could not be sold every year at these prices. In our view, the market is more likely to be served by episodic deliveries of smaller quantities of lunar rocks collected by astronauts or lunar tourists rather than from dedicated deliveries from a mining operation targeted specifically at this market.

3. Lunar Mementos Manufactured on the Moon

a. Product

Like necklaces containing lunar material and lunar rocks, there will almost certainly be demand for artifacts manufactured on the Moon due to their novelty. Products could consist of plastic or metal artifacts manufactured using three-dimensional (3-D) printers from materials brought from Earth or made of regolith or metals smelted on the Moon.

b. Business

Equipment such as 3-D printers or smelters, and at least some materials (e.g., plastic) will need to be brought to the lunar surface to manufacture mementos. Because output will be limited as prices will need to be high to cover the cost of transportation, the most likely equipment would be small 3-D printers that would use plastic or metals to manufacture small items. Costs

A 3-D printer weighs as much as 39 kilograms (Fusion3 n.d.). The cost of transporting such a printer to the Moon could run $109,200 (39 kilograms times $2,800 per kilogram to carry it to the Moon on Starship). A kilogram of product would cost $10,200 per kilogram to transport material to the Moon and back: $2,800 per kilogram to transport raw material to the Moon and $7,400 per kilogram to return the finished product. If we assume that one printer could make just 1,000 necklaces, a 50 gram plastic lunar-made necklace, for example, would cost at least $619 to manufacture (50 grams times $10,200 per kilogram in transportation for $510 in transportation costs and $109 to cover the costs of the 3-D printer.) The price of such a necklace would probably run close to $1,000 to cover manufacturing and distribution costs, and retail mark-ups, which is affordable for many people.

c. Demand Assessment

As shown by the sales of the jeweler, Once a Moon, there is a market for these types of novelties. Assuming that a plastic lunar-made necklace was priced at $1,000, based on Once a Moon's owners view that prospective demand for jewelry containing bits of lunar rock could run 10,000 to 15,000 pieces per year, demand for 50-gram lunar mementos could run 625 kilograms a year. At lunar costs of $619 per piece, the total lunar market might run $6.2 to $9.3 million per year ($619 times 10,000 and 15,000 necklaces, respectively).

4. Lunar Memorials

a. Product

Two companies are marketing lunar space memorials, whereby a symbolic portion of cremated remains is launched into space or to the lunar surface. In 1992, the ashes of "Star Trek" creator Gene Roddenberry were sent into space aboard Space Shuttle Columbia (Wenz 2018). Since Roddenberry, the remains of almost 1,000 individuals have been launched into space (Celestis website n.d.). Most of the ashes have been either been sent into orbit or have touched space, only to be consumed in the atmosphere as the capsule falls back to Earth. Eugene M. Shoemaker's ashes became the first to be sent to the Moon in 1999 as part of the Lunar Prospector mission (Trosper 2014). NASA has also sent ashes of Clyde Tombaugh on the New Horizons mission to Pluto, which Tombaugh discovered in 1930 (Leary 2006).

Lunar space memorials are one niche within the growing market for non-traditional means of burial (Beard and Burger 2017). Examples among the current market offerings are turning cremated remains into an environmentally safe cement structure to create artificial reef formations; manufacturing diamonds from the ashes of the deceased; putting ashes inside of shotgun shells or bullets, or even into fireworks. The rise in cremations has contributed to this phenomenon, allowing for these non-traditional memorials. In 2018, in the United States 53 percent of the deceased were cremated (CANA 2019).

b. Business

In anticipation of upcoming lunar missions, space burial companies have begun to advertise lunar memorial flights. These providers intend to launch symbolic portions of cremated remains to the lunar surface. They also offer options to launch inert DNA samples or "memory sticks" containing songs, photos, or messages. Currently, two such companies exist with plans to launch lunar memorials using CLPS providers: Celestis and Elysium Space (Celestis n.d.; Elysium n.d.).

For lunar memorials, a small portion of cremated remains is placed into a capsule that once full weighs approximately 3.5 grams. A DNA substrate weighs about the same, so the individual memorials could be either DNA samples or cremated remains. These capsules are collected and placed into a lunar lander. Unlike other payloads that may be deployed directly onto the lunar surface, the capsules will remain inside the lander indefinitely. The capsules can be transported on any rocket; the cremated remains do not require power, heating, cooling, or radiation protection.

c. Costs

The companies providing lunar memorial services will pay launch costs as well as other expenses. One company has listed a price of $1,200,000 per kilogram to the lunar surface (Astrobotic 2019). If transportation costs to the lunar surface fall, this per kilogram cost would as well.

d. Demand Assessment

The two current providers charge $11,950 and $12,500 per capsule, for an average price per lunar memorial of $12,225 (interviews). This compares with an average funeral cost for traditional, terrestrial services of about $11,000 (Miller 2016). The current annual demand is about 142 individual memorials a year, which at a capsule weight of 3.5 grams per person implies 0.5 kilograms per year. At an average price of $12,225 per capsule, the current market is $1,735,950 annually. Subtracting launch costs of $1,200,000 per kilogram or $600,000 for half a kilogram, yields a gross profit of $1,135,950 before deducting labor and marketing costs and other expenses, so this should be profitable market.

Interviewees indicated that the demand for these memorials could grow to about 285 individual memorials annually, or roughly 1 kilogram annually over the next 10 years, doubling the size of the market. Current demand has run about 60 percent from the United States, 25 percent from Asia, and the remaining 15 percent from other regions of the world. At one kilogram of ashes launched per year, lunar revenues from this activity would be the cost of launching and landing a kilogram or two of ashes on the Moon. We assume that the market could eventually exceed 500 sets of remains a year, which would amount to 1.8 kilograms. As noted in Chapter 4, Astrobotic charges $1.2 million per kilogram to land a payload on the Moon. If the funeral industry sends two kilograms of ashes a year to the Moon, total lunar revenues from this activity would be $2.4 million dollars. If charges were just $7,400 per kilogram, our lower estimate, the lunar revenues from this activity would be just $14,800 per year.

The market could become much larger. According to Beard and Burger (2017), as Baby Boomers face the impending end of their lives, the funeral industry is finding that demand for customized services is increasing. However, even if all 2.8 million people who die each year in the United States (CDC 2020) decided to send 3.5 grams of their ashes to the Moon, the total demand for launch services would be 9,487 kilograms or 9.5 metric tons, less than 10 percent of the capacity of one Starship launch. In short, although profitable, this economic activity would not add substantially to demand for heavy launches.

B. Demand from Businesses

1. Advertising

a. Product

Missions to the Moon provide opportunities for companies to advertise their products or, more broadly, to create a stronger brand image by sponsoring the mission, activity, or companies involved. Corporate sponsorships differ from classic advertisements in that they involve longer-term engagements under which the company wishes to seek a brand association with its partner.

b. Business

Companies could contribute—either financially or through in-kind technology development—to a lunar transportation company or lunar mission. Such a sponsorship or partnership could involve placing the company's logo onto the launch vehicle or lunar lander, or using the lunar company's name in advertisements and marketing. Because of their visibility, rockets, lunar landers, and habitats are likely to be the primary locations for sponsorships. Companies interested in branding themselves as innovative or technologically driven would likely find sponsoring lunar missions to be particularly beneficial (Saatchi & Saatchi 2016). Companies might wish to position themselves as the official provider of a product for lunar missions. For instance, vehicle manufacturers may wish to be a sponsor of the lunar rover. The company would probably provide technical assistance as well as funds.

c. Costs

A 4-year agreement to be a global partner for the Olympics is believed to cost around $200 million, spanning one Summer Olympics and one Winter Olympics (Broudway 2017). In terms of visibility, the Olympics represents the height of corporate sponsorship. Other events, such as golf tournaments, may represent more realistic analogies to lunar sponsorships. Sponsorships of golf tournaments cost between $8 million and $13 million; marketing partnerships cost $1 million to $40 million (Saatchi & Saatchi 2016). Major events such as the Professional Golf Association tournament, the Olympics, and the Super Bowl generally have at least 10 sponsors. One author estimates that the naming rights to put one's name on a lander, habitat, or other lunar system could bring in $2.5 million per year for a lander and $5 million for a rover (Anderson 2013).

d. Demand Assessment

While most existing lunar transportation companies do not have a corporate sponsor, some have; these companies have attracted anywhere between one and seven sponsors.

Astrobotic has two sponsors, DHL and Caterpillar, who have contributed undisclosed amounts. Astrobotic has also developed a corporate partnership with Airbus Defence and Space (Astrobotic 2019a; Astrobotic n.d.). Germany's Planetary Transportation System (PTS) has two corporate partners—Audi and Vodafone—as well as a media partner, Red Bull Media House (PTS n.d.; PTS 2018). Japan's ispace has seven corporate partnerships; however, these companies tend to be investors, although they do benefit from being associated with ispace (interview). Each of these companies has been able to leverage corporate sponsorships or partnerships to increase funding, and in some cases, technical expertise. The corporate sponsors and partners have been able to use these relationships for advertisements and increasing brand visibility. In at least one instance, a company is using this partnership to investigate a potential market (interview). National pride is a significant driver for sponsorships. The vast majority of sponsorships and partnerships remain within their respective country with a few exceptions.

To estimate potential revenues from sponsorships for lunar transportation providers, we assume that initial sponsors would pay about $1 million at most, based on the estimated amounts of advertising revenue generated per sponsor by existing lunar transportation companies (interview). At the high end, if we assume that all 22 lunar lander companies discussed in Chapter 3 attract a single corporate partnership, the expected revenue would be $22 million ($1 million times 22). At the low end, we estimate that only a few, perhaps five companies, successfully attract sponsors willing to pay $1 million per year, for a total of $5 million per year.

It is unclear how sustainable this market will be. Some interviewees suggested that as the cadence of lunar missions increases, companies could become less interested in sponsoring lunar activities, and these sponsorships may decrease, not only in number but also in amount of money spent.

2. Virtual Reality

a. Product

Virtual reality (VR) generates a computer-simulated, fully immersive environment that allows the user to interact with 3-D worlds, generally using either virtual reality headsets or multi-projection environments. VR is distinct from augmented reality (AR), which uses sensors and various algorithms to simulate computer-generated objects in real environments. While the number of people who can visit the Moon is limited, many people might be interested in experiencing a virtual trip to the Moon. One of the many companies involved in VR for households—such as Sony, HTC, Nintendo—could collaborate with a commercial lunar company to develop VR programs for people to virtually explore the lunar surface, visit Apollo heritage sites, and view Earth and other nearby celestial bodies.

b. Business

In order to create such a VR program, either a laser scanner or 360-degree video camera would be placed at a location on the Moon. The laser scanner could capture a twenty-foot radius (interview data). Alternately, a 360-degree video camera could be mounted on a rover, which could take footage over a larger area for the end-user to "explore." Both the laser scanner and a 360 video camera will likely weigh about 5 kilograms each (interview).

c. Cost

The weight of the laser scanner and camera are each 5 kilograms, and each would be operated robotically. If the equipment were launched by Astrobotics, at $1.2 million per kilogram, costs would be $12 million for transportation costs (5 kilograms for the laser scanner and 5 kilograms for the camera for 10 kilograms times $1.2 million per kilogram). If a 360-degree camera is used, it would need to be mounted on a rover, which would cost an additional $6 million, if it could be rented from a lunar habitat for a total cost of $12 million. If the scanner or camera could be transported by Starship, per kilogram transport costs would be much lower, as low as $2,800 per kilogram by our estimation, but arrangements would need to be made to offload the scanner or camera and set them up. We did not have a basis for estimating these additional costs.

d. Demand Assessment

Using computer-generated imagery (CGI) to simulate the lunar environment might cost about $300,000 due to the expensive nature of high-end animation (expert interview). If a lunar environment filmed on the Moon cost $6 million or more just for transporting equipment to the Moon, a user would likely choose CGI based on cost alone. VR game sales often run in the single million dollars (interview data). If the VR company had to pay $6 million or more for the lunar environment, it would probably not be able to recoup costs. Therefore, we find this application uneconomic. However, an interviewee noted that while developing such a program would not be economically viable, it would likely garner enough attention from the public and press that a company may be motivated to do so for advertising reasons.

3. Mining Precious Metals for Sale on Earth

a. Product

Lunar rocks contain many metals in demand on Earth, which could potentially be processed on the Moon and transported to Earth for sale. Candidate lunar metals and elements that could be mined, refined, and sold on Earth include precious metals, rare Earth elements, and common metals, like iron and aluminum. The platinum group metals are a set of six elements that have similar physical and chemical properties: ruthenium (Ru), rhodium (Rh), palladium (Pd), osmium (Os), iridium (Ir), and platinum (Pt). Their most notable characteristics are their ability to serve as a catalyst for chemical reactions, resist chemical corrosion, and provide stable electrical properties when used in electronics. The automotive industry is the principal consumer of PGMs, using them in catalytic converters to reduce exhaust emissions.

To identify which of these metals might have realistic prospects for sale on Earth, we filter out those whose prices are less than our estimated *lower bound* costs of transporting them to Earth, $7,400 per kilogram. Those metals or elements whose terrestrial prices are higher than the cost of transport are the only ones that might be mined.

As shown in Table 23, only PGMs and gold are sufficiently valuable to investigate whether they could be extracted on the Moon and sold on Earth. Rare Earth elements and common metals, such as iron and aluminum, are too cheap to make it feasible to mine and refine them on the Moon and transport them to Earth. Prices for most of the rare Earth elements are less than $60 a kilogram; prices for common metals are less than $3 a kilogram, so they are not good candidates to bring back to Earth (See Table G-1 in Appendix G.).

Table 23. Prices and Concentrations of Platinum Group Metals

Element	Price per kilogram on Earth today
Gold	$39,417
Ruthenium	$8,681
Rhodium	$77,966
Palladium	$35,945
Osmium	$32,151
Iridium	$47,583
Platinum	$27,907

Source: STPI Calculations, See Table G-1.

b. Business

As described in Chapter 4, PGMs could be mined on the Moon using a host of small robots, excavators, and haulers, to excavate lunar material and haul it to a central processing plant. The ore would then be refined and the metal would be transported to the Earth.

Mining companies create mines at locations where ore concentrations are high and extraction costs relatively low. As noted in Appendix F, m-type asteroid impact craters are likely to have higher concentrations of PGMs than lunar regolith. Concentrations are still small; however, platinum, the most plentiful of the PGMs, has been measured at 11.3 parts per million from meteorites from asteroids (Appendix Table G-1). This implies that even on an asteroid with higher concentrations of PGMs, 88,500 kilograms of ore would need to be extracted to produce 1 kilogram of platinum.

c. Costs

In chapter 4, we estimated the costs of the rovers needed to excavate and haul enough raw lunar material to produce 1 to 100 metric tons of PGMs. The costs of these rovers alone would contribute over $100,000 per kilogram to the cost of PGMs on the lunar surface. The $100,000 per kilogram cost does not include the cost of refining the raw lunar material into PGMs and transportation costs to return them to terrestrial markets from the lunar surface. Thus, this is a lower bound on the cost per kilogram of returning lunar PGMs to Earth.

d. Demand Assessment

The most valuable PGM in terrestrial markets is Rhodium (Table 23) at $78,000 per kilogram. This price is below the lower bound we have estimated for the cost of lunar PGMs ($100,000 per kilogram). Thus, this activity is not economically viable.

4. Mining Helium (He-3) for Sale on Earth

a. Product

Helium-3 (He-3) is a rare isotope of Helium, generated almost exclusively from the decay of tritium from U.S. and Russian stockpiles of nuclear warheads. In the United States, it is primarily used in neutron detectors (27 percent of consumption); neutron scattering experiments by the Department of Energy—Science (20 percent); and medical imaging (8 percent) (Kouzes 2009). He-3 has also been proposed as a potential fuel for hypothetical aneutronic fusion electric power generators (Wittenberg 1986).

Because the Moon does not have an atmosphere or magnetic field, solar winds deposit He-3 on the Moon's surface (Brodt 2015). As a consequence of these deposits by solar wind, researchers from the University of Wisconsin determined from Apollo samples that concentrations of He-3 are much higher on the Moon (10–20 parts per billion) than on the Earth (7.2 parts per trillion). Because of these higher concentrations, some U.S. experts have advocated mining lunar He-3 on the Moon (Schmitt 1986), as have advocates in Russia, China, and India.

b. Business

Mining lunar He-3 would require transporting mining equipment to the lunar surface, excavating regolith, separating out the He-3, and transporting it back to Earth. The University of Wisconsin Fusion Technology Institute has drawn up a series of designs for mining equipment for lunar He-3 (Gajda 2006). Its latest design consists of equipment for excavation, filtering, cooling, and storage. The miner would excavate the ore; it would travel in concentric circles—moving spirally outward from a starting point. A bucket-wheel would first scoop regolith onto an internal conveyor belt, which would be passed through filters and then into a solar-powered heating chamber, where the gases would be extracted. The gases would be transferred to a pressurized container, where they would be cooled to very cold temperatures so as to separate out the He-3, which would then be transported back to Earth, probably once a year.

As per the researchers at University of Wisconsin, the equipment would be designed to excavate one square kilometer at a depth of three meters per year, or 4.96 million tons of lunar regolith per year. The equipment would extract 74 kilograms per year, assuming an average He-3 concentration of 15 parts per billion, equivalent to 560,000 liters of He-3 per year.

c. Costs

In 2006, Schmitt and Kulcinski estimated that "development of … lunar mining, processing, and refining capability and supporting facilities … would consume about $2.5 billion of investment capital over about five years" (Schmitt 2006). The equipment would be large, 352 cubic meters, and weighs 10 metric tons, which would necessitate a heavy lift launcher. It is unclear how the 560,000 liters—a substantial volume, even if not very massive—would be brought back to Earth.

d. Demand Assessment

The U.S. Government stockpiles He-3, collecting it from the decay of tritium in nuclear weapons (Slocum 2016). The U.S. He-3 stockpile is owned and operated by the Department of Energy. In recent years, it has been replenished by about 8,000 liters of He-3 per year. The supply is shared with other government offices through an interagency exchange.

The U.S. Government has publicly auctioned surplus He-3 to private sector companies. In 2008, it sold 70,000 liters at an auction price of $100 per liter for a total market size of $7 million (Slocum 2016). The U.S. Government experienced a shortage of He-3 in 2010. At that time, many U.S. agencies were instructed to switch to alternative technologies when available, such as boron-triflouride proportional counters (BF3), an electrical device that detects various types of ionizing radiation. In the last He-3 auction, held in 2014, the U.S. Government sold 4,000 liters at a price of $2,750 per liter. U.S. annual consumption of He-3 is currently estimated at 6,000 liters per year (Slocum 2016). At a price of $2,750 per liter, the current market is worth $16.5 million per year.

As noted above, some engineers have argued that He-3 could be used as a fuel in aneutronic fusion reactors that would generate electricity (Wittenberg 1986). In our analysis, we do not consider additional demand for He-3 from this source. Commercial nuclear fusion generators, aneutronic or based on other technologies, do not currently exist, and will not be available for decades, if ever (Close 2007). We do not believe that a fleet of commercial aneutronic nuclear fusion generators could be designed, constructed, and in operation by 2030—our cutoff date for the technologies—and be competitive with natural gas, solar, wind generators, or fission reactors. We note that grid power from fusion reactors based on the currently favored design, the Tokomak, is not expected to become available until the second half of the 2100s (Behr 2020).

Consequently, at current prices, we do not foresee additional likely demand for Helium-3 in the coming two decades. If prices were to fall back to $100 a liter, however, the quantity demanded could rise back towards the 2008 peak of 70,000 liters per year, displacing substitute technologies that were adopted when He-3 prices rose.

As noted above, a single miner could produce 560,000 liters a year. When supply was 70,000 liters per year, the auction price of He-3 was $100 per liter. Given that output would be eight times more than the previous peak in demand, it is difficult to imagine that lunar He-3 could be sold for more than $100 a liter. In other words, maximum annual revenues would be on the order of $56 million per year. Using Schmitt's and Kulcinski's estimate of a capital cost of $2.5 billion, projected revenues imply a payback period of 44 years, without even considering transportation or operating costs. In this analysis, we consider 10 years a minimum payback period for an investment. Thus, we conclude this technology, even if were technically feasible, would not be economically viable in the timeframe of interest (2030–2040).

5. Lunar-based Solar Power Beamed to Earth

a. Product

With rising concerns about climate change to which emissions of greenhouse gases from fossil fuel-fired power plants contribute, utilities and companies are increasingly turning to "clean" energy, sources of electricity that do not emit carbon dioxide. On Earth, the primary sources of "clean" energy are renewables, which include hydroelectricity, photovoltaic solar, thermal solar, wind, geothermal, and nuclear. To provide "clean" energy, some people have proposed setting up very large arrays of solar panels (greater than a kilometer in diameter) in space and beaming energy down to Earth (Feingold 1997; Sebold 2004; Mankins 2012). One variant of this approach would be to site solar panels on the Moon or in cislunar space and beam energy from these panels to Earth. The potential advantage of placing the solar panels outside of Earth's orbit would be to reduce the possibility of increased space debris resulting from collisions between the very large arrays and other space objects.

b. Business

Mankins (2012) has written one of the more recent proposals for generating electricity and then transmitting it to Earth. Earlier technologies employed rigid solar panels. Mankins (2012) lays out a technology located in geostationary Earth orbit that uses a large array of individually pointed thin-film mirrors that concentrate sunlight onto photovoltaic cells for conversion into electricity and then into a coherent microwave beam. The beam is then transmitted to a receptor on Earth. Mankins argues that the system would provide nearly continuous power, while terrestrial solar power generation is limited to periods of daylight with a relatively cloud-free sky.

Mankins notes that the system could also be stationed in Earth-Moon Libration points, lunar orbit, or Sun-Earth Libration points (Mankins 2012). Such a system would need an apparatus in Earth orbit that could relay the power to the Earth's surface. Another option would be to manufacture solar panels from lunar material and place them on the lunar surface, saving the costs of launch for systems either orbiting the Earth or located in cislunar space.

c. Costs

In 2012, Mankins estimated that the levelized cost of electricity for a pilot plant (18 megawatts) would be $3.26 a kilowatt-hour, or $3.60 in 2018 dollars. The levelized cost for a first apparatus of 500 megawatts would be $0.15 a kilowatt-hour, or $0.17 in 2018 dollars. Under his Aggressive Technology Advances Scenario, the levelized cost would be $0.09, or $0.10 in 2018 dollars for a system of 2,000 megawatts (Mankins 2012).

Assuming that all the components of the system would need to be built and launched from Earth, a system located in cislunar space would face the additional costs of launch to get to that point. Mankins estimates that the mass of the 500-megawatt system would run 11,795 metric tons (Mankins 2012). Based on estimates of the cost per kilogram to lunar orbit, the additional costs of locating the system near the Moon as opposed to geostationary orbit would be substantial.

d. Demand Assessment

Solar-powered electricity produced in geostationary orbit would not be competitive with other sources of renewable energy; thus, a system in cislunar space designed to provide electricity to Earth would be even less so. Under the most optimistic assumptions, at $0.10 a kilowatt-hour in 2018 dollars, space-based solar power systems produce energy that is more than twice as expensive as terrestrial solar ($0.0488 per kilowatt-hour) or wind ($0.0428 a kilowatt-hour) (EIA 2019). Arguments that space-based solar does not have to contend with the same intermittency issues as terrestrial renewables are weak because utilities have already solved many of the intermittency issues related to these technologies through demand management, drawing on geographically disbursed sources of supply, and other technologies. Costs of battery backup are falling rapidly. Further, terrestrial nuclear power does not suffer from intermittency issues; expected levelized costs of energy for nuclear power plants that could enter service in 2025–2040 are estimated in the range of $0.06–$0.08 per kilowatt-hour (EIA 2019).

Some proponents of space-based solar power have argued that it could be used to provide electricity to remote locations, such as mines. Remotely located mines are already shifting to terrestrial solar power. For example, BHP, which operates the Escondida copper mine in Chile—the largest in the world—is installing terrestrial solar; so is Anglo American at its mine in Chile (Lewis 2019). As the launch costs and additional apparatus needed to generate electricity in cislunar space and transmit it to Earth would be higher than from geostationary orbit, we find that cislunar space-based solar power production is uneconomic and would not be adopted. We did not estimate costs associated with generation of solar power in cislunar orbit for use on the Moon itself.

We did not analyze the economics of manufacturing solar panels on the Moon and positioning them on the lunar surface or launching them into cislunar space. We assess that the technology for manufacturing large-scale solar panels on the moon is unlikely to mature and enter commercial operation for use in our timeframe of interest (2030–2040). The technology to mine and process metals from the lunar regolith or asteroid craters is currently nascent, even at low production volumes. Even if the raw materials necessary for solar cells can be sourced from lunar material at scale, few companies exist that have the expertise to manufacture solar panels that can survive and operate in a space environment. While some challenges of solar panel production may be alleviated in a lunar environment due to reduced gravity or enhanced vacuum, other challenges remain, such as radiation hardening, and unforeseen challenges await.

6. Manufacturing in the Lunar Vacuum

a. Product

Some companies in our database propose to use the lunar vacuum to manufacture products. This is a form of vacuum engineering, which is the process of using a vacuum to produce a good or service. The pressure of a vacuum may be measured in units of Torr; one Torr is equal to roughly 100 Pascal or 1 millibar. A vacuum level is classified as being High Vacuum (HV) if it is less than 10^{-3} Torr, Ultra-High Vacuum (UHV) if it is less than 10^{-7} Torr, and Extremely High Vacuum (XHV) if it is less than 10^{-12} Torr. Each of these vacuum levels corresponds to distinct use cases. The vacuum on the lunar surface ranges from 10^{-10} Torr during the day to 10^{-12} Torr at night (Landis 1990), making it a UHV.

The most commercially relevant class of products produced in UHV environments are thin film materials. Thin films can be used to produce advanced solar cells, semiconductor electronics, coatings for high-power laser optics, batteries, fuels cells, etc. (Oviroh et al. 2019). These products may be delivered to users in space (e.g., thin film solar arrays) or to users on Earth (e.g., optics for high power lasers).

b. Business

One company hopes to use a small rover to scoop up raw lunar regolith, roughly process it to retrieve some semiconducting material, and then use thin film deposition to have the rover deposit arbitrarily long thin film solar cells directly onto the lunar surface (Ignatiev 2012). The solar cells would be of substantially lower efficiency than typical solar cells used for space applications; however, this may be acceptable if the small rover can deposit enough solar cells to meet the overall energy needs of a lunar base. This application is effectively a space-based solar power scenario and, as mentioned in the previous discussion on lunar power for transmission back to Earth, we did not estimate the cost or demand associated with providing power to lunar customers. Similarly, we do not analyze this scenario further. We restrict our analysis to looking at demand from terrestrial sources for products manufactured in a lunar vacuum.

c. Costs

It is not necessary to estimate the costs of producing products in the lunar vacuum to demonstrate that it is unlikely to be an economically viable venture for serving terrestrial customers. Instead, we qualitatively analyze the potential benefits of using the lunar vacuum and demonstrate that the same or better benefits can be achieved more cheaply in Earth orbit. As the same benefits are cheaper in Earth orbit than on the Moon, there is no reason to use the lunar vacuum to produce goods for sale on Earth.

There are two main benefits to using the vacuum of space for manufacturing compared to using a terrestrial vacuum. The first benefit is that space allows for an effectively unlimited chamber volume. By contrast, the volume of terrestrial vacuum chambers tends to decrease as the vacuum becomes more pure; large volume vacuum chambers may reach around 10^{-8} Torr, while the best vacuum chambers reach 10^{-10} Torr in a 1 cubic meter chamber. This inverse relationship between chamber volume and vacuum purity is due to the technical difficulties of pulling a hard vacuum. Smaller chamber volumes restrict the potential activities that can take place in the UHV.

While the vacuum on the lunar surface allows for a 10^{-10} Torr vacuum of unlimited chamber volume, the same effect can be achieved in LEO. While the vacuum in LEO is generally no better than 10^{-8} Torr, the Wake Shield Facility (WSF) experiment dragged a large metal disk behind the space shuttle, creating a 10^{-10} Torr vacuum in its wake. Further, the WSF demonstrated the use of molecular beam epitaxy in the wake to produce various thin film materials, proving the technological viability of thin film production in free space.

The second benefit of using the vacuum of space is that higher purity vacuum levels are possible than can be readily achieved on Earth. Similar to our argument above, the WSF experiment suggests that vacuum levels of 10^{-14} Torr are possible in LEO. Alternatively, the natural vacuum levels of medium Earth orbit and GEO are 10^{-12} Torr and 10^{-14} Torr, respectively.

d. Demand Assessment

The costs of mining and processing lunar materials to manufacture products on the lunar surface would be greater than simply launching the raw materials from Earth to a manufacturing facility in orbit around Earth. Similarly, the cost to return the final products to Earth would be greater for a lunar manufacturing plant than for a facility in Earth orbit. These costs would be passed on to the prospective customers of the products. The potential benefits of using the lunar vacuum can be achieved using the vacuum of near-Earth space. For these reasons, we do not view vacuum manufacturing on the Moon as a viable alternative to processing materials in a vacuum in Earth orbit or in terrestrial vacuum chambers. We do not analyze the economic viability of vacuum manufacturing in Earth orbit.

7. Hazardous Waste Disposal

a. Product

A number of facilities, including hospitals, civilian nuclear power plants, and chemical plants generate hazardous wastes. These wastes pose biological, radiological, and chemical threats to humans and the environment. Waste management firms have specialized processes for disposing of these wastes, but disposal is often expensive. In some cases, such as spent nuclear fuel, permanent solutions for disposal have yet to be developed. In light of the technological difficulties and costs of disposing of some of these wastes, some analysts have suggested using the Moon as a place to dispose of hazardous wastes (Koelle and Stephenson 2001).

b. Business

Depositing hazardous waste on the Moon would involve placing the waste into canisters, loading it into a rocket fairing, and then landing it on the Moon, presumably with a lander so as to prevent the containers from bursting apart. Presumably, just one or a very few clearly demarcated sites would be chosen for the waste, as the waste would prevent other uses of the lunar surface at those sites.

c. Costs

As noted above, we estimate that the cost of soft landing a kilogram of any material on the surface of the Moon at $2,800 per kilogram. Although the waste would need to be packed into very strong canisters to prevent its spread in the event of a launch failure on Earth, we assume that the costs of packaging and integration would fall within our estimate of the cost of softly landing these canisters on the Moon.

d. Demand Assessment

For chemical and biological wastes, disposal technologies have been developed to safely recycle or destroy the offending materials. For these materials, the question of whether to dispose of them by putting them on the Moon or disposing them on the Earth boils down to one of cost, not safety or other concerns.

We searched for standardized estimates of the costs of disposing of chemical, medical, and other biological hazardous wastes. For chemical wastes, we used the highest cost item for disposal, mercury thermometers, listed from a hazardous waste disposal organization at $6.15 a pound or $13.56 per kilogram (CSWD 2020). Pierce (2008) cites a cost of $600 per ton to incinerate medical waste, or $0.66 per kilogram in 2008. Inflating that cost to 2018 prices yields a cost of $0.77 per kilogram. At launch costs of $2,800 a kilogram, a lunar hazardous waste repository would not be competitive.

Sweden is building an underground repository for radioactive spent nuclear fuel at an estimated cost of 147 billion Swedish krona or $16.3 billion (SKB 2020). The repository is designed to hold 12,000 tons of spent nuclear fuel (Karagiannopoulos 2018), which implies a cost of $1,357 per kilogram. This cost is about half of our estimate of $2,800 to launch a kilogram to the Moon.

In the United States, nuclear waste is currently stored at nuclear power plants. At an operating nuclear power plant, cost of storage is estimated at $300,000 per year for the whole plant. For a closed plant, the cost of storage is estimated at $8,000,000 per year. We estimate that on average, the nuclear waste stored at a power plant is 1,067 metric tons.[8] Dividing these annual costs by 1,067 yields storage costs of $0.28 per kilogram per year at operating plants and $7.50 at closed facilities. Taking the net present value of a stream of payments for both costs over 100 years at a 7 percent discount rate (OMB n.d.) yields storage costs per kilogram of $4.29 and $114.51, respectively. Launch costs to the Moon of $2,800 per kilogram are uneconomic compared to current storage costs.

In addition to these cost hurdles, Article IX of the Outer Space Treaty can be viewed as potentially prohibiting State Parties from launching contaminants like chemical,

[8] There are 75 nuclear power plant sites in the United States and the total volume of spent nuclear fuel in the United States is estimated at 80,000 metric tons (LA Times 2019). This yields an average of 1,067 metric tons per site.

biological and nuclear waste into space (UNOOSA Article IX 1967). The treaty does not say anything regarding private entities contaminating the Moon, especially if private entities can demonstrate that they are burying waste and not causing "harmful contamination." However, Article VI of the Treaty requires all private entities to have continual supervision and authorization in space, so State Parties may get involved.

To use the Moon as a site for hazardous waste disposal may be highly controversial, and face global opposition and diplomatic challenges, not the least of which would be from Articles of the Outer Space Treaty.

While the United States Government has no on-orbit authority and therefore cannot explicitly prohibit waste disposal on the Moon, the Federal Aviation Administration (FAA) regulates commercial launch and reentry activities and the operation of launch and reentry sites as carried out by U.S. citizens or within the United States. It is responsible for conducting public safety payload review, if that payload safety concern is not the responsibility of any other government agency. Therefore, companies offering to dispose of hazardous wastes on the Moon would also likely have to receive permission from the FAA for launch. If the results of the payload review do not satisfy FAA's regulations, that launch would be unlikely to be granted a license to launch (correspondence with FAA).

8. Superconducting Supercomputing on the Moon

a. Product

Some individuals have proposed placing supercomputers or servers in space or on the Moon so as to manage the expected vast streams of data from deep space, and to exploit the lower temperatures of those locations for this equipment (STPI interview with expert; Rath 2012; Ouliang 2012; Cozmuta 2014). Operators have found that supercomputers designed to be cooled to 4 degrees Kelvin (K), where materials begin to superconduct, perform much better than supercomputers designed to operate at ambient temperatures. Superconducting supercomputers require substantial amounts of power for cooling, however—about 2 megawatts for exascale computing (expert interview).

b. Business

If a supercomputer were to be placed in a permanently shadowed crater on the Moon, it would have to be cooled from 40 degrees K (-233 Celsius), the temperature of the Moon in shade (Paige et al. 2010) via (Crawford 2015), to 4 K, requiring significantly less cooling than it would on the Earth. Servers also need to be cooled to operate efficiently. Placing them in a cold environment could also result in substantial savings in cooling costs. A supercomputer placed on the Moon would require about 0.5 megawatts to be cooled from

40 K (the temperature of LEO in shade) to 4 K rather than the 2 megawatts it does on Earth, for a net savings of 1.5 MW in generating capacity.[9]

c. Costs

In Chapter 4, we estimated that the cost for a solar-powered generator on the Moon would range from $20–40 per kilowatt-hour. In addition, the servers and supercomputers would need to be transported to the Moon at an estimated cost of at least $2,800 per kilogram, assuming the lower cost alternative. Additional costs would include site preparation and installation on the Moon, costs that we have not even attempted to estimate. The equipment would also require maintenance, which would pose substantial design and logistical problems. Time lags in terms of transmitting data would also pose a challenge.

d. Demand Assessment

Theoretically, supercomputers and servers located on the Moon would require one-fourth the electricity to cool the equipment to 4 degrees K than is needed on Earth (Crane et al. 2018). However, the cost of electricity on the Moon is $20–40 dollars per kilowatt-hour; in the United States the average retail price of electricity is $0.12 a kilowatt-hour. Because the lower lunar price is nearly 200 times more than the terrestrial price, even with savings in electricity of 75 percent, it would cost substantially more to operate a supercooled supercomputer or server on the Moon than on Earth. We therefore did not find this proposed activity economically viable.

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[9] This estimate assumes about 5 kilowatts (kW) dissipated at 4 K and a refrigerator operating at ~10 percent of Carnot efficiency to cool the system from 40 K to 4 K, because temperatures in space are not cold enough for superconducting. Additional power would be needed to transfer data between space and Earth (interviewee).

7. Summary

In this report, we examined the demand drivers of lunar and cislunar activities through 2040, with a focus on non-NASA commercial demand. In particular, we assessed the commercial feasibility of a number of lunar goods and services that have been proposed for sale to households and business, and projected potential demand and estimated potential revenues for the activities that appear commercially feasible. Table 24 summarizes our findings.

For government demand, we found that the budget available for government-funded human lunar missions could be about $63 billion over 17 years, from 2024–2040. This figure is the sum total of funds available to the private sector to support the lunar human exploration activities of NASA and partner governments. In light of our estimated cost of a human mission to the Moon ($2.6 billion at the low end, and $4.9 billion at the high end), under this budget cap, it would be feasible to launch at least one mission a year to the Moon under the low cost scenario, but no more than seven missions over a decade under the high cost scenario. Given the cost of one small science mission is about the same as our assumptions concerning the funds available for lunar science missions (about $240 million annually), it should be feasible to launch one lunar science mission annually.

For households, we found that only markets for lunar tourism, lunar rocks, burials on the Moon, and lunar artifacts exist or are likely to exist. For businesses, other than advertising, there was no good or service that was economically viable in the timeframe of interest. All other activities are not economical, for one or more of four reasons: the underlying technology is underdeveloped (e.g., He-3 mining); there are no likely buyers in the 2040 timeframe (e.g., precious metals for sale on Earth); the cost of providing the services exceeds revenues obtained from selling it (e.g., space solar power); or the product is cheaper to produce terrestrially than to produce on the Moon (e.g., hazardous water).

Table 24. Private Lunar Markets

	Product/Service	Cost	Demand (Annual)	Revenue (Annual)	Economic Viability
Household Demand	***Lunar tourism* - Flyby**				
	Using SLS/Orion	$1.2B	0	0	No
	Using Starship	$35M/customer	20+ customers	$700M	Yes
	***Lunar tourism* – Landing on Moon**				
	Using SLS/Orion (includes lander, rover and habitat)	$1.2B/Customer (assuming 2 customers per year)	0	0	No
	Using Starship (includes lander, rover and habitat)	$75M/customer	20 customers (assumes customers will pay up to 10% of their net worth for trip)	$1.5B	Yes
	Lunar Trinkets				
	Jewelry with Lunar Dust	$11,400-$194,000 per kilogram	0.1-7.5 kg per year	$21,500-1.6M	Yes, episodically
	Lunar rocks for sale	$7,400/kg	1,180 kg	$8.75M	Yes, episodically
	Artifacts manufactured on Moon	$619/artifact	625 kg	$6.2-9.3M	Yes
	Burials on the Moon	$1.2M/kg	2-9,487 kg	$14,800-$2.4M (assuming higher end is unrealistic)	Yes

	Product/Service	Cost	Demand (Annual)	Revenue (Annual)	Economic Viability
Business Demand	***Advertising***	$1M	5-22 company sponsors	$5-22M	Yes
	Virtual reality	$6M just to transport equipment	$300,000 for terrestrial equipment 0	N/A	No
	Platinum group metals for sale on Earth	Greater than $100,000/kg to excavate the material	0 Excavation costs exceed prices of most expensive metals	N/A	No, as primary revenue stream. Unclear, as secondary revenue stream.
	In-situ production of volatiles				
	Water for surface operations	Greater than $5,000/kg to produce 25 MT/year	Unknown, likely much less 25 MT/year	N/A	Unclear. Did not model low-volume production costs.

Product/Service	Cost	Demand (Annual)	Revenue (Annual)	Economic Viability
LOX:LH2 propellant for cislunar customers	$9,000/kg (high cost, low volume) - $1,000/kg (low cost, high volume); Costs are for on the lunar surface; cost per kilogram of propellant delivered to cislunar space would be higher	< 500 MT of propellant needed in cislunar space Propellant from the lunar surface is more expensive in cislunar space than propellant delivered from Earth	N/A	No, if Starship meets its cost and performance targets. Unclear, otherwise. Lunar propellant is unlikely to capture the LEO-to-GEO market, which is half of in-space demand for propellant.
LOX for sale on lunar surface	$8,000/kg (high cost, low volume) – $1,000/kg (low cost, high volume)	Unknown. Possibly non-zero if Starship buys LOX on lunar surface for return journey to Earth	N/A	Unclear. Depends on demand for lunar surface tourism with Starship
Helium-3 for sale on Earth	ROI could be 50 years given demand or prices on Earth	0	N/A	No
Lunar solar power for Earth	N/A	Best case scenario is twice as expensive as terrestrial power 0	N/A	No

Product/Service	Cost	Demand (Annual)	Revenue (Annual)	Economic Viability
Hazardous waste disposal	$2,800 per kg	Cost on Earth $0.77 per kg 0	N/A	No
Manufacturing in lunar vacuum	N/A	Vacuum creation in Earth orbit would be cheaper 0	N/A	No
Computer Servers	Cost of power alone is 200 times that on Earth	0	N/A	No

Appendix A. Database of Companies: Names and Basic Info

Key for Funding: Government, foreign or domestic (Gov); Private Investment or Customers (PI); Private Philanthropic/Self-funding (PP); None or Non-Profit (N); Unknown (U)

The funding refers specifically to funding for lunar programs, not necessarily for the entire company, although that is often the case.

Company	Country	Sector	Sub-Sector	Key Products/ Services	Funding
4th Planet Logistics	United States	Structure/Habitat	Surface Habitat	Habitats in Lava Tubes on the Moon and Mars	PP
Advanced Space	United States	PNT Services		Peer-to-peer navigation system	Gov
Aerojet Rocketdyne	United States	Transportation; Supply Chain	Orbit to Orbit	Designs for a Lunar Transfer Vehicle (from Launch Vehicle to Surface); Engine construction for the SLS	Gov
AGILE Space Propulsion	United States	Supply Chain		Advanced Space Engine (ASE) thrusters	U
AI Space Factory	United States	Structure/Habitat; ISRU	Surface Habitat; Use/Output	Habitats on Mars and the Moon; ISRU for 3-D printing	Gov & PI
Airbus	Germany	Structure/Habitat	In-Space Habitat	Construction of in-Space Habitats for the ESA	Gov
ArianeSpace	France	Transportation	Surface to Orbit	Launch Vehicles; ISRU demonstration	Gov & PI
Astrobotic	United States	Transportation	Lander; Rover	Payload delivery services; ISRU testing for the ESA	Gov & PI

Company	Country	Sector	Sub-Sector	Key Products/ Services	Funding
AstronetX PBC	United States	PNT Services; Science		Remote Sensing Payloads for DOD, NASA, and Scientists	N
Atlas Space Operations	United States	Communication		Communications systems	PI
Bigelow Aerospace	United States	Structure/Habitat	In-Space Habitat	Habitat for Lunar Gateway and potentially the lunar surface	Gov & PP
Blue Horizon	Luxembourg	Structure/Habitat	Surface Habitat	Establishing a Bio-ISRU, developing sustainable habitats	PI
Blue Origin	United States	Transportation; Supply Chain	Lander; Surface to Orbit	Lunar Lander, Launch Vehicle Services, ISRU Studies	Gov & PP
Boeing	United States	Transportation; Structure/Habitat	Surface to Orbit; In-Space Habitat	Lunar Lander, Lunar Habitat, Launch Services for Lunar Gateway	Gov
Bradford Space	United States	Transportation	Orbit to Orbit	Propulsion system from LEO to Earth departure	Gov & PP
Caterpillar Construction	United States	ISRU	Mining/Processing	Autonomous industrial robots	U
Celestis	United States	Private Goods	Memorials	Burial of Cremated Remains on the Moon	PP
Ceres Robotics	United States	Transportation; Structure/Habitat	Rover; Lander; Habitation Needs	Design and Construction of Robots	Gov
Cislunar Marketplace	United States	Non-profit	Advocacy	Providing a forum in which contributors to future space development can discuss strategies to expand the space economy	N
Cislunar Space Development Company	United States	Transportation	Orbit to Orbit	Re-usable space based transfer vehicles	U

Company	Country	Sector	Sub-Sector	Key Products/ Services	Funding
Deep Space Systems	United States	Transportation	Lander	CLPS Small Lunar Lander	Gov
Draper Labs	United States	Transportation; Supply Chain	Lander	Launch Services as a CLPS Provider	Gov
Dynamic Imaging Analytics	United Kingdom	Supply Chain		Imaging Systems for Lunar Rover	Gov
Dynetics	United States	Supply Chain	Lander	CLPS Small Lunar Lander-- descent element	Gov
Elysium Space	United States	Private Goods	Memorials	Launches symbolic portion of human remains to the lunar surface	PI
Exolife	United States	Structure/Habitat	Surface Habitat	3-D printed habitat	PI
Exploration Architecture Corporation (XArc)	United States	Structure/Habitat	Surface Habitat	Surface Habitat Design	U
Firefly Aerospace	United States	Transportation	Surface to Orbit; Lander	Lunar Lander, Launch Services	PI
For All Moonkind	United States	Non-profit	Advocacy	Advocacy for the protection of Lunar Heritage sites	N
Frontier Aerospace Corporation	United States	Supply Chain		Deep Space Engines (DSE) for Astrobotic's Peregrine	Gov
Goonhilly Earth Station	United Kingdom	Communication		Satellite Communications, Tracking, and Operations	Gov
Helios	Israel	ISRU	Processing	Reactor	U
Honeybee Robotics	United States	ISRU	Mining/Processing	Robotic solutions, PlanetVac and LISTER	Gov

Company	Country	Sector	Sub-Sector	Key Products/ Services	Funding
Indicium	Canada	Communication		Fully independent data center for lunar and space missions	U
Infinity Fuel Cell and Hydrogen Inc.	United States	Supply Chain		Fuel Cells for Space Applications	Gov
Instarz	United States	Structure/Habitat	Surface Habitat	Lunar Habitat	U
Intuitive Machines	United States	Transportation	Lander	Development of a CLPS lander	Gov
ispace	Japan	Transportation; ISRU	Lander; Mining/Processing	Support for Draper Lab's Lunar Lander; eventually ISRU	PI
Laser Zentrum Hannover e.V.	Germany	ISRU	Use/Output	ISRU	Gov & PI
LiftPort Group	United States	Transportation	Elevator	Lunar Elevator using carbon nanotubes	PI
Lithoz	Austria	ISRU	Use/Output	ISRU	Gov
Lockheed Martin	United States	Transportation; Structure/Habitat	Lander; In-Space Habitat	Lunar Habitat, Orion Crew Module, Lander	Gov
Lunar Outpost	United States	Structure/Habitat	Habitation Needs	Development of a thermal management system	Gov
Lunar Resources	United States	ISRU; Manufacturing	Mining/Processing; Photovoltaics; Others	Development of Defense-Focused, orbital platforms	Gov
Lunar Station	United States	PNT Services		Surveying and Navigational services for the Lunar Surface	PI

Company	Country	Sector	Sub-Sector	Key Products/ Services	Funding
Maana Electric	Luxembourg	ISRU; Manufacturing	Mining/Processing; Use/Output; Photovoltaics	Solar Panels constructed using local resources	Gov
Made in Space	United States	ISRU	Mining/Processing; Use/Output	Space manufacturing technologies	Gov & PI
Masten Space Systems	United States	Transportation	Lander; Surface to Orbit	Lunar Landers for CLPS, engines	Gov & PI
Maxar Technologies (Space Systems/Loral, and Canadian subsidiary MacDonald, Dettwiler and Associates Ltd. (MDA))	United States	Communication; Supply Chain		Satellite communications; propulsion systems	Gov
Moon Express	United States	Transportation	Lander	Development of Lunar Lander and Prospecting on Lunar Surface	Gov & PI
NanoRacks	United States	Structure/Habitat	In-Space Habitat	Habitat; Mission Support Services	Gov & PI
NGK Spark Plug	Japan	Supply Chain		Solid State Battery	PI
Northrop Grumman (and subsidiary Orbital ATK)	United States	Structure/Habitat; Supply Chain; Transportation	In-Space Habitat; Lander; Orbit to Orbit	Habitat; Human Lunar Lander; Launch Vehicle	Gov
OffWorld	United States	ISRU	Prospecting; Mining/Processing; Use/Output	Autonomous industrial robots	PI

Company	Country	Sector	Sub-Sector	Key Products/ Services	Funding
OHB System AG	Germany	Transportation	Lander	Support for Lunar Rover; Conducts Studies on Lunar Missions	Gov
Once a Moon	United States	Private Goods	Jewelry	Selling jewelry with lunar meteorite samples	PI
Open Lunar Foundation	United States	Non-profit	Mission Design	Creating plans for a lunar base for $5 billion	PP
OrbitBeyond	United States	Transportation	Lander	Payload delivery services	Gov
Paragon Space Development Corporation	United States	Structure/Habitat	Habitation Needs	ISRU and Environmental Control Systems	Gov
Planetoid Mines Corporation	United States	ISRU	Prospecting; Mining/ Processing	Prospecting and mining water on the Lunar South Pole	PI
Project Moonrise	Germany	ISRU	Use/Output	ISRU	PP
PTS or Planetary Transportation Systems (formerly PTScientists)	Germany	Communication; Transportation	Lander	Lunar lander, lunar rover	Gov & PI
Puli Space Technologies	Hungary	Transportation	Lander	Lunar Landers for CLPS, engines	U
Rocket Lab	United States	Transportation; Communications	Surface to Orbit	Launch Services for Small Satellites	PI
Sierra Nevada Corp.	United States	Structure/Habitat; Transportation	In-Space Habitat; Lander	Lunar Habitat; Propulsion System Prototype; possibly Lander	Gov
Skidmore, Owings & Merrill	United States	Structure/Habitat	Surface Habitat	Architecture for Surface Habitat	PI

Company	Country	Sector	Sub-Sector	Key Products/ Services	Funding
Skycorp Incorporated	United States	Transportation	Orbit to Orbit	Lunar lander, Lunar outpost	U
Skyhaven Systems	United States	Supply Chain		Support systems for electronics and life systems; support for ISRU	Gov
Skyre Inc. (aka Sustainable Innovations)	United States	ISRU	Use/Output	Extracting Propellant from Water Ice	Gov
Space Applications Services	Belgium	ISRU; Transportation	Prospecting; Mining/Processing; Use/Output; Lander	Mission Control; Rover	Gov
Space Engine Systems	Canada	Transportation	Surface to Orbit	Space Plane Launch	PP
Space Mining Technologies	Germany	ISRU	Prospecting; Mining/Processing	ISRU for fueling	U
Spacebit	United Kingdom	Transportation	Rover	Lunar Rover that can fit into a CubeSat	PP
SpaceIL	Israel	Transportation/Non-Profit	Lander	Beresheet, lunar lander	PP
SpaceX	United States	Transportation	Surface to Surface	Commercial Launch Services; one descent element study	Gov & PI
Surrey Satellite Technology Ltd	United Kingdom	Communication		Navigation and Communications Systems	Gov
TeamIndus (incorporated as Axiom Research Labs)	India	Transportation	Lander	Small lunar lander (~22lbs)	PP

Company	Country	Sector	Sub-Sector	Key Products/ Services	Funding
Tethers Unlimited, Inc.	United States	Transportation; Communications	Orbit to Surface	Tether system for lunar transit	Gov
Toyota	Japan	Transportation	Rover	Lunar Rover	Gov
TransAstra	United States	ISRU	Prospecting; Mining/Processing; Use/Output	Optical Mining on asteroids and the Moon	Gov
Tyvak Nano-Satellite Systems Inc.	United States	Transportation	Lander	Lander for CLPS	Gov
United Launch Alliance	United States	Transportation	Surface to Orbit	Launch Vehicles	Gov
Virgin Orbit	United States	Transportation	Surface to Orbit	Launch Vehicles	Gov
Xplore	United States	Science	Planetary Science	Providing transportation to the Moon on their XCRAFT launch vehicle-- "Xplore conducts mission planning, spacecraft engineering, regulation, insurance, communications, and operations so you don't have to."	PP

Appendix B. Database of Companies: Descriptions Relevant to Cislunar Activities

Company	Description Relevant to Cislunar Activities
4th Planet Logistics	4th Planet Logistics is currently investigating the possibility of inhabiting lava tubes on the Moon and Mars. Currently, they are testing the concept in an underground lava tube in Iceland.
Advanced Space	Advanced Space LLC designs software and specialized services for NASA, the U.S. Air Force, and commercial operators. Advanced Space is partnering with NASA Goddard to advance lunar navigation technologies. They intend to mature a navigation system between Earth and the Moon that could supplement NASA's Deep Space Network and support future exploration missions. As of 2019, NASA awarded an additional $13.7 million to develop and operate a CubeSat mission to the same lunar orbit targeted for the Gateway. This program is called the Cislunar Autonomous Positioning System Technology Operations and Navigation Equipment (CAPSTONE). CAPSTONE is expected to be the first spacecraft to operate in a near rectilinear halo orbit around the Moon as a peer-to-peer navigation system that scales with increasing demand and can be utilized by both government and commercial space missions.
Aerojet Rocketdyne	Aerojet is one of 11 recipients of the NASA Next Step Appendix 4 grant, for studies and prototypes of human lander systems. Aerojet is completing one transfer vehicle study. They must leverage their own funding (≥20 percent) for these projects. Aerojet is also creating designs for a Lunar Transfer Vehicle to ferry the Descent and Ascent Elements from the Gateway to LLO. For the SLS, Aerojet is constructing four RS-25 engines and one RL10 main engines. Aerojet Rocketdyne was also a NExtSTEP-1 recipient for advanced propulsion. They used the award to complete the development on a Power Processing Unit that will convert the electrical power generated by a spacecraft's solar arrays into the power needed for its patented 250kW multi-channel Nested Hall Thruster. For this project, they partnered with the University of Michigan, NASA GRC, and JPL.
AGILE Space Propulsion	Founded by a former Aerojet Rocketdyne engineer, AGILE originally was a rocket engine testing facility that has expanded to create "mission-optimized" propulsion systems. AGILE is currently working on a propulsion system for Lunar Lander descent engines.

Company	Description Relevant to Cislunar Activities
AI Space Factory	AI Space Factory has developed a 3-D printable Martian habitat, for which they won NASA's 3-D Printed Habitat Challenge. They have used the award money to support their efforts since. They intend to use ISRU to print this habitat. They have constructed a version of this design on Earth, in upstate New York, and AI Space Factory is renting out the home as a luxury vacation home. For this rental service, the company emphasizes the environmental sustainability of this project, which is entirely recyclable and compostable.
Airbus	Airbus is a contractor with the European Space Agency working to construct in-space habitats (European Service Modules) for the Lunar Gateway, two of which are under or have completed construction. ESA has selected Astrobotic to partner with Airbus to conduct a lunar ISRU study.
ArianeSpace	ArianeSpace is a subsidiary of ArianeGroup, which is a joint venture of Airbus and the French group Safran. They conduct business in two sectors: 1) aerospace, in orbital propulsion systems and equipment; 2) defense and security. Their main launch vehicles share the heavy-lift Ariane 5, medium-lift Soyuz-2, and solid-fueled Vega for lighter payloads. The Ariane 6 is under development. Ariane 6 is intended to be more cost-effective and able to launch more frequently in a year than its predecessor. ArianeGroup's CEO intends to offer rideshare missions to the Moon in 2023 with Ariane 6. They are considering both public and private customers for this mission. ArianeSpace also is partnering with PTS/PTScientists for their ESA ISRU demonstrator mission.
Astrobotic	Astrobotic has a diverse set of customers—companies, universities, non-profits, individuals—but NASA is by far their largest funding source. Astrobotic is one of three partners selected by NASA for their Lunar Cargo Transportation and Landing by Soft Touchdown (Lunar CATALYST) initiative, which is a no-funds SAA. This SAA is designed to encourage the development of robotic lunar landers that can be integrated with U.S. commercial launch capabilities. They are planning to deliver payloads tailored to customer need, delivered by their Peregrine Lander. NASA also awarded them $5.6 million to develop a rover, named MoonRanger. The ESA has also selected Airbus and Astrobotic to conduct ISRU testing on the lunar surface. Astrobotic also received a NASA contract for a Tipping Point contract for $10 million for a lunar technology demonstration mission, advancing low cost, reliable, high-performance, stand-alone Terrain Relative Navigation (TRN) sensor suite. This sensor suite is designed to deliver robotic landers.

Company	Description Relevant to Cislunar Activities
AstronetX PBC	They are developing remote sensing payloads for scientific measurements and space domain awareness. Their timeline for their small (cubesat-scale) payloads is 1 to 2 years, and then 2 to 5 years for ESPA grande glass payloads, and then 5+ for larger payloads. AstronetX PBC is targeting cislunar and lunar surface environments in anticipation of NASA and DOD interest.
Atlas Space Operations	ATLAS is partnering with Astrobotic to deliver and operate the first-ever laser communications terminal on the Moon. Through this partnership, Astrobotic will be able to offer up to one gigabit per second of data to its customers. Their regular products are Freedom Platform and Freedom Network, two services that provide software-centric, cloud-based approach to streamline operations and reduce overhead for satellite programs. ATLAS was also selected to for a Space Communications and Navigation (SCaN) program grant to study methods to evolve NASA's existing communications network. The combined funding award was $4 million between eight companies.
Bigelow Aerospace	Bigelow Aerospace has been developing inflatable habitation modules since the 1990s. In 2012, NASA signed a $17.8 million contract for their Bigelow Expandable Activity Module (BEAM) to attach to the ISS. Their current focus is on their B330 module, which could theoretically attach to the ISS, a private space station, or the Lunar Gateway, but Bigelow has its sights set on the Lunar Gateway. The B330 is designed to operate in lunar orbit or on the lunar surface, buried beneath the regolith. Securing the Lunar Gateway contract is a key part of Bigelow's long-term goals, particularly if the company wants to move beyond subsiding off financial contributions from their founder. In 2017, Bigelow and ULA proposed a joint-project called the "Lunar Depot," which would be a B330 Module launched on successive Vulcan 562 missions to take the module to lunar orbit to act as a laboratory and hotel on the Moon. There have been no updates on this program.
Blue Horizon	Blue Horizon was founded by OHB Venture Capital in 2017. For space, they specialize in closed loop systems and habitats; Bio-ISRU; and pharmaceutical, biological, and medical research in space environments. Terrestrially, they develop habitats; provide toxicity tests, environmental monitoring, and risk assessment; and microorganism-mineral interactions for reversing desertificiation, bio-mining, and soil remediation. They are attempting to develop what they call a "CubeHab," some sort of sustainable lunar habitat. There are no publicly available details on the design. They are also working on a STOP Desertification program "as another element based on advanced research already performed on Moon material."

Company	Description Relevant to Cislunar Activities
Blue Origin	Blue Origin was recently awarded three Space Act Agreements pertaining to the Lunar Missions: 1) with JSC and GSFC to cover the development of a guidance and navigation system for the lander to enable precise landings, 2) Johnson and GRC to support the development of a fuel cell for the lander, 3) MSFC and LRC to work on high-temperature materials for engine nozzles for use on lunar landers. Blue Origin has been selected for a NASA NextSTEP Appendix D track one to identify technology gaps associated with ISRU. Blue Origin was also selected for a NextSTEP Appendix E grant to conduct one descent element study, one transfer vehicle study, and one transfer vehicle prototype for Lunar Landers. Blue Origin was also selected to be one of 14 CLPS providers. They were added to the CLPS program because NASA wanted more providers with large payload capacities. Recently (Oct 2019), Blue Origin has partnered with Draper, Lockheed, and Northrop Grumman to develop a human lunar lander for NASA. Blue Origin will be the prime contractor and provide descent stage. Blue Origin was also given a non-reimbursable Space Act Agreement as an industry partnership with NASA to work with Johnson and Goddard to mature a navigation and guidance system for safe and precise landing at a range of locations on the Moon. Blue also is partnering with Glenn and Johnson to mature a fuel cell power system for the Blue Moon lander, so that the system could provide uninterrupted power during the lunar night. Blue is partnering with Marshall and Langley to evaluate and mature high-temperature materials for liquid rocket engine nozzles to be used on lunar landers. Blue was given $10 million to partner with NASA to mature their cryogenic liquid propulsion.
Boeing	Boeing is currently leading the production of the Space Launch System (SLS), which NASA has committed to for the Artemis missions. They are also developing the Boeing Deep Space Habitat, the ground prototype of which is currently being tested at NASA Huntsville. This project was conducted as part of NextSTEP-2 Appendix A. Boeing was also one of 11 companies selected for a NextSTEP Appendix E contract to study and/or develop prototypes for a potential lunar landing system. For this, Boeing conducted a descent element study, two descent element prototypes, on transfer vehicle study, one transfer vehicle prototype, one refueling element study, and one refueling element prototype.

Company	Description Relevant to Cislunar Activities
Bradford Space	Bradford Space has over 100 launches to date, a team of over 75 employees, and presence in the U.S., Netherlands, Sweden, and Luxembourg. They construct propulsion systems, including non-toxic propulsion, gloveboxes, and instruments for satellites and spacecraft. Their spacecraft Explorer uses its own propulsion system to go from LEO to an earth departure trajectory, taking advantage of the relatively low cost and high availability of commercial rideshare launches to LEO. Explorer does not seem to be designed with the Moon specifically in mind, but could have potential lunar applications.
Caterpillar Construction	Caterpillar has been developing autonomous mining equipment for decades. There are no public plans in the works for a NASA/Caterpillar partnership, but they are a sponsor and partner of Astrobotic.
Celestis	Celestis offers "space burial" services for deceased loved ones either to space and back to Earth; into Earth orbit; to lunar orbit or surface; or into deep space. Their lunar service places cremated remains or DNA on the surface of the Moon. The base cost of this service is $12,500. They were the first company to offer memorial spaceflight missions. They have been operating for two decades.
Ceres Robotics	Ceres Robotics was established by former NASA employees. They are attempting to design and construct robots for the creation of facilities and habitats. Recently, Ceres was chosen by NASA to join the CLPS program. They expect their lander to be available in 2023.
Cislunar Marketplace	The Cislunar Marketplace is a consortium led in cooperation by the National Space Society (NSS) and the Space Development Foundation. Their agenda is improved access to space; prospecting in cislunar space; tech development, demonstration, and deployment; enabling sustained expansion; providing clean, affordable energy; and a cislunar stepping stone. They list over 200 organizations including academic, government, non-profit, and commercial who have participated in the workshops that led to the formation of the Cislunar Marketplace. They are "planning workshops in conjunction with upcoming space conferences," the most recently listed is from 2017.
Cislunar Space Development Company	Cislunar Space Development Company intends to develop reusable space-based transfer vehicles, transportation nodes, and lunar landers. Their plans for primary services include geosynchronous transfer orbit insertion and delivery to geosynchronous equatorial orbit, Earth-Moon Lagrange Point 1, and the lunar surface. They are a CONFERs member. They have significant online presence in media.
Deep Space Systems	Formerly a subcontractor to Lockheed Martin, Deep Space Systems has diversified into satellite ready cameras. Deep Space Systems was

Company	Description Relevant to Cislunar Activities
	selected as a CLPS provider. It could possibly return around 0.3 kilograms of samples from the lunar surface.
Draper Labs	Draper has recently (Oct 2019) partnered with Blue Origin, Lockheed Martin, and Northrop Grumman to human lunar lander. Draper will be providing guidance systems and avionics for the lander. Draper is also one of 14 CLPS providers selected by NASA. Draper provides overall management and coordination for a team that is also composed of General Atomics Electromagnetic Systems, ispace, Inc., and Spaceflight Industries. Beyond leadership, Draper provides payload operations, the flight computer, and guidance, navigation, and control systems for the lunar lander. General Atomics Electromagnetic Systems will carry out the lunar lander manufacturing, assembly integration and testing in the U.S. ispace will act as the design agent and provide high-frequency rideshare opportunities. Spaceflight Industries Inc. will orchestrate launch services, including integration, mission management, launch and range documentation, and pre- and post-operations.
Dynamic Imaging Analytics	Dynamic Imaging Analytics is creating the imagers that will be utilized by the Lunar Volatiles Mobile Instrumentation (LUVMI) rover, which is being developed by the LUVMI-X Consortium. This consortium is composed of European partners from Belgium, Germany, and the UK and is funded by the EU's Horizon 2020 research and innovation program.
Dynetics	Dynetics originally distinguished itself in small satellites, with the Fast Affordable Scientific Satellite (FASTSAT). Since, they have held contracts with NASA/Boeing SLS Core Stage Exhaust Gas Heat Exchanger, NASA/Radiance SLS Core Stage Pathfinder, and NASA SLS Universal Stage Adapter. In the commercial sector, Dynetics has worked with ULA to test the Vulcan. For DOD, they were selected to develop small satellites for U.S. Army Space and Missile Defense Command/Army Forces Strategic Command (USASMDC/ARSTRAT), Lonestar. Dynetics was also awarded a NextSTEP-1 award to develop a rapid, highly efficient system to remove CO2 from spacecraft cabins. Dynetics is also leading a team, which includes Sierra Nevada, to bid for the Human Lander System.
Elysium Space	Elysium offers memorials for private citizens either as a "Shooting Star Memorial," which sends the remains into Earth Orbit, or the "Lunar Memorial," which sends the remains to the Moon's service. They have already sent one mission into Earth Orbit, and have a Lunar Memorial payload planned for 2021.

Company	Description Relevant to Cislunar Activities
Exolife	Exolife has several videos on their site displaying ambitious plans beyond Earth's orbit: a 3-D printed lunar habitat, a space launch vehicle, and an exo-life finder telescope (ELF). ELF was crowdfunded ($35k), and there are no details on its construction. Their web presence is non-existent except for their website.
Exploration Architecture Corporation (XArc)	Exploration Architecture Corporation is planning a commercial lunar settlement program, LEAP2, to address space architecture issues in lunar exploration, economic development, mining, and sustainment at a lunar site, Marius Hills Skylight. These current project areas include remote sensing to understand the lunar surface and the distribution of potential mineral resources for mining; reconnaissance to ensure use of different robotic tools; and habitation. There are no details listed for the final category. Their web presence is non-existent except for their website.
Firefly Aerospace	Firefly is developing a family of launch vehicles and in-space services, with a focus on affordability, convenience, and reliability. Firefly has signed an agreement with Israel Aerospace Industries, which owns the intellectual property of the Beresheet lunar lander design. Firefly intends to build a lunar lander based on Beresheet, named Genesis. Genesis will be proposed to NASA's CLPS to deliver payload services to the Moon. If selected, Genesis would be launched on a Firefly Beta rocket or a Flacon 9 rocket in late 2021.
For All Moonkind	For All Moonkind is a volunteer international non-profit organization working with the United Nations to manage the preservation of history and human heritage in outer space. Their work has resulted in the creation of the One Small Step Act to permanently protect the Apollo landing sites from disturbances by codifying existing NASA preservation recommendations. They were granted the status of Permanent Observer to the United Nations Committee on the Peaceful Uses of Outer Space.
Frontier Aerospace Corporation	Frontier Aerospace Corporation was given a $1.9 million contract to partner with NASA to advance their Deep Space Engine (DSE) by flight demonstration as part of the Astrobotic Peregrine Lunar Lander mission.
Goonhilly Earth Station	Goonhilly Satellite Earth Station is a large telecommunications site in Cornwall, England. Goonhilly has a partnership with the European Space Agency and Surrey Satellite Technology for commercial lunar mission support services. This project is called the lunar Pathfinder Mission. Their partnership agreement calls for the upgrade of Goonhilly. Surrey Satellite Technology will construct the spacecraft, which will be tracked and operated by Goonhilly.

Company	Description Relevant to Cislunar Activities
Helios	Helios is developing a reactor to process lunar and Martian soil into oxygen and metals. Their website has little information, and there is little online presence besides their website (news releases, interviews, etc.). They have only four employees listed.
Honeybee Robotics	HoneyBee Robotics is a long-standing R&D company that has completed over 300 advanced projects for NASA, DOD, academia, and industry. Their past space experience is with the Mars Rovers, for which they built the Rock Abrasion Tool, the Icy Soil Acquisition Device, the Sample Manipulation System, and Dust Removal Tool. Developing the PlanetVac, a technology for acquiring and transferring regolith from the lunar surface to instruments (for in-situ analysis) or sample returned container based on a dust tolerant pneumatic approach-- originally funded by NASA SBIR, Spacetech REDDIT, and the Planetary Society. LISTER is an instrumentation designed to measure the heat flow from the interior of the Moon.
Indicium	Indicium Space is attempting to create a fully independent data center that allows for complete confidentiality, cyber security, encryption, and advanced security means for sensitive data. Physical separation and attack-free geographical position will allow for secure operations to guarantee the security of the data. Clients will have full control over the transmitted data and each client will have their own terminal that allows communication to the server on the Moon, isolating them from the internet connection.
Infinity Fuel Cell and Hydrogen Inc.	Infinity Fuel Cell and Hydrogen Inc. is collaborating with NASA Johnson to develop a flexible power and energy product to reduce cost and improve reliability. This technology could be implemented in lunar rovers, surface equipment, and habitats.
Instarz	Instarz is an early-stage startup developing a prototype for a sustainable lunar habitat. Their press releases indicate that they intend to create and launch their '"fully-equipped, self-assembling lunar ecosystem" by the end of 2026. Their design is expandable and will not require external provisions, allowing up to eight astronauts to inhabit it for as long as 12 months. They appear to have two full-time employees, and have had over 80 interns (undergrad and grad).
Intuitive Machines	Intuitive Machines has developed several airborne drones and spacecraft, including the Universal Reentry Vehicle (URV). Their Nova-C lunar lander draws direct heritage from NASA's Project M lunar lander and Project Morpheus. The core team from these missions founded Intuitive Machines.

Company	Description Relevant to Cislunar Activities
ispace	ispace is a private, Japanese company that originated from the Google Lunar XPRIZE competition, in which ispace managed Team HAKUTO, one of the five finalists. ispace is trying to create the world's first commercial lunar exploration program, "HAKUTO-R", which will consist of ispace's first two lunar missions. NASA awarded Draper a contract to send science and technology payloads to the lunar surface, and Draper is partnering with ispace on lunar lander design. Hakuto-R is planning to exploit lunar water ice in the future. To extract Moon ice, they are considering two methods: 1) mirrors to shine light into the craters; and 2) greenhouse-style structures to warm the ice and capture it as it evaporates.
Laser Zentrum Hannover e.V.	Laser Zentrum Hannover has partnered with TU Braunschweig to develop Project MOONRISE. This project is attempting to make a lunar base by using powerful lasers to essentially melt Moon dust into rigid shapes. LVH is also a member of a consortia of public and private sector organizations working to develop a lunar rover, LUVMI-X. This project is funded by the European Space Agency.
LiftPort Group	LiftPort Group intends to exploit the reliable gravitational and orbital mechanics of cislunar space to create a tether between the lunar surface and cislunar space. They intend to provide a propellant-less delivery of cargo to and from the lunar surface. The company's plans have not come to fruition and is currently inactive.
Lithoz	The ESA and Lithoz recently partnered to demonstrate the ability to produce highly detailed spare parts—such as screws and gears—from lunar regolith simulant. The series of parts were successfully 3-D printed, and ESA and Lithoz will continue with testing the strength and mechanical performance of the parts.
Lockheed Martin	Lockheed Martin is the primary contractor building the Orion Crew Module. Their contract with NASA is for the production and operation of six Orion missions and the ability to order up to 12 in total. Lockheed is partnering with Blue Origin, Northrop Grumman, Draper to develop a human lander for NASA. Lockheed will build a crew-rated ascent stage. This partnership was preceded by a NASA NextSTEP Appendix E contract to conduct studies for a potential human landing system. Lockheed conducted one descent element study, four descent element prototypes, one transfer vehicle study, and one refueling element study. For NASA NextSTEP Appendix A, Lockheed was one of six companies selected to develop a prototype for a lunar habitat. Their habitat, Multi-Purpose Logistics Module (MPLM), is currently being tested at NASA Kennedy. Lockheed is also part of the small sat awardees for NASA NextSTEP-1 for Orion's Exploration Mission (EM-1). Their LunIR will

Company	Description Relevant to Cislunar Activities
	conduct a lunar flyby of the Moon to collect infrared sensor data to enhance our knowledge of the lunar surface.
Lunar Outpost	Lunar Outpost has a line of solar-powered air quality sensors sold on earth. They have a NASA contract of an undisclosed amount to develop a thermal management system for the Lunar Gateway—Mobile Autonomous Prospecting Platform (MAPP), and their air quality monitors are currently in the prototype habitat for NASA's Lunar Gateway.
Lunar Resources	Lunar Resources, Inc. is "focusing on manufacturing and energy generation in the space environment utilizing space resources to create breakthrough technologies to facilitate the large-scale commercialization of the Moon." They are developing technologies to fabricate functional coatings and thin-film materials in the vacuum of space. The USAF selected Lunar Resources and Rhea Space Activity (RSA) to develop concepts for the deployment of a variety of defense-focused, space-based, orbital platforms. This project has been named "IN-SILICO."
Lunar Station	Lunar Station offers Lunar Navigational Services. The two programs in this suite are Moon Hacker and Moon Watcher. This company is attempting to support companies and governments in the planning and operating stages of their operations. Moon Hacker is their analytical platform that draws data from topography to provide emergent insights for customers. Moon Watcher provides 24-hour reconnaissance for customers using a variety of satellites. The combination of these programs is intended to allow missions to identify ideal sites for landing, traverse the lunar surface safely, and explore the lunar surface and sub-surface for elements of value for mission operations.
Maana Electric	Maana Electric's TerraBox is a fully automated factory designed to produce solar panels using only sand and electricity as inputs. The TerraBox fits within shipping containers, allowing the TerraBoxes to be transported to deserts across the globe. Maana Electric won the Luxembourg SpaceStarters Award in 2017. This organization has about 12 employees.
Made in Space	"Made in Space is the industry leader for space manufacturing technologies, combining additive manufacturing with robotic assembly and autonomous quality verification to pioneer a new generation of functional structures built in space." They currently do not have lunar plans, but their in-space manufacturing capabilities and 3-D printing technologies could be adapted for lunar and cislunar applications. They were founded in 2010 and have approximately 100 employees.

Company	Description Relevant to Cislunar Activities
Masten Space Systems	Masten Space Systems is an aerospace manufacturer startup that has been operating since 2004 and has eight employees. They have built a number of launch vehicles and engines, and were among the first companies to have vertical-takeoff, vertical landing (VTVL) rockets. Masten is one of three partners selected by NASA for their Lunar Cargo Transportation and Landing by Soft Touchdown (Lunar CATALYST) initiative, which is a no-funds SAA. This SAA is designed to encourage the development of robotic lunar landers that can be integrated with U.S. commercial launch capabilities. Masten was also selected as a CLPS provider.
Maxar Technologies (Space Systems/Loral, and Canadian subsidiary MacDonald, Dettwiler and Associates Ltd. (MDA))	Maxar's Subsidiary, MDA, was awarded a NASA NextSTEP-2 Appendix E contract to develop a refueling element study and one refueling element prototype. Maxar is partnering with NanoRacks to demonstrate metal cutting on-orbit, for NanoRacks habitat plan. Maxar was selected to build and perform a spaceflight demonstration of the power and propulsion element spacecraft, which is the first element for the Lunar Gateway. Dynetics is collaborating with Maxar to provide support in the design process. Maxar's Canadian subsidiary (MDA) has been selected by the Canadian Space Agency to provide a conceptual design for a lunar rover and by the Korean Aerospace Research Institute (KARI) to provide a communications subsystem for the Korean Lunar Exploration program. Maxar's Space Systems/Loral (SSL) was chosen for a NASA NextSTEP Appendix E contract, which is for studies and prototypes of human lunar lander systems. SSL's contract was for one refueling element study and one refueling element prototype.
Moon Express	Moon Express is an American, privately held company originally started to compete for the Google Lunar X Prize. In 2016, Moon Express became the first private company to get U.S. approval for a lunar mission, although this mission is yet to occur. NanoRacks is providing the global payload and mission sales, marketing, management and technical support to Moon Express's customers. Moon Express is one of three partners selected by NASA for their Lunar Cargo Transportation and Landing by Soft Touchdown (Lunar CATALYST) initiative, which is a no-funds SAA. This SAA is designed to encourage the development of robotic lunar landers that can be integrated with U.S. commercial launch capabilities.

Company	Description Relevant to Cislunar Activities
NanoRacks	As an awardee of a NASA NextSTEP-2 Appendix A contract, NanoRacks is developing a concept for a habitat for the Lunar Gateway. Their habitat design, Independence-1, plans to refurbish and repurpose a spent rocket propellant tank, leveraging the natural vacuum of space to flush the tank of residual propellants. They are launching a demonstration for the robotic cutting of a second stage representative tank material on-orbit. This will be the first structural metal cutting mission in space. NanoRacks is also providing global payload and mission sales, marketing, management, and technical support to Moon Express's commercial, academic, and government customers and expedition partners.
NGK Spark Plug	NGK Spark Plug Co, LTD, is a Japanese comprehensive ceramics processing manufacturer. Their product offerings include spark plugs, automotive sensors for internal combustion engines, semiconductor packages, cutting tools, bio ceramics, and industrial ceramics. NGK Spark Plug is partnering with ispace.
Northrop Grumman (and subsidiary Orbital ATK)	Northrop Grumman has recently (Oct 2019) teamed up with Blue Origin, Lockheed Martin, and Draper to build a human lunar lander. Northrop Grumman will build a transfer stage to move the lander from the Lunar Gateway to low-lunar orbit. As of early summer 2019, NASA concluded that out of all of the NextSTEP habitation candidates, Northrop Grumman was the only company that could deliver on their desired schedule. This was based off the fact that 1) the Cygnus (an expendable American automated cargo spacecraft developed by Orbital Sciences and now built and launched by Northrop Grumman) is in active production, 2) significant progress has been made to adapt the Cygnus for habitation, 3) the small size of their module allows it to be launched on commercial launch vehicles with existing payload fairings. This decision is not binding, and is contingent on Northrop Grumman submitting a proposal and NASA finding the price fair and reasonable. Northrop Grumman is also providing the Solid Rocket Boosters for the SLS.
OffWorld	OffWorld is developing a "new generation of … industrial robots" designed to be small and robust; adaptable; solar electric; autonomous and fast learning; and modular and reconfigurable. They intend to sell these robots to terrestrial mining companies in order to fund their lunar ambitions.

Company	Description Relevant to Cislunar Activities
OHB System AG	OHB System AG is a subsidiary of the Bremen-based space and technology group OHB SE. OHB performed a self-financed study for the DLR to prepare program proposals for lunar exploration—the Mona Lisa study, which has already been incorporated into lunar initiatives planned by DLR and the ESA. Between, 2007 and 2010 OHB led a study for the ESA on the feasibility of designs for a small lunar lander. This study was called NEXT Lunar Lander. In 2018, OHB System AG signed a contact with the ESA for a study "Conceiving a Lunar Base Using 3-D Printing Technologies." OHB is a member of the LUVMI-X Corporation. In 2014, LuxSpace (a Luxembourg-based child of OHB Systems) flew Manfred Memorial Moon Mission (4M mission), which was the first private lunar probe to successfully fly by the Moon.
Open Lunar Foundation	Open Lunar Foundation is funded by technology executives and engineers. They intend to create technology for exploring and living on the Moon as a collaborative effort, not beholden to a particular country. They intend to begin with smaller, cheaper missions to put various probes and robotic systems on the lunar surface before constructing the base. They also attempt to support technology development and encourage collaboration across the industry. Famous participants/contributors include: Chris Hadfield, Pete Worden, former director of Ames, and Steven Jurvetson, who provided the funding that prevented SpaceX's bankruptcy in 2008.
OrbitBeyond	OrbitBeyond won a contract to be a CLPS provider, but their $97 million NASA contract was terminated in 2019 on terms agreeable to both parties, as OrbitBeyond did not think they could meet the deadlines set by NASA. NASA has stated that they are still able to bid for future CLPS contracts.
Paragon Space Development Corporation	Paragon's expertise is in "the development of innovative and affordable life support and thermal control solutions." Their hardware has flown on NASA vehicles (Orion, Space Shuttle, and the ISS), Russian crafts (Soyuz and Mir), and commercial spacecraft. Paragon is currently developing the Humidity Control Subassembly (HCS) for the Boeing Crew Space Transportation System (CCTS) and Crew Space Transportation (CST)-100. They provide the tubing for life-support systems on NASA Orion. They have partnered with Oceaneering Space Systems to build an EVA spacesuit for the ISS. For Lunar missions, Paragon is developing an environmental control and life support system, as well as an ISRU-derived water purification and Hydrogen Oxygen Production (IHOP) subsystem.

Company	Description Relevant to Cislunar Activities
Project Moonrise	Project MOONRISE is a joint-project of Laser Zentrum Hannover and TU Braunschweig. This project is attempting to make a lunar base by using powerful lasers to essentially melt Moon dust into rigid shapes. This technology will be launched as part of PTScientists' Moon mission. Laser Zentrum Hannover e.V. (LZH) is an independent, non-profit research institute, supported by the Niedersachsen Ministry for Economic Affairs, Employment, Transport and Digitalization. The Institute of Space Systems (IRAS) of the TU Braunschweig works on developing methods, technologies, and approaches for the sustainable use and safety of space infrastructure. Tu Braunschweig is the largest technical university in Northern Germany.
PTS or Planetary Transportation Systems (formerly PTScientists)	PTScientists was originally a contender for the Google Lunar XPRIZE, but was not a finalist. They have since won a contract for an ESA study on lunar landers and the possibility of mining lunar regolith. PTS is working with Audi, Vodafone, OMEGA, and On to develop a spacecraft ALINA, the Autonomous Landing and Navigation Module, to transport a pair of lunar rovers (built by Audi) to explore the Apollo 17 Landing site. They also intend to set up the first LTE communications base-station on the Moon. PTScientists went bankrupt in July 2019, but was acquired for an undisclosed amount by Zeitfracht Group.
Puli Space Technologies	Puli Space Technologies was a Hungarian contender for the Google Lunar XPRIZE, which concluded in 2018. Puli does not appear to have been very active since the conclusion of the XPRIZE. They are sending a time capsule from Hungary on Astrobotic's first mission.
Rocket Lab	Rocket Lab is a private American aerospace manufacturer with a New Zealand subsidiary. Their lightweight orbital rocket Electron provides dedicated launches for smallsats and CubeSats. They are developing a new rocket, Photon, that will be used to launch small payloads into lunar orbit as soon as 4th Quarter 2020.
Sierra Nevada Corp.	SNC was one of six companies selected by NASA to develop a ground prototype for a lunar habitat. Their module, Large Inflatable Fabric Environment (LIFE) habitat, recently arrived at Johnson for testing. SNC has also developed a full-scale prototype for the Power and Propulsion Element (PPE) for the Lunar Gateway. Sierra Nevada officials have also expressed their interest in utilizing the Dream Chaser for NASA's Lunar Gateway. Sierra Nevada has joined a Dynetics-led team to bid for NASA's Human Lander System.

Company	Description Relevant to Cislunar Activities
Skidmore, Owings & Merrill	Skidmore Owings & Merrill LLP (SOM) is an American architectural, urban planning and engineering firm. It is one of the largest architectural firms in the world, and their expertise is in high-end commercial buildings. Through their partnership with ESA and MIT's Aerospace Engineering Department, SOM is developing the plans for the Moon Village. Keeping in mind the lunar conditions—lack of atmosphere, radiation, harsh temperatures, etc.—SOM, MIT, and ESA are planning a village with individual pressurized modules that will inflate and expand. It will have three to four-story structures with workspaces, living quarters, and environmental control & life support systems. There is no update on the status of their proposal since April 2019. During IAC, SOM also had conversations with NASA on a potential SAA to investigate lunar architecture further.
Skycorp Incoporated	According to their website, they have "worked on many advanced technologies since [their] inception to build credibility and a portfolio of capabilities that apply to space systems development." Their most notable project was taking control of the International Sun Earth Explorer 3 (ISEE-3), a former NASA spacecraft that was rebooted to receive data from its working instruments. This spacecraft gathers data from the Sun, Earth, and Moon. There is little public information regarding Skycorp's current Moon plans. They are developing a bi-directional ferry system from various orbits.
Skyhaven Systems	Skyhaven Systems is a R&D firm that works in defense, energy, aerospace, and environmental sectors. They've been selected by NASA to work on component-level development and testing in simulated space environments. Specifically, Skyhaven is investigating separation processes for hydrogen from hydrogen and helium mixtures, as well as thermal interface materials.
Skyre Inc. (aka Sustainable Innovations)	Skyre Inc. is developing a system to make propellant from frozen water at the Moon's poles. They were selected by NASA to do so through a Tipping Point solicitation, and they have partnered with Marshall Space Flight Center to do so.

Company	Description Relevant to Cislunar Activities
Space Applications Services	Space Applications Services has partnered with PTScientists and ArianeGroup to conduct a study and prepare for a mission to mine lunar regolith. ESA has contracted ArianeGroup to conduct this study, and PTScientists will provide the lunar lander, and Space Applications Services will provide the ground control facilities. Space Applications Systems was also chosen by the ESA to lead consortia of public and private organizations to develop a lunar rover, LUVMI-X. This consortium is made up of Open University, the Technical University of Munich, OHB, Dynamic Imaging Analytics, DLR, and Laser Zentrum Hannover. Space Applications has also led an international ISRU-related consortium with 28 different partners. Space Applications is a prime contractor in three projects for the ESA ISRU Mission—a Phase 0 and Phase A/B1 study (ALCHEMIST) of a demonstrator payload to produce 100 grams of water or oxygen on the Lunar surface by 2025, and an Earth-based demonstrator of the reduction of iron oxides from Lunar regolith.
Space Engine Systems	Space Engine Systems is a Canadian aerospace company that is attempting to develop a light multi-fuel propulsion system to power a reusable single-stage-to-orbit and hypersonic cruise vehicle. They are focusing on developing a "space plane." Their CEO has stated his interest in lunar missions, but there are no concrete plans or partnerships to suggest this will be reality anytime soon.
Space Mining Technologies	Their focus is on water extraction. This company has a small (10) team. Beyond a single presentation at the International Moon Village workshop and a presentation at IAC2018 on Lunar Propellants, there is little to suggest any real activity.
Spacebit	Spacebit is a developing very small lunar rovers that can fit into a CubeSat. Their rover is four-legged robot that weighs about 1 kilogram. They intend to use swarm technology exploration plan after proof of concept. They are currently planning to send up a single rover as a demonstration on Astrobotic's Peregrine in 2021.
SpaceIL	SpaceIL is a nonprofit established to land the first Israeli spacecraft on the Moon. Their lunar lander, Beresheet ("Genesis") was the first privately funded landing on the Moon, although the spacecraft crashed. Most of the mission’s budget was covered by private donors, with the Israeli government funding 2.5 percent of the $100 million project. They are trying again with Beresheet 2.

Company	Description Relevant to Cislunar Activities
SpaceX	SpaceX's lunar plans are focused on the development of their Starship, which they hope will be able to transport people to the Moon by 2023. SpaceX also plans to launch a CLPS provider (Intuitive Machines' Nova-C) to the Moon on its Falcon 9. SpaceX has been awarded two Space Act Agreements in relation to its Moon plans. One is with KSC to advance technology for landing large vehicles on the Moon, such as modeling the interaction of the vehicle's engine plumes with the surface. The other is with GRC and MSFC to study in-space propellant transfer. SpaceX was also awarded a NASA NextSTEP-2 Appendix E contract to develop one descent element study for lunar missions. SpaceX is partnering with Glenn and Marshall to advance technology needed to transfer propellant in orbit, an important step in the development of Starship.
Surrey Satellite Technology Ltd	Surrey Satellite technology Ltd was a spin-off company of the University of Surrey, and is now fully owned by Airbus Defense and Space. Their main focus is on the smallsat market. SSTL is designing a low cost 35 kilograms lunar communications satellite mission called DoT-4 with a 2021 launch. Surrey Satellite Technology Ltd, Goonhilly Earth Station (GES), and the ESA have also signed a collaboration agreement for Commercial Lunar Mission Support Services (Lunar Pathfinder Mission) to develop a European lunar telecommunications and navigation infrastructure, including the delivery of payloads and nanosats to lunar orbits. SSTL is in charge of building the spacecraft, and Goonhilly will be tracking and operating the craft.
TeamIndus (incorporated as Axiom Research Labs)	One of the five finalists for the Google Lunar X-Prize. Their micro-rover (Ek Choti si Asha or ECA) is planned to operate for a single lunar day and weighs less than 22 lb. At one point, they had a contract with the Indian Space Research Organization, which fell apart due to lack of funding in 2016. OrbitBeyond's $97 million NASA contract was terminated in 2019 on terms agreeable to both parties. TeamIndus's website is not active.
Tethers Unlimited, Inc.	Tethers Unlimited creates satellite components and is developing high-performance component technologies to enable a range of in-space services: in-space servicing and refueling of satellites, in-space manufacturing of satellite components, in-space assembly of space systems, and in-space networking to support advanced space missions. They currently have no publicly available information on possible lunar ambitions, other than the development of SPIDER and ARTIE. Both are funded by NASA SBIR grants. The Androgynous Robotic Tool-change interface (ARTIE) is a miniaturized power and data grapple interface for use on robotic assets. ARTIE could possibly be used for the Gateway. Sensing and Positioning in Deep Environments with Retrieval (SPIDER) is akin to the tethered skycams used in sports arenas. The system can

Company	Description Relevant to Cislunar Activities
	perform landing, mobility, and sampling operations while suspended over a lunar crater, while avoiding the contamination and stability problems that lunar rovers would face during crater exploration.
Toyota	Toyota has a 3-year joint research agreement with JAXA to develop an electric, manned, pressurized lunar rover. The tentative launch date is 2029; date for completion of the model is 2022.
TransAstra	Funded by NASA Innovative Advanced Concepts (NIAC) program (Phase Three support), but has plans to transition to selling propellant to NASA and commercial flights to eventually become economically viable. Currently developing their asteroid mining orbital demonstrator (MiniBee). Their team and board are reputable.
Tyvak Nano-Satellite Systems Inc.	Tyvak Nano-Satellite Systems Inc. is one of 14 CLPS providers. Their background is in designing and building nanosatellite and CubeSat space vehicle products and services for government and commercial customers.
United Launch Alliance	ULA's Vulcan Centaur rocket will be the launch provider for Astrobotic's first payload. Bigelow and ULA have announced plans for lunar orbiting facility, with ULA providing the launch vehicle on two of their Vulcans. ULA has a 30-year vision that foresees a self-sustaining cislunar economy that supports 1,000 people, in which their Advanced Cryogenic Evolved Stage (ACES) is a key part. ACES will be a liquid oxygen/liquid hydrogen upper stage to their Centaur rocket that will be reusable and refuel able. ULA was given $10 million for their Integrated Vehicle Fluids Flight Demonstration, to support extended-duration cryogenic upper stage operations, which has applications for lunar landers.
Virgin Orbit	Virgin Orbit is a company within Richard Branson's Virgin Group. Virgin Orbit intends to provide launch services for small satellites. The company has over 300 employees. They are developing their LauncherOne vehicle to launch smallsats to sun-synchronous orbit with a payload capacity of about 300-500 kilograms. They are also developing a three-stage variant that would be capable of launching 100 kilograms to the Moon, 70 kilograms to Venus, or 50 kilograms to Mars. The estimated cost per launch is $10-12 million for SSO launches. The cost for lunar missions has not been released.
WayPaver Foundation	WayPaver Foundation was founded in 2015 with a grant from the Lamp Post Group. They are awarding grants to develop technologies in key areas to enable sustainable human presence on the Moon's surface. They have also developed the Lunar Settlement Index, which identifies key areas in need of technological development for lunar settlement. There is no information available about any projects funded to date.

Company	Description Relevant to Cislunar Activities
Xplore	Their launch vehicle XCRAFT is scheduled for construction in 2020, and flights are scheduled to start in 2021. They intend to use their spacecraft for data-collection and transporting scientific payloads to the Moon and other planets. They plan to sell their data to the government and academia.

Appendix C. Description of Lunar Companies by Sector

Transportation Services

The largest sector with 36 companies or 43 percent is Transportation. The Transportation sector was further divided into sub-sector based on the mode of transportation. These Transportation sub-sectors are Lunar Landers; Earth to Orbit Launch Vehicles; Earth to Lunar Surface Launch Vehicles; Orbit to Orbit Transfer Vehicles; Space Tethers; Space Elevators; and Lunar Rovers. Seven companies are involved in two types of transportation simultaneously, and the remaining 29 are offering a single mode of transportation.

The Transportation sector has by far the most representation with 36 companies worldwide. Twenty-five or about 69 percent of transportation companies are based in the United States, by far more than any other country. Germany and Japan come next with two transportation companies, followed by the United Kingdom, Belgium, Canada, France, Hungary, India, and Israel which each have a single transportation company.

There are twenty-two companies worldwide developing or contributing to lunar landers, 15 of which are in the United States. The remaining seven companies involved in lunar lander development are in Germany, Hungary, India, Japan, Israel, and Belgium. Out of the 22 companies designing landers, 10 companies are entirely lunar focused. The other 12 companies have a broader array of space-based services that includes a lunar lander.

Nine companies intend to offer surface to orbit launch services. All of these companies offer a broader array of space-based launch services. Seven of these companies are based in the United States. France and Canada each have one company planning such services. Out of all nine companies, six were well established, or stage three; two were less established but had flight heritage, funding, or government contracts; and one company was in its nascent stages.

A single company is intending to offer (in the coming decades) launch services from Earth's surface directly to the lunar surface. This is a stage three or well-established company based in the United States.

Five companies intend to offer orbit to orbit transfer services. All of these five companies are based in the United States. Three of these companies are well-established companies that offer a variety of space-based services. Two of these companies are entirely lunar focused, one of which operates at a level two and the other at level one in terms of business development.

A single company is intending to utilize space tethers to move objects from the lunar surface into lunar orbit or vice versa. This company is based in the United States and is well established, or stage three in terms of business development.

A single company is intending to construct a space elevator from the lunar surface. This company is nascent, or stage one, and based in the United States.

Four companies are developing lunar rovers. Japan and the United Kingdom each have a single rover manufacturer. The United States has two such companies. Out of all rover companies, three are entirely lunar focused. The fourth is a terrestrial company. Two of the rover companies are well established, another operates at a stage two in terms of business development. The remaining company is nascent or in stage one.

In-Situ Resource Utilization (ISRU)

We identified 18 companies interested in in-situ resource utilization on the Moon or in cislunar space. We divided these companies into those seeking to prospect; mine or process materials; and those who intend to utilize in-situ resources to manufacture or produce output. Nine of these companies—50 percent—are located in the United States. Three companies—about 17 percent—are based in Germany. Japan has two companies interested in ISRU. Austria, Luxembourg, Israel, and Belgium each have a single company interested in ISRU.

Five companies were interested in prospecting for materials to be utilized in situ. One of these companies is well established; three operate at stage two; and one is in its nascent stages. Three American companies are interested in prospecting materials for ISRU. Two other companies are interested in such activities, one in Belgium and one in Germany.

Twelve companies are planning on mining and processing in-situ materials. Out of these 12 companies, seven are based in the United States. Two companies are based in Japan. The remaining three companies are based in Belgium, Germany, and Luxembourg. One of the companies planning on mining or processing in-situ materials is in its nascent stages. Five of these companies are in the intermediate business stages. Six of these companies are well established.

Eleven companies are planning to utilize in-situ materials in manufacturing or construction. Six of these companies are located in the United States, and two are located in Germany. Three others are based in Belgium, Luxembourg, and Austria. None of these nine companies are in their nascent stages. Seven were in the intermediate stage of their business. The remaining four are well-established businesses.

Structures and Habitats

We identified 17 companies that are developing lunar habitats or structures. We divided these companies into those developing In-Space Habitats; Surface Habitats; and Habitation Support. Out of these 17 companies, five were offering other services in addition to habitat construction. Fifteen of these companies are located in the United States, and the remaining two are located in Germany and Luxembourg.

Seven of the 17 habitat companies are designing in-space habitats, which includes inflatable habitats as well as more traditional capsules. Six out of the seven are based in the United States; the seventh is in Germany. All seven of these companies are well-established companies that offer a variety of space-based services.

Eight of the 17 habitat companies are designing surface habitats, which include 3-D printed structures and structures built within lunar lava tubes. Seven of these companies are based in the United States; the eighth is in Luxembourg. One of these companies offers both space-based and terrestrial products and operates at stage two. One of these companies is well established and primarily terrestrial, but designing a lunar surface habitat as a "one-off." Two offer a variety of space-based services—one as a well-established entity and the other is in its nascent stage. Two companies are entirely lunar focused and are in nascent stages.

Three of the 17 habitat companies are providing habitation support, which includes robotics in support of construction and ECLSS systems. All three of these companies are based in the United States. One is a well-established company, the other are at stage two in terms of business development.

Communications

There are currently eight companies that intend to provide communications systems or services in cislunar space or on the lunar surface. Four of these companies are based in the United States, two in the United Kingdom, and one each in Germany and Canada. Six of the companies planning to offer lunar communications services offer a broader array of space services, and two are exclusively lunar focused. Two of the lunar communications companies are well established or operate at stage three in terms of business development. One of these companies is in its nascent stages, or a stage one. Five lunar communications companies operate at stage two.

Position, Navigation, and Timing (PNT) Services

Three companies are planning to offer Position, Navigation, and Timing or PNT services. All three of these companies are based in the United States. One is in nascent stages; the other two are intermediate.

Private Goods

We identified two companies offering lunar memorial services. Both of these companies are in the United States, and both offer lunar memorials as one out of many space-based memorial services. One of these companies is well established and the other is at the second stage.

We identified one company offering jewelry from lunar meteorites. While this company does not currently use materials directly sourced from the Moon, they would be interested in using such materials as they become available. This company is nascent, or stage one, and is based in the United States.

We identified two companies interested in offering lunar tourism as a service. Both of these countries are based in the United States. One is a stage three or established company and also offers transportation services. Another is stage two, or developing, and rather seeks to facilitate lunar tourism, not directly transport customers.

Supply Chain Manufacturers

We identified 13 companies providing supply chain manufacturing in support of lunar operations. Ten of these companies are based in the United States, two are in Japan, and the remaining company is in the United Kingdom. None of these companies is entirely lunar focused. Ten provide a variety of space-based manufacturing support. One is a supply chain manufacturer for both terrestrial and space companies. Two are primarily terrestrial supply chain manufacturers except for a single lunar project. Four of these companies are at stage two in terms of business development; the remaining nine are well established.

Science or Data-Collection

We identified two companies providing scientific data-collection or developing remote sensing payloads as a service. Both of these companies are in the United States and are in the nascent stages of development.

Appendix D. Questionnaire

1. What products or services on the Moon or in cislunar space are you offering or plan to offer?

2. Why did you decide to target the Moon and cislunar space as a market?

3. What is your organization's strategy to develop these products or services and develop a lunar/cislunar market?

4. What is your timeline to develop these projects?

5. Who are your current or prospective customers? If you cannot name them, can you please mark from the list below the category in which they fall?
    - NASA
    - Another U.S. Government agency
    - Foreign government or international organization(s)
    - U.S. commercial or private sector customers
    - International or private sector commercial customers
    - Households
    - Other

6. What technologies or systems does your company need to achieve its objectives? (Launch / Space tugs or other means of getting to lunar orbit/ Space station orbiting the Moon/ In-Situ resource extraction/ Operations technologies/ Other)
    - How will each of these systems affect your operations? What are the key aspects of each capability?
    - What is the technology readiness level (TRL) of your technology?

7. What do you see as your competitive advantage? E.g. unique technology; new operational model; no particular advantage, just exploiting a market failure, etc.

8. How large is your organization currently, and what are your plans for growth?

9. What barriers do you foresee in achieving your strategy?

10. What is the expected cost for your service or good?

11. How much funding have you acquired to date and from what sources?

12. How much more funding do you need to raise to bring your products or services to market? What is your timeline to raise this funding? Which funders are you targeting to raise these funds?

13. What factors are driving or will drive the demand for lunar and cislunar goods and services that you offer? More broadly, what factors will drive the demand for the lunar and cislunar economy as a whole?

14. What specific regulatory, legal, and policy changes would open commercial markets related to the moon and cislunar space?

15. What other firms or individuals do you recommend we contact to better understand demand drivers for the lunar and cislunar economy?

16. Is there any other advice or observation that you would like to share regarding the lunar and cislunar economy?

Appendix E. List of Interviewees

Organization Type	Organization Name	Point Person	Interview Date
Academic/Other	Aerospace Industries Association (AIA)	Mike French	December 10, 2019
	Bryce Space and Technology	Aschley Schiller	December 5, 2019
	Coalition for Deep Space Exploration	Mary Lynne Dittmar	December 17, 2019
	Commercial Spaceflight Federation (CSF)	Tommy Sanford	November 26, 2019
	For All Moonkind	Michelle Hanlon	January 10, 2020
	Open Lunar Foundation	Chelsea Robinson	January 16, 2020
		Peter Eckart	November 27, 2019
		Sagi Kfir	December 18, 2019
Industry, Foreign	ispace	Kyle Acierno	January 30, 2020
	Planetary Transportation Systems GmbH (PTS), or Part Time Scientists/ Plan	Robert Boehme	January 7, 2020
	Toyota	Suenaga Kazuya	30 January 2020
Industry, U.S.	AI Space Factory	David Malott	December 13, 2019
	Astrobotic	Dan Hendrickson	December 18, 2019
	Blue Origin	David Kornuta	January 24, 2020
	Boeing	Arthur Beckman	December 12, 2019
	Celestis	Charles Chafer	January 7, 2020
	Cislunar Space Development Company, LLC	Dallas Bienhoff	December 19, 2019
	Firefly	William Coogan	December 13, 2019
	Gramercy Technology	Jeremy Patuto	February 27, 2020
	HoneyBee Robotics	Kris Zacny	December 27, 2019

Organization Type	Organization Name	Point Person	Interview Date
	Lockheed Martin	Robert P. Chambers	January 13, 2020
	Lunar Resources	Alex Ignatiev	December 16, 2019
	Made in Space	Andrew Rush	December 20, 2019
	Maxar	Al Tadros	December 13, 2019
	MoonExpress	Ben Roberts	December 10, 2019
	Northrop Grumman	Jim Armor	January 21, 2020
	OffWorld	Jim Keravala	December 20, 2019
	Once a Moon	Jack Kimmel	February 5, 2020
	Rocket Lab	Richard French	January 7, 2020
	Skycorp Inc.	Dennis Wingo	January 8, 2020
	SpaceX	Nicholas Cummings	December 18, 2019
	Tethers Unlimited	Rob Hoyt	January 6, 2020
	TransAstra	Joel C. Sercel	December 12, 2019
	United Launch Alliance	Bernard Kutter	February 4, 2020
	XPLORE	Jeff Rich	December 4, 2019
NASA	NASA Science Mission Directorate	Steven Clarke	January 24, 2020
	NASA Propulsion and Power	John H. Scott	January 27, 2020
Other	Air Force Research Laboratory	Chuck Finley	15 January 2020
	Space Fund	Rick Tumlinson	February 3, 2020

Appendix F. Transportation Cost Breakdowns

The tables referenced in Chapter 4 are provided below.

Table F-1. Human Landing System – Low Cost Option

Cost	Launch Vehicle	Descent Stage	Ascent Stage
Development ($M)		1000	2000
Unit Fabrication ($M)		60	120
Maintenance per Use ($M)		0	30
Launches Per Transit			
Cargo to Lunar Surface	1	1	0
Crew to Lunar Surface	1	1	1
Other Parameters			
Dry Mass [t]		3	2.4
Propellant Mass [t]		12	2.8
Payload Mass [t]		6.5	1.3
ISP [s]		450	450
Lifetime Uses		1	3
Launch Site $M per Launch		0	0
Quantities for Decade beginning 2030			
Launches (Cargo to Lunar Surface)	10		
Launches (Crew to Lunar Surface)	10		
Total Uses of Each Unit for Decade			
Total Uses (Cargo to Lunar Surface)	10	10	0
Total Uses (Crew to Moon)	10	10	10
Total Uses	20	20	10
Units Built over Decade			
Units Needed		20	4
Total Cost over a Decade			

Cost	Launch Vehicle	Descent Stage	Ascent Stage
Unit Cost ($M)		1200	480
Maintenance ($M)		0	240
Launch ($M)		0	0
Dev (amortize 10 yrs) ($M)		1000	2000
SUM ($M)		2200	2720
Average Cost per launch			
Cost per launch ($M)	150	110	272
Final Cost			
Cargo – Launch of Descent ($M)	260		
Crew – Launch of Ascent and Descent ($M)	532		
Crew – Average Per Mission with Reuse ($M)	371		

Note. The $150 million launch cost is used for all launches. A cargo mission only launches the descent stage. First crew cost is to send an integrated ascent and descent stage. Second crew mission cost is the average cost per use, factoring in the reusability, which is a weighted average of the integrated HLS launch and subsequent launches of just the descent stage (i.e. cargo cost).

Table F-2. Human Landing System – High Cost Option

Cost	Launch Vehicle	Descent Stage	Ascent Stage
Development ($M)		5000	10000
Unit Fabrication ($M)		250	500
Maintenance per Use ($M)		0	0
Launches Per Transit			
Cargo to Lunar Surface	1	1	0
Crew to Lunar Surface	1	1	1
Other Parameters			
Dry Mass [t]			
Propellant Mass [t]			
Payload Mass [t]			
ISP [s]			
Lifetime Uses		1	1
Launch Site $M per Launch		0	0
Quantities for Decade beginning 2030			
Launches (Cargo to Lunar Surface)			
Launches (Crew to Lunar Surface)			
Total Uses of Each Unit for Decade			
Total Uses (Cargo to Lunar Surface)	10	10	0
Total Uses (Crew to Moon)	10	10	10
Total Uses	20	20	10
Units Built over Decade			
Units Needed		20	10
Total Cost over a Decade			
Unit Cost ($M)		5000	5000
Maintenance ($M)		0	0
Launch ($M)		0	0
Dev (amortize 10 yrs) ($M)		5000	10000
SUM ($M)		10000	15000
Average Cost per launch			
Cost per launch ($M)	150	500	1500

Cost	Launch Vehicle	Descent Stage	Ascent Stage
Final Cost			
Cargo Lunar Transit ($M)	650		
Crew Lunar Transit No Reusable ($M)	2150		
Crew Lunar Transit Avg With Reuse ($M)	-		

Note. All of the notes from the previous table apply here. Note that the high cost option is modeled by the Apollo LEM and is not reusable.

Table F-3. Cost Breakdown and assumptions for Starship Version 1 flying a one-way mission to the lunar surface. Maximum payload is 90 metric tons.

Cost	Super Heavy	Super Tanker	Crewed Starship
Development	1000	1000	
Unit Fabrication	230	130	
Maintenance per Use	0.2	0.5	
Launches Per Transit			
Cargo to LEO	1	1	
Cargo to Lunar Surface	14	14	
Crew to Lunar Surface	0	0	
Other Parameters			
Dry Mass [t]	200	130	
Propellant Mass [t]	3300	1200	
ISP [s]			
Lifetime Uses	10	10	
Launch Site $M per Launch	0.2	0	
Propellant $M/ton	0.000168		
Quantities for Decade beginning 2030			
Launches (Cargo to LEO)	120		
Launches (Cargo to Lunar Surface)	10		
Launches (Crew to Moon)	10		
Total Uses of Each Unit for Decade			
Total Uses (Cargo to LEO)	120	120	
Total Uses (Cargo to Lunar Surface)	140	140	
Total Uses (Crew to Moon)	0	0	
Total Uses	**260**	**260**	
Units Built over Decade			
	26	**26**	
Total Cost over a Decade ($M)			
Unit Cost	5980	3380	
Maintenance	46.8	117	

Cost	Super Heavy	Super Tanker	Crewed Starship
Launch	52	0	
Fuel	196.56		
Dev (amortize over 10 years)	1000	1000	
SUM	**7275**	**4497**	
Average Cost per Launch ($M)			
	28.0	**17.3**	

Table F-4. Cost Breakdown and assumptions for Starship Version N flying a return mission to the lunar surface and back. These estimates apply to: delivery of 84 metric tons to the lunar surface and returning with nothing; delivery of nothing and returning to Earth with 44 metric tons; and a payload of 29 metric tons traveling both directions.

Cost	Super Heavy	Super Tanker	Crewed Starship
Development	1000	1000	3000
Unit Fabrication	230	130	200
Maintenance per Use	0.2	0.5	10
Launches Per Transit			
Cargo to LEO	1	1	0
Cargo to Lunar Surface	13	13	0
Crew to Lunar Surface	13	12	1
Other Parameters			
Dry Mass [t]	200	130	130
Propellant Mass [t]	3300	1200	1200
ISP [s]			
Lifetime Uses	20	20	5
Launch Site $M per Launch	0.2	0	0
Propellant $M/ton	0.000168		
Quantities for Decade beginning 2030			
Launches (Cargo to LEO)	120		
Launches (Cargo to Lunar Surface)	10		
Launches (Crew to Moon)	10		
Total Uses of Each Unit for Decade			
Total Uses (Cargo to LEO)	120	120	0
Total Uses (Cargo to Lunar Surface)	130	130	0
Total Uses (Crew to Moon)	130	120	10
Total Uses	**380**	**370**	**10**
Units Built over Decade			
	19	**19**	**2**
Total Cost over a Decade ($M)			
Unit Cost	4370	2470	400
Maintenance	72.2	180.5	80

Cost	Super Heavy	Super Tanker	Crewed Starship
Launch	76	0	0
Fuel	285.264		
Dev (amortize over 10 years)	1000	1000	3000
SUM	**5803**	**3651**	**3480**
Average Cost per Launch ($M)			
	15.3	**9.9**	**348.0**

Table F-5. Version N using lunar-mined LOX. The per-launch costs are approximately the same as without ISRU; however, the payload mass increases to 100 metric tons traveling both directions.

Cost	Super Heavy	Super Tanker	Crewed Starship
Development	1000	1000	3000
Unit Fabrication	230	130	200
Maintenance per Use	0.2	0.5	10
Launches Per Transit			
Cargo to LEO	1	1	0
Cargo to Lunar Surface	6	6	0
Crew to Lunar Surface	6	5	1
Other Parameters			
Dry Mass [t]	200	130	130
Propellant Mass [t]	3300	1200	1200
ISP [s]			
Lifetime Uses	20	20	5
Launch Site $M per Launch	0.2	0	0
Propellant $M/ton	0.000168		
Quantities for Decade beginning 2030			
Launches (Cargo to LEO)	120		
Launches (Cargo to Lunar Surface)	10		
Launches (Crew to Moon)	10		
Total Uses of Each Unit for Decade			
Total Uses (Cargo to LEO)	120	120	0
Total Uses (Cargo to Lunar Surface)	60	60	0

Cost	Super Heavy	Super Tanker	Crewed Starship
Total Uses (Crew to Moon)	60	50	10
Total Uses	**240**	**230**	**10**
Units Built over Decade			
	12	**12**	**2**
Total Cost over a Decade ($M)			
Unit Cost	2760	1560	400
Maintenance	45.6	114	80
Launch	48	0	0
Fuel	179.424		
Dev (amortize over 10 years)	1000	1000	3000
SUM	**4033**	**2674**	**3480**
Average Cost per Launch ($M)			
	16.8	**11.6**	**348.0**

Table F-6. Version N with partial reusability. The cargo delivery missions do not require the return of the Cargo Starship (which is modeled as a Super Tanker).

Cost	Super Heavy	Super Tanker	Crewed Starship
Development	1000	1000	3000
Unit Fabrication	230	130	200
Maintenance per Use	0.2	0.5	10
Launches Per Transit			
Cargo to LEO	1	1	0
Cargo to Lunar Surface	6	6	0
Crew to Lunar Surface	13	12	1
Other Parameters			
Dry Mass [t]	200	130	130
Propellant Mass [t]	3300	1200	1200
ISP [s]			
Lifetime Uses	10	10	5
Launch Site $M per Launch	0.2	0	0
Propellant $M/ton	0.000168		
Quantities for Decade beginning 2030			

Cost	Super Heavy	Super Tanker	Crewed Starship
Launches (Cargo to LEO)	120		
Launches (Cargo to Lunar Surface)	10		
Launches (Crew to Moon)	10		
Total Uses of Each Unit for Decade			
Total Uses (Cargo to LEO)	120	120	0
Total Uses (Cargo to Lunar Surface)	60	60	0
Total Uses (Crew to Moon)	130	120	10
Total Uses	**310**	**300**	**10**
Units Built over Decade			
	31	**30**	**2**
Total Cost over a Decade ($M)			
Unit Cost	7130	3900	400
Maintenance	55.8	135	80
Launch	62	0	0
Fuel	232.344		
Dev (amortize over 10 years)	1000	1000	3000
SUM	**8480**	**5035**	**3480**
Average Cost per Launch ($M)			
	27.4	**16.8**	**348.0**

Appendix G. Lunar Resources

Availability of Metals for Construction and PGMs

First, we investigate the presence of iron (Fe) on the Moon, partially because it may be used for lunar construction, and because its presence correlates highly with the most likely source of platinum group metals—asteroid impacts—that we will also address here. We do not treat the presence of other metals, such as rare Earth elements, because their terrestrial cost per kilogram is far below the cost of transporting them from the surface of the Moon to Earth. We also do not investigate the use of metals that seem unlikely to be used for lunar or orbital construction, such as titanium and aluminum. These metals might be used for construction or novel forms of hybrid propulsion, but their use in aerospace systems is generally driven by an incentive to reduce mass, so as to escape Earth's gravity and atmosphere. This incentive is diminished on the Moon because of the reduced gravity and lack of atmosphere. Aerospace systems manufactured on the Moon may not need to minimize system mass.

Iron can be found on the lunar surface at three types of sites: basaltic plains, regolith, or in craters where it has been deposited by asteroid impacts. Iron is approximately 14 to 17 percent by mass in all mare basalts (Crawford), especially pyroxene, olivine, and ilmenite. If one were already mining these minerals for their oxygen, iron would be one of the by-products. Iron found natively in the regolith may be approximately 0.5 percent of the regolith by mass; however, given the presence of the iron as nanophase particles embedded in glass or as sub-micron particles in the regolith, it is unclear whether native iron can be extracted.

The potentially most significant source of iron may be from impacts of M-class asteroids. We follow the logic outlined by Wingo (2004) to estimate the amount of potentially recoverable asteroid material. Depending on the speed of impact, modeling suggests that 15 to 63 percent of an impacted M-class asteroid's mass may remain in the vicinity of its impact crater as a shell covering the crater surface, for impact velocities of 20 km/s and 15 km/s, respectively (Schnabel et al. 1999). The average impact speed of an asteroid on the lunar surface is estimated at approximately 16 km/s, which falls within the impact speed range above (Center for Lunar Science and Exploration n.d.). Assuming a linear relationship between impact speed and remaining mass, a 16 km/s impact would leave approximately 53 percent of the mass of the asteroid in a recoverable condition. Wingo assumes that the impactor that created Diablo Canyon, with a crater diameter of about 1 kilometer, was at least 100,000 tons (Masaitis 2006); this appears to be a conservative estimate. That means a single M-class asteroid impact site, with a 1-kilometer crater rim diameter, may have left behind 15 to 53 kilotons of recoverable metals.

Much of this recoverable mass is theorized to still be inside the crater; the mass is thought to line the basin of the crater in the form of a shell that may be only meters thick. Wingo reports that there are approximately 28,000 craters on the lunar surface with a diameter of approximately 1 kilometer that were produced by m-class asteroid impacts. According to this line of reasoning, larger craters may have far greater amounts of metals that survived impact. While this is reasonable, it is not clear what fraction of this metal may be reachable from the lunar surface. As an extreme example, the remains of the impactor that caused the Aitken Basin crater (rim diameter of 2,000 kilometers) is estimated to be hundreds of kilometers below the surface (James et al. 2019), rendering it wholly inaccessible. For this analysis, we will restrict ourselves only to those small craters which are abundant and most likely, though not certain, to leave their recoverable mass near enough to the lunar surface for exploitation.

M-class meteorites are primarily composed of iron and nickel, with the iron content ranging from approximately 80 percent to 94 percent, nickel making up the vast majority of the remaining mass. For our analysis, we will use abundances of 85 percent for Fe and 14 percent for Ni. Thus, a single impact crater of 1km in diameter created by an M-class asteroid may have left at least 12,000 metric tons of recoverable Fe and 2,000 metric tons of recoverable Ni.

The platinum group metals are a set of six elements that have similar physical and chemical properties: ruthenium (Ru), rhodium (Rh), palladium (Pd), osmium (Os), iridium (Ir), and platinum (Pt). Reported ranges of platinum concentrations in M-type asteroids range from 0.07 to 142 parts per million (ppm), with an average of approximately 11 ppm (Ryan 1990; Hoashi 1993). To put this in perspective, platinum mines on Earth do not typically reach the concentrations of platinum associated with M-class asteroids. The Bushfeld Igneous Complex in South Africa, the largest platinum mine in the world, has concentrations of *all* PGMs of 8.1, 8.7, and 7 to 27 ppm at three different sites; the Stillwater, Montana mine has PGM concentrations of 22.3 ppm (Seymour 2012).

Using current estimates for the concentration of precious metals in m-class asteroids (See Appendix F), 2018 prices for those metals, and assuming full recovery of the material, that if a Moon miner could locate a 1-kilometer crater caused by an m-type asteroid, a reasonable range for the value of precious metals found in that vicinity would be $16 to $57 million dollars (x multiplied by y). It is clear that precious metals and PGMs from a single small crater are not likely to be sufficient to cover development costs. Thus, a mining architecture for PGMs for sale on Earth might necessarily consist of widely distributed mines that are not able to share resources among themselves.

Availability of Volatiles for Propellant

The volatiles of greatest interest for rocket propellants are Hydrogen (H), Carbon (C), and Oxygen (O). Pure hydrogen can be used as rocket fuel, or it can be combined with carbon to produce methane and other hydrocarbon fuels. Fuel needs an oxidizer with which to combust and release its energy, for which oxygen is the natural choice for lunar production. We do not investigate other volatiles here as they are of relatively lesser importance. Lunar helium is treated separately in Section B.4.

Oxygen is abundant on the lunar surface, though mostly bound within silicate minerals (Office of Technology Assessment 1991). The most studied process for oxygen extraction uses ilmenite ($FeTiO_3$), which is common in the equatorial basalt mares, but scarce near the poles. The process requires the presence of hydrogen as a catalyst to pull the oxygen out of the ilmenite and produces water, which would subsequently be electrolyzed into H_2 and O_2. Theoretically, this process may only require tens of kilowatt-hours to produce one kilogram of O_2; however, experiments suggest that the true energy requirements may run in the megawatt hours per kg of O_2, due to the high temperatures (700–1,000 degrees C) required to produce the reaction (Crawford 2015). We assume that mining of oxygen from lunar basalt is unlikely to occur in meaningful quantities if lunar water mining operations are successful. This is largely because oxygen will be a "waste" product from the electrolysis of water into propellant. Therefore, we will not estimate a cost for a mining architecture that mines oxygen from minerals, but focus instead on water as the source of oxygen.

Water may be present on the Moon in PSRs, pyroclastic deposits, and in hydrated minerals. PRSs are areas of the lunar surface that never receive direct sunlight. Their temperatures are measured to be below 40 K (Paige et al. 2010 via Crawford 2015), and they have long been thought to be capable of freezing and trapping water molecules as ice. The NASA Lunar Crater Observation and Sensing Satellite (LCROSS), a robotic mission launched to assess the nature of hydrogen detected at the polar regions of the Moon, definitively confirmed this hypothesis when it measured water present in PSR regolith at 5.6 ± 2.9 percent by mass (Colaprete et al. 2010). This water may come from comets, hydrated meteorites, or interactions of the regolith with the solar wind (Crawford 2015). The total surface area of the Moon covered by PSRs is estimated at 13,400 square kilometers in the northern hemisphere and 17,600 square kilometers in the southern hemisphere (McGovern et al. 2013). Using the one sigma range of water density measured by LCROSS, we can calculate the range of regolith densities within the PSRs, multiply the densities with the volume of lunar surface that is in the top meter of all PSR regions, to find that the top meter of the lunar surface may contain approximately 1.3 to 4.3 billion metric tons of water trapped in PSRs. By comparison, Earth's fresh liquid surface water in lakes and rivers are approximately 9.3 trillion metric tons.

Water can potentially also be found outside of the PSRs. Remote sensing data has found evidence that suggests that there are hydrated minerals in the high latitude regions (Pieters et al. 2009). Hydrated minerals contain water (H_2O) and hydroxide ions (OH) embedded in the structure of the mineral; the water is not liquid and would require the application of substantial heat to liberate these volatiles from their mineral matrix. Estimates of the concentration of water in hydrated minerals range as high as 770 ppm; however, the true values may be substantially lower. Similarly, there is evidence that water may exist in pyroclastic deposits. Apollo samples observed concentrations of 30 ppm, while some estimates suggest concentrations as high as 1,500 ppm by mass (Crawford 2015). Despite lower concentrations of water than PSRs, pyroclastic deposits are potentially attractive because they occur at lower latitudes (e.g., the Apollo landing sites) where energy from sunlight is abundant (Crawford 2015). They may also cover a similar amount of lunar surface areas as PSRs (Crawford 2015). Because water in the polar PSRs is abundant and we believe that polar missions are more likely than low-latitude missions for mining water, our cost estimates will focus on the mining of polar water for propellant.

The abundance of carbon, which would be required for the creation of methane for fuel, is highly uncertain. Crawford reports that it may be found in regolith at concentrations of 124 plus or minus 45 ppm by mass, having been implanted by the solar wind (Crawford 2015). These concentrations are unlikely to represent the concentrations found in the PSRs, which were measured by the LRO-LAMP instrument on the LCROSS mission. Initially, Gladstone reported that carbon monoxide was 5.7 percent of the mass of the measured PSR (Gladstone et al. 2010). Such supposedly abundant carbon monoxide, roughly the abundance of water by mass, would enable the production of large amounts of methane. However, a year later, an erratum to the original paper was published that revised the abundances of all reported atomic volatiles downward by a factor of approximately 5, and revised the carbon monoxide abundance to only 0.7 percent. At concentrations this low, we have decided not to estimate the cost of producing methane on the surface of the Moon.

Table G-1. Concentrations and Prices of Precious Metals in a kilogram of M-type Asteroid Material or Lunar Regolith

Class	Element	$/kg	PPM in M-type	PPM in Regolith	$/kg for M-type Material	$/kg for Regolith
Precious	Silver	$583				
Precious	Gold	$39,417	1.13	0.0000062	0.044541	$0.04
PGM	Ruthenium	$8,681	6.2	2080	0.05382	$0.05
PGM	Rhodium	$77,966	2.08	4750	0.162168	$0.16
PGM	Palladium	$35,945	4.75	4610	0.170736	$0.17
PGM	Osmium	$32,151	4.61	3700	0.148215	$0.15
PGM	Iridium	$47,583	3.7	11300	0.176057	$0.18

Class	Element	$/kg	PPM in M-type	PPM in Regolith	$/kg for M-type Material	$/kg for Regolith
PGM	Platinum	$27,907	11.3	0.0000062	0.315347	$0.32
Bulk	Iron	$0.09				
Bulk	Nickel	$14				
Bulk	Cobalt	$33				
Bulk	Titanium	$5				
Bulk	Aluminum	$2				
REE	Scandium	$3,458				
REE	Yttrium	$33				
REE	Lanthanum	$5				
REE	Cerium	$5				
REE	Praseodymium	$95				
REE	Neodymium	$53				
REE	Promethium	NA				
REE	Samarium	$16				
REE	Europium	$31				
REE	Gadolinium	$29				
REE	Terbium	$646				
REE	Dysprosium	$307				
REE	Holmium	$57				
REE	Erbium	$26				
REE	Thulium	NA				
REE	Ytterbium	$17				
REE	Lutetium	$643				
Semi	Silicon	$2				

Appendix H. Tourism Cost Curves

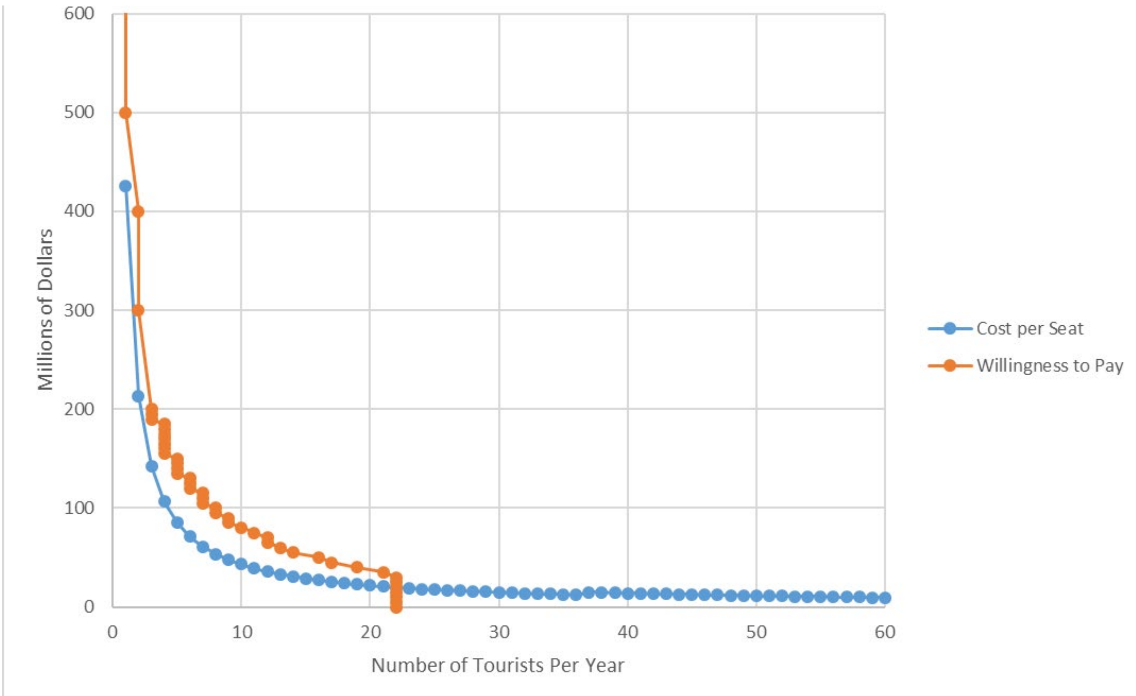


Figure H-1. Cost and Willingness to Pay [Starship Flyby and 3.2% Willingness to Pay]

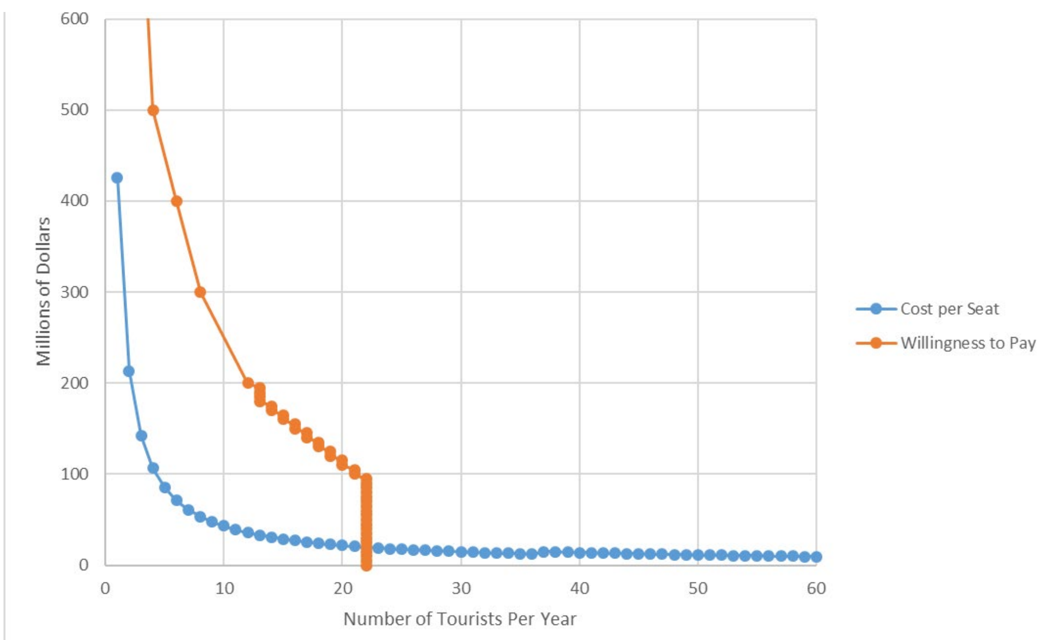
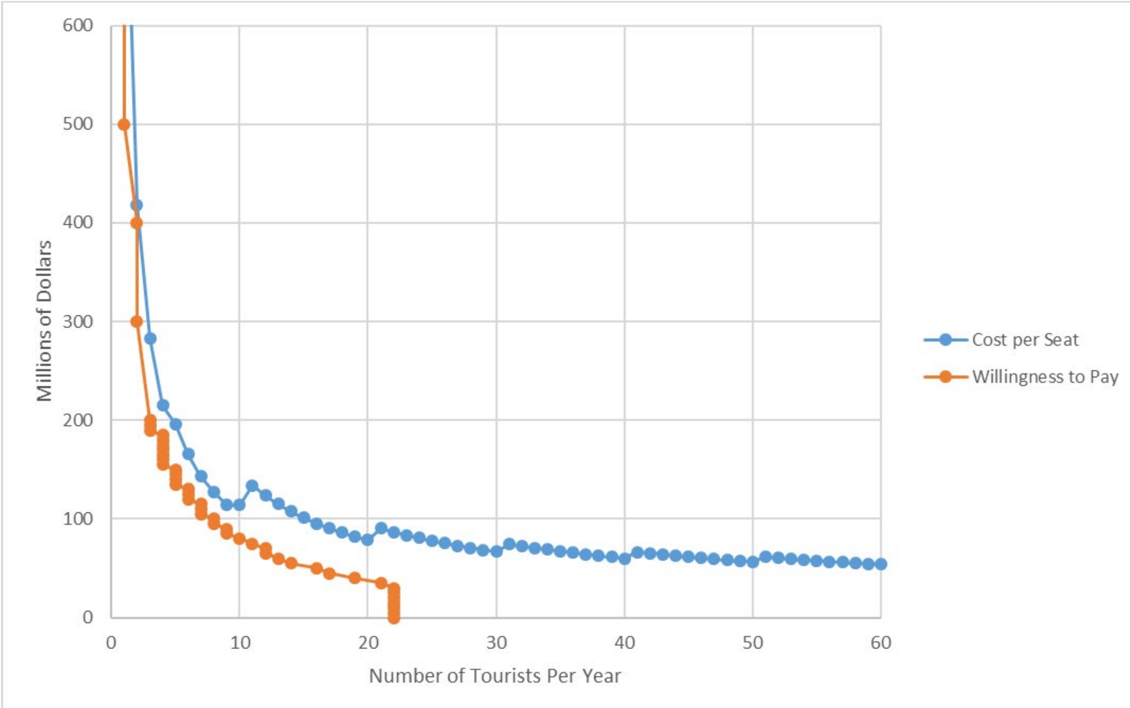


Figure H-2. Cost and Willingness to Pay [Starship Flyby and 10% Willingness to Pay]

Figure H-3. Cost and Willingness to Pay [Starship Landing and 3.2% Willingness to Pay]



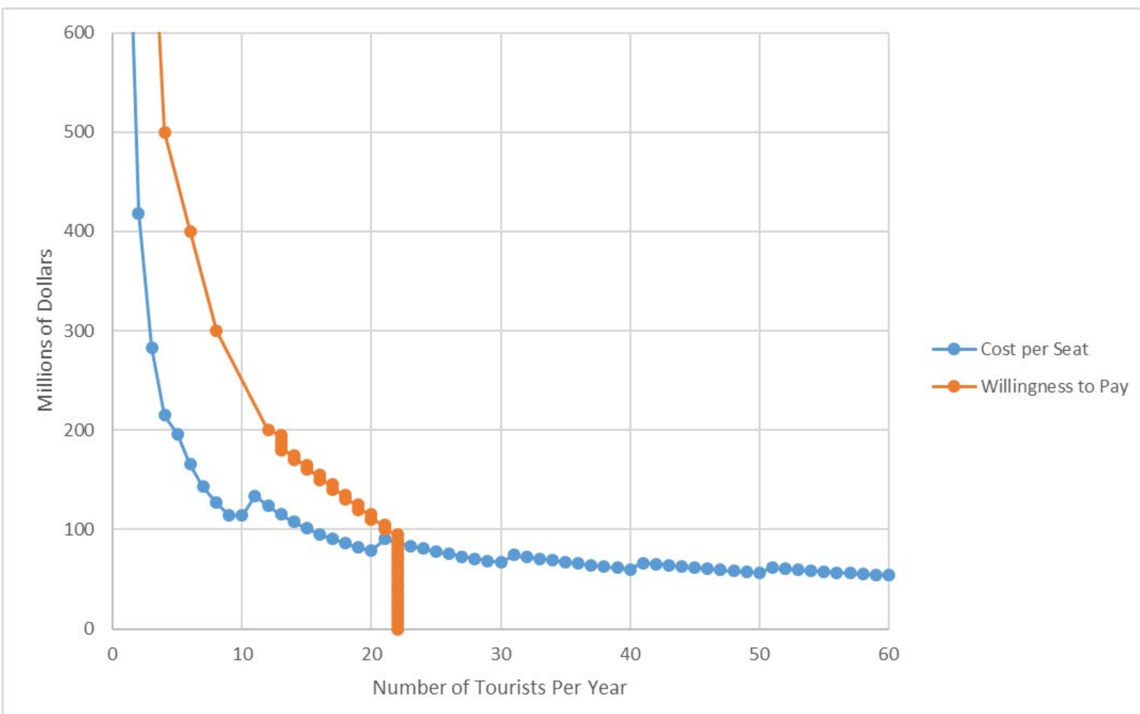


Figure H-4. Cost and Willingness to Pay [Starship Landing and 10% Willingness to Pay]

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Abbreviations

3-D	three-dimensional
AR	augmented reality
CGI	computer-generated imagery
CLPA	Commercial Lunar Propellant Architecture
CLPS	Commercial Lunar Payload Services
CSA	Canadian Space Agency
DMF	dry mass fraction
DOD	Department of Defense
DOE	Department of Energy
ECLSS	Environmental Control and Life Support Systems
ESA	European Space Agency
FAA	Federal Aviation Administration
GEO	geosynchronous Earth orbit
He-3	Helium-3
HLS	Human Landing System
HV	high vacuum
IDA	Institute for Defense Analyses
ISRO	Indian Space Research Organisation
ISRU	in-situ resource utilization
ISS	International Space Station
JAXA	Japan Aerospace Exploration Agency
K	kelvin
KARI	Korea Aerospace Research Institute
kW	kilowatts
kWh	kilowatt-hour
LEM	Lunar Excursion Module
LEO	low Earth orbit
LH2	liquid hydrogen
LLO	low lunar orbit
LOX	liquid oxygen
LRV	Lunar Roving Vehicle
MW	megawatt
NASA	National Aeronautics and Space Administration
O&M	operations and maintenance
OMB	Office of Management and Budget
OSTP	Office of Science and Technology Policy
PGM	platinum group metals
PNT	position, navigation, and timing
PSRs	permanently shadowed regions
PTS	Planetary Transportation System

PVEX	Planetary Volatiles Extractor
SSTO	single-stage-to-orbit
STPI	Science and Technology Policy Institute
TLI	trans-lunar injection
TRL	technology readiness level
UHV	ultra high vacuum
VIPER	Volatiles Investigating Polar Exploration Rover
VR	virtual reality
WSF	Wake Shield Facility
XHV	extremely high vacuum

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14. ABSTRACT
For the next several years, a return to the Moon is likely to be the preeminent goal of the U.S. human space endeavor, with an initial landing of U.S. astronauts expected in the 2020s. Subsequent to the initial landing, the National Aeronautics and Space Administration (NASA) plans to develop a lunar base for a longer-term sustainable presence on the surface of the Moon. Some in the space industry have argued that a return to the Moon may lead to the creation of a more commercially oriented lunar economy that involves mining operations, tourism, scientific exploration and other activities, to be funded by governments, individuals, and businesses. To ascertain whether private sector demand could support commercial lunar activities, we examine the present contours and future scale of demand drivers of lunar and cislunar activities through 2040, with a focus on non-NASA commercial demand. This study was performed between September 2019 and March 2020. We looked at, but did not evaluate, demand for lunar goods and services to enhance U.S. national security, because of the lack of information at an unclassified level. We identified goods and services that might generate sufficient non-government revenue to be commercially viable. We also highlighted other goods and services that will require enhanced support from the U.S. government if they are to become economically viable.

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