Space Resource Economic Analysis Toolkit: The Case for Commercial Lunar Ice Mining

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TABLE OF CONTENTS

1.0 EXECUTIVE SUMMARY

An integrated engineering and financial modeling approach and Excel toolkit has been developed and used to evaluate the potential for private sector investment in space resource development, and to assess possible roles of the public sector in fostering private interest. This report presents the modeling approach and its results for a transportation service using propellant extracted from lunar regolith to provide transfer between low Earth orbit (LEO) and geosynchronous orbit (GEO).

The modeling approach started with the definition of an economic case study, including a thorough analysis of the customer base leading to the development of a demand model. These inputs form the foundation for developing an engineering model of a modular, scalable commercial space architecture designed to meet demand. A cost model derived non-recurring, recurring and operations costs, which became inputs for a 'standard' financial model, as used in any commercial business plan. This financial model generated pro forma financial statements, calculated the amount of capitalization required, and generated return on equity calculations using two valuation metrics of direct interest to private investors: market enterprise value and multiples of key financial measures. Finally, sensitivity analysis with respect to key strategic, market and technological inputs helped to further explore the conditions for financial viability.

This modeling approach is illustrated on a lunar propellant case study. Two separate architectures were developed that model the conversion of water held in permanently shadowed lunar craters into propellant for use in near-Earth space transportation, in particular to convey payloads from low Earth orbit (LEO) to geosynchronous Earth orbit (GEO). Both models generated nearly identical economic results, identifying the technical and financial conditions under which the architectures could become commercially attractive.

Production and transportation system masses were estimated for each of the two architectures, and cost analysis was made using the NAFCOM and SOCM cost models. Data from the cost models were analyzed using standard financial analysis tools to determine under what conditions the architectures might become commercially viable. Analysis of the architectural assumptions were used to identify the principal areas for further research, which include technological development of lunar mining and water extraction systems, power systems, reusable space transportation systems, and orbital propellant depots. The architectures and their commercial viability are strongly sensitive to the assumed concentration of ice in the lunar deposits, suggesting that further lunar exploration to determine whether higher-grade deposits exist could be economically justified. Business assumptions, in particular the implications of government support of the R&D required for system development, were also explored.

This use of the modeling approach on two architectural variants of a lunar propellant case study demonstrates how to rapidly test various assumptions and identify interesting architectural options, key areas for investment in exploration and technology, or innovative business approaches that could produce an economically viable industry. The same approach could be used to evaluate other possible commercial ventures in space, providing feedback about the respective roles of NASA and the private sector in space resource development and solar system exploration.

2.0 INTRODUCTION

NASA is studying options for expanded solar system exploration, and the NASA Exploration Team (NExT) is exploring alternative mission architectures and enabling technologies. An important consideration in these studies is the potential role for the private sector in supporting solar system exploration, and how NASA can leverage private sector capabilities to achieve its objectives more cost-efficiently. However, while there is a broad consensus that private sector participation is desirable, there has been a limited amount of work within NASA to address this question from the perspective of the private sector. Chartered by NExT, the Jet Propulsion Laboratory (JPL) chose the Colorado School of Mines (CSM), and CSP Associates, Inc. to help them develop an economic modeling tool to complement engineering studies by simulating the private sector investor's point of view.

Although qualitative arguments can be made for the benefits of on-orbit servicing, space manufacturing, planetary surface mining, etc, no realistic conclusion can be reached without quantitative analysis of the financial viability of a private venture. In order to reach solid conclusions regarding economic feasibility a flexible, integrated financial and engineering model was required. The multi-disciplinary science, engineering and financial team was gathered in order to model all aspects of the proposed commercial venture, and bridge the gap between NASA and the private sector. The model developed and described herein was applied to a specific case study of commercial lunar propellant utilization. However, it is believed that this approach and especially the modeling approach and toolkit will be useful for many other architectures and space-based ventures.

A scenario to sell in-space transport based on lunar propellant was proposed as the first case study to examine the potential for space resource economic viability. Smitherman (2001) showed that there is a significant market for LEO-to-GEO transport based on cryogenic H_2/O_2 propellants. Although that study assumed Earth-based propellant, the Moon is actually much closer to LEO in terms of delta-V requirements than the Earth's surface. In addition, the Lunar Prospector's mission data indicated sufficient concentration of hydrogen (presumed to be in the form of water ice) to form the basis for lunar in-situ mining activities to provide a source of H_2/O_2 propellants. Such propellant could also be very useful to NASA's solar system exploration missions if provided at the Earth-Moon L1 Lagrange point, highlighting the potential for public as well as private interest. Finally, preliminary engineering analysis based on known terrestrial mining and processing technologies showed that the required architecture mass would be much smaller than the total mass of propellant it could produce and deliver to L1 or LEO. Based on these preliminary checks, the team set out to analyze LEO-to-GEO transport using lunar-based propellants.

Note that the presence of ice on the Moon, its concentration and abundance, and its physical properties are conjectures at this point. The technology for working within permanently shadowed craters on the lunar surface, where temperatures are less than 100 K, is at a conceptual state of development at best. Also, there is no present customer that can readily accept propellant that could be produced from these water deposits, although propellants are used in substantial quantities to convey payloads such as communications satellites from LEO to GEO. The model's assumptions are described, but they should be taken as propositions that remain to be demonstrated, not facts. Nevertheless, analysis of the architecture model allows one to discuss which of the assumptions are most critical and to provide some guidance for further exploration and technology development.

2.1 THE BASIS FOR SPACE RESOURCE VALUE

A number of studies have shown the potential offered by space resource utilization for space missions. Eagle Engineering (EEI, 1988) conducted a systematic study of the potential for using lunar oxygen in support of lunar missions. Other studies have described similar applications for Mars missions (e.g. NASA, 2001). Duke (1998) analyzed possible lunar ice extraction techniques and (Rice, 2000) showed how using this ice to produce lunar-based cryogenic H_2/O_2 propellants would reduce the Earth launch mass for a reference lunar outpost mission by up to 68%. Based on similar assumptions of NASA lunar transportation requirements, Nelson (2001) calculated the price a private venture would need to charge for transfer of cargo and astronauts to the Moon. Borowski (1997) studied the improvements in lunar transportation that could be brought about by nuclear thermal propulsion. For low Earth launch costs and given transportation requirements, Stancati (1999) showed that using lunar-based LOX and LH_2 and nuclear thermal propulsion could enable technical improvements in Earth launch mass of up to 51%, but with negligible cost improvements. These are only a few examples of a wealth of interesting engineering studies that characterize what we might call the "potential for space resources supply".

Although much less numerous, there also have been a few studies to characterize the "potential for space resources demand". The commercial space transportation study (CSTS, 1994) carried out a systematic, quantified analysis of potential markets for future launch services. Smitherman (2001) quantified the demand for cryogenic propellants in LEO for LEO-to-GEO transfer. Between these two bodies of research and analysis (the "supply" and the "demand"), there is a clear gap: Among all the architectures proposed for space resources development, do any suggest (financially) viable private ventures?

High-level definition of the lunar propellant case study began with a combination of engineering and financial "common sense." First, an identifiable, predictable market must exist. For example, the projected market for in-space transportation services was derived from current government and commercial launch demand to various orbital destinations. Second, there must be good potential for market capture, i.e. a potential for providing the resource cheaper than direct or functionally equivalent competitors. In the case of LEO-to-GEO transfer based on lunar propellant, two already-established competitors exist that guide initial pricing assumptions: (1) direct launch into GEO, and (2) use of Earth-based propellants transported to a LEO fuel depot (e.g., Smitherman, 2001).

Because a commercially viability venture relies on private investment, a model that represents costs and benefits in private sector investors' terms was needed. To do this, an engineering system architecture must be developed, costs of development, production and operation of the system must be estimated, and a reasonable set of market assumptions adopted. The integrated model then can be used to determine financial feasibility.

2.2 TRANSPORTATION AND LOGISTICS

Transportation in space is a major consideration because of its high cost. Indeed, high launch costs are one of the primary reasons an in-space fuel source has value. While the unit cost of in-space production of a resource can be expected to be much higher than on Earth, its in-space transportation cost from the place of production to the place of use in space has the potential for being much lower than launch cost from Earth. A secondary argument for value is the potential for reuse and refueling of orbital transfer vehicles, which can be compared with the current practice of expending launch vehicle elements after their first use. If inexpensive propellant can be provided in space, these otherwise disposable vehicles may gain in value.

Non-engineering professionals often think of space transportation in terms of distance. The idea that LEO is closer to Earth than the Moon is only true in terms of distance (LEO lies roughly 0.1% of the distance to the Moon - see Table 2.1). A more relevant variable, and the one most commonly reported in the aerospace literature, is the change in velocity required to reach a specific orbit (ΔV, typically reported in km/s). However, the best metric for the energy it takes to get from one orbit to another, and therefore for the amount of propellant needed, can be found by squaring ΔV (ΔV^2 is reported in units of mega joules per kilogram – a direct measurement of energy). Table 2.1 shows distance, ΔV and ΔV^2 for the Earth-Moon system. Note that by using the ΔV^2 metric, LEO is 83% of the way to the Moon. Add the efficiency of aerobraking, and LEO is over 96% of the way to the Moon (the ΔV to aerobrake from the Earth-Moon L1 Lagrangian point to LEO is only 500 m/s, compared with 4.6 km/sec for a propulsive maneuver). This clearly demonstrates the transportation energy advantage that the Moon holds over the Earth (see Figures 2.1 - 2.3 for a graphical sketch of the Earth-Moon system in ΔV^2 scale), for operations in LEO or higher orbits. Values in Table 2.1 assume the use of Hohmann transfers, which are typical of high-thrust systems (advantages of high-thrust cryogenic systems over low thrust ion propulsion include faster transit times, technological heritage and lower costs).

Table 2.1. Comparison of scales in the Earth-Moon system.

Location	Distance (km)		Delta V (km/sec/kg)		Delta V^2 (MJ/kg)	
	increment	cumulative	increment	cumulative	increment	cumulative
Earth-LEO	400	400	9.5	9.5	90.3	90.3
LEO-GEO	29022	29422	3.8	13.3	14.4	104.7
GEO-L1	256100	285522	0.8	14.1	0.6	105.3
L1-LLO	92400	377922	0.9	15.0	0.8	106.1
LLO-Moon	100	378022	1.6	16.6	2.6	108.7

Note that the values for ΔV have been calculated for most known sources of space resource materials (exceptions include unidentified asteroids). Transportation systems in space must carry their own propellants and it is straightforward to take a design for a transfer vehicle, determine its performance, and utilize the rocket equation to determine the amounts of propellant needed to make a particular transfer.

Figure 2.1. Earth-Moon Transportation Energy using ΔV scale (1” = 4.3 km/s/kg).

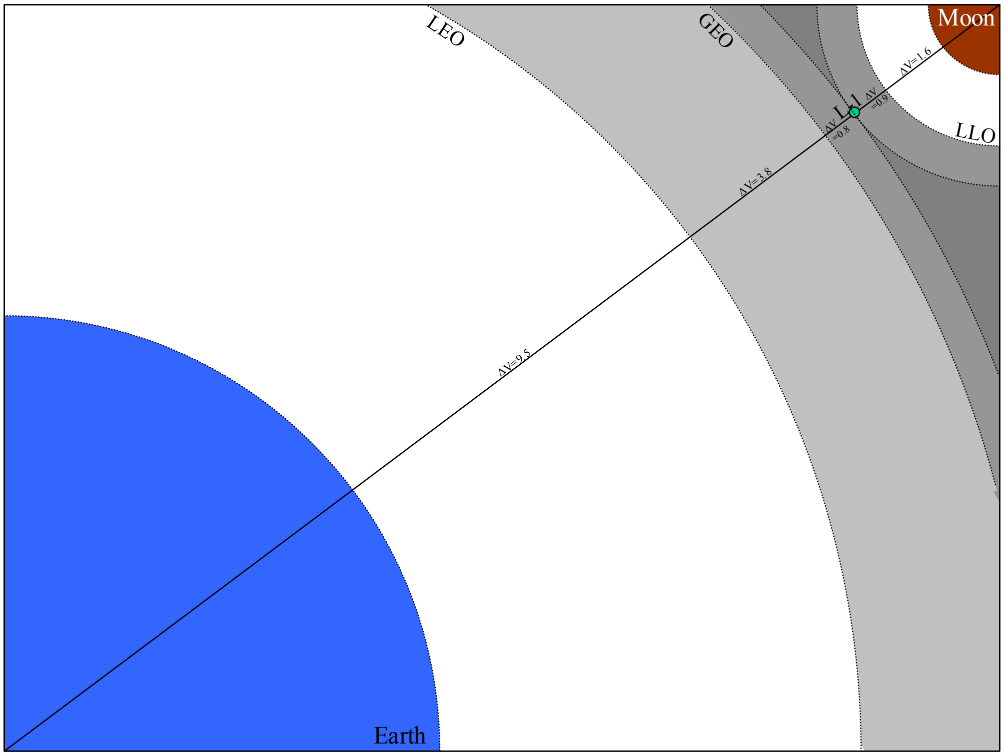


Figure 2.2. Earth-Moon Transportation Energy using ΔV^2 scale (1” = 32 Mj/Kg)

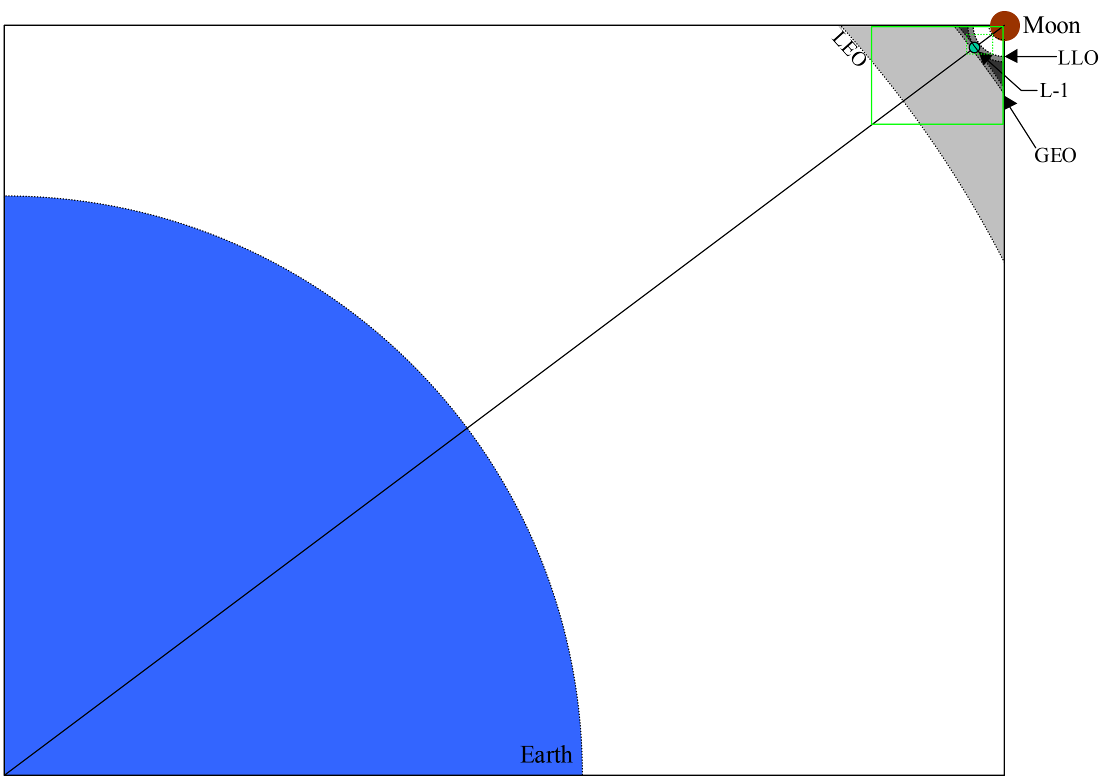
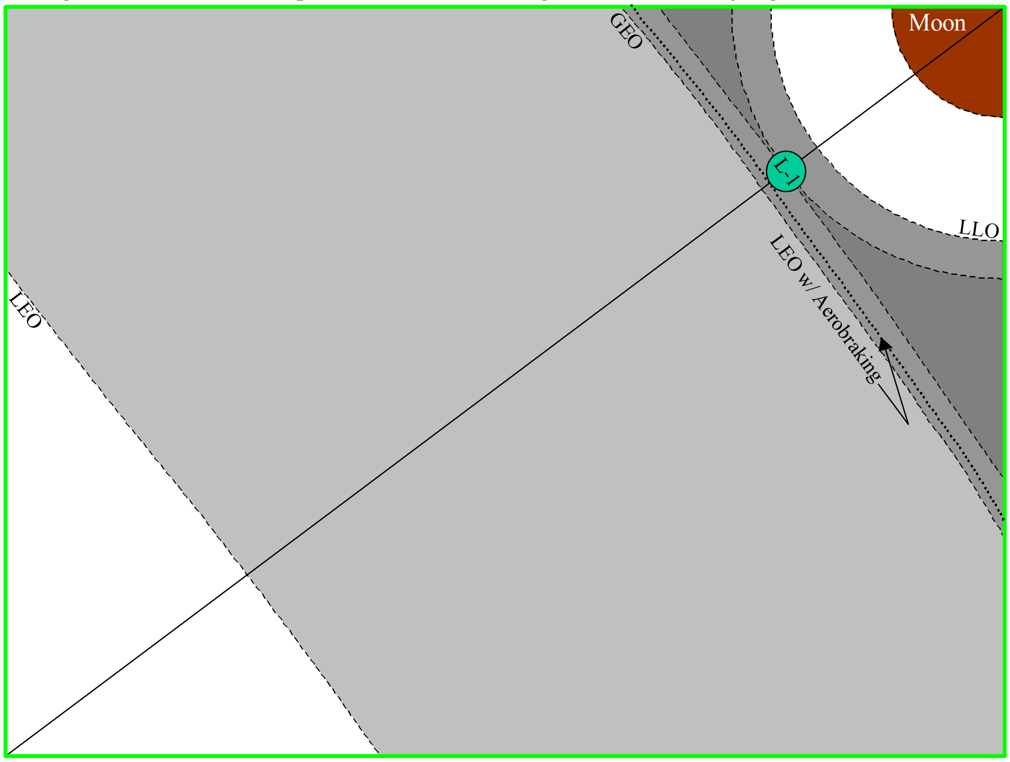


Figure 2.3. ΔV^2 close-up of the LEO-Moon region (1" = 4.25 Mj/Kg).



2.3 SPACE MINERAL RESOURCES

For many years, the possible presence of water ice in the lunar regolith has been one of the rationales used in the lunar science community to justify further lunar exploration, on the basis of its perceived value as a resource. The existence of permanently shadowed craters near both the lunar North and South poles was confirmed by the Clementine (see Nozette et al., 1995). Lunar Prospector data (see Feldman et al., 2001) demonstrates enrichment in the hydrogen concentrations in these polar regions, suggesting ice concentrations on the order of 1.5 weight percent of the regolith (i.e., one ton of lunar regolith may contain as much as 15 kilograms of water ice according to Neutron Spectrometer data). This value represents an average over a large area (the footprint of the Lunar Prospector Neutron Spectrometer instrument is a 60km arc – see Feldman, 2001), and the chance of higher ice concentrations is good. While the discovery of ice has increased the public perception that commercially significant resources may exist on the Moon, the demonstration of commercial feasibility is a more complex matter.

Other mineral-based resources also exist in space. Among those frequently cited are noble metals in stony iron and iron asteroids and lunar helium-3, both of which involve the extraction of trace constituents from regolith. The basis for considering these resources is that there is an identifiable demand on or around Earth. However, space resources will most likely be used in space. Therefore, it is likely that those that are most easily and reliably obtained will be used first. These could include water, wherever it is found, oxygen for propellant, metals and silicate minerals for construction or manufacturing, silicon for solar cells, etc.

3.0 INTEGRATED MODELING APPROACH

The previous sections reviewed the rationale for considering a private venture producing lunar water-based propellant for use in Earth orbit. This section proposes a general integrated financial and engineering modeling approach to assess the financial viability of such a venture. This approach will be used in the following sections to conclude on the case study.

Multi-disciplinary science, engineering and financial inputs are required in order to model all relevant aspects of a private venture in space and bridge the gap between NASA and the private sector. An integrated financial and engineering model based on a private investor perspective is one way to bridge this gap, for three main reasons:

- First, an architecture optimized from an engineering point of view is not necessarily the most interesting for a private investor. For example, in the framework of a growing demand, economies of scale could lead the engineer to build up in the first year the capacity needed ten years down the line; while the private company might prefer investing in a scalable architecture, and build up capacity only as demand increases.
- Second, the metrics of interest to private sector investors differ from those that public sector engineers traditionally use for economic analyses. A 'business case analysis' is required to translate the engineering costs estimates into the metrics of interest to private sector investors.
- Third, an informed and effective public policy and strategy for space exploration demands that architecture trades, and initiatives regarding the private sector assess a wide range of scenarios. A single business case yields a specific outcome that is a function of its baseline assumptions. For NASA to effectively incorporate the private sector into its long-term plans, it should explore a wide range of potential space ventures, the conditions under which they would flourish, the steps that NASA can take to encourage them, and the public benefits/costs of those steps. To make these numerous case studies fast, accurate and comparable, a common analytic framework is required.

3.1 THE CASE FOR A PRIVATE INVESTMENT PERSPECTIVE

As a team of public-sector aerospace engineers designs a space architecture, the only economic information they typically compute are the architecture cost elements (development, production, launch, operations). Applying a government discount rate and adding up yearly costs yields the Net Present Value (NPV) metric they widely use to compare designs for commercially oriented missions. For example, to assess the potential of using Orbital Transfer Vehicles (OTVs) to transfer satellites from LEO to GEO, one would compare the lifecycle NPV of a GEO mission without OTV, to the lifecycle NPV of the same GEO mission with OTV. If the latter turns out to be more expensive, the venture is clearly not viable. If on the other hand the mission with OTV is cheaper, there might be a potential market for OTV transfer. Is that sufficient for private companies to start investing in the venture? Unfortunately it is not, particularly in today's competitive capital markets.

Capital markets view commercial space as unpredictable, illiquid and high risk: high capital intensity, extensive R&D and regulatory costs translate into long and expensive product development cycles. Markets are often immature and unpredictable, or perceived to offer limited growth potential. Governments often subsidize competition, and market exit is difficult or 'sticky'. Shareholdings are illiquid and long term. Accordingly, any venture starts against significant financial impedance, and a simple NPV calculation does not give the information on which a private company would actually base its investment decision.

The first question asked by an investor is: "What are the discounted net present value and the effective rate of return on my equity investment?" Two common metrics used to answer this question are discounted Enterprise Value and discounted Price to Earnings multiple value in "Year X":

- Year X is defined in terms that an investor might be willing to endure – at most seven to ten years. If a venture cannot show interesting value in that timeframe, decision makers will turn to their other investment choices, especially in the framework of uncertain demand.
- The Enterprise Value (EV) is typically used when a company is privately held, and thus there is no public market valuation for the equity. EV in Year X is essentially the cumulative net value of the cash that the investors would achieve if they sold their stake in Year X.
- The discounted Price-Earnings (P:E) metric is used when the equity is publicly traded. P:E measures the value of the shares of stock as a multiple of the company's earnings per share. In essence, this valuation predicts what the shares will be worth in Year X, and thus provides a basis for calculating the real rate of return for the equity investor.

In both cases, the appropriate discount rate accounts not only for the effects of inflation, but also for the perceived risk of the venture: a dollar of return today is more predictable, and less risky than a dollar of return in the future. A decision to invest requires that the discounted future return on the investment not only be positive, but exceed an acceptable threshold, relative to the business' perceived level of risk and alternative uses of that capital.

If the rate of return for EV and/or P:E is sufficient, the private investor might then want to consider a "breakeven' analysis". Typically, this moves from top to bottom of an Income Statement: Gross margin breakeven (how soon can we make revenues greater than our direct costs of production?); EBITDA breakeven (how soon can we make revenues greater than our on-going cost of running the business?); EBIT breakeven (how soon can we make net revenues after accounting for the depreciation of our capital) and Net breakeven (how soon can we make money after paying the interest on our loans and taxes?). The financial attractiveness of a venture improves as these breakeven periods contract; conversely, as breakeven period lengthen, investors become less tolerant of risk and will impose a higher discount rate to account for uncertainties.

3.2 THE FINANCIAL MODEL

CSP Associates, Inc. developed a generic financial model to translate engineering cost numbers into the financial parameters just described. The tool models in a very generic way the three principal financial accounting documents that are used to calculate the performance of a private sector enterprise and yield the desired valuation metrics:

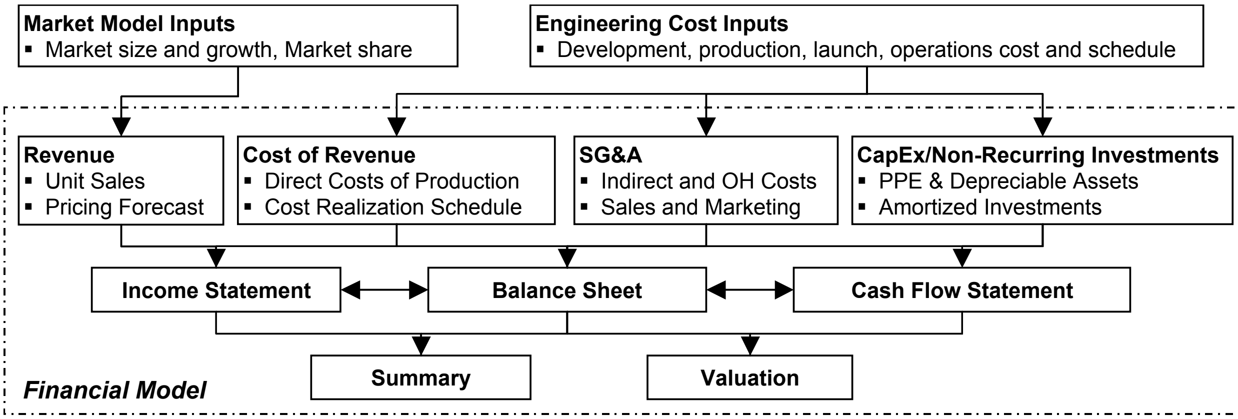
1. An Income Statement documents the profits and losses of the venture. Starting with the generated revenues, it subtracts first the cost of goods sold, then the sales, general and administrative costs (SG&A), the estimated depreciation and amortization, the debt interest payments, and calculates the taxes, to finally yield a net income.
2. A Balance Sheet provides an annual snapshot of the firm's year-end assets (sum of current assets such as cash and receivables, plus long-term assets such as the value of physical plant) versus its liabilities (sum of current payments owed by the company, long term debt, investor's equity and retained earning/losses).
3. A Cash Flow Statement characterizes the venture's cash flows, in other words, where the required funds come from (revenues and financing) and what they are used for (recurring and non-recurring expenses, financing costs). The statement incorporates assumptions on the firm's capital structure strategy, i.e. the proportion of debt and equity used for funding.

As illustrated in Fig. 3.1, these Pro-Forma statements require four types of financial inputs that in turn rely on outputs from the demand and engineering analyses:

1. The Revenue inputs require a quantitative estimate of demand as a function of time, in terms of quantity of demand (forecasted number of units of the product consumed each year), market share of the venture (percentage of this total product market captured by the venture each year), and unit price through time.
2. The Cost of Revenue inputs describe the direct marginal cost of producing each additional unit, each year. For a space venture, these typically include manufacturing, operations and delivery cost.
3. The SG&A (sales, general and administrative) inputs describe the indirect costs of business operations; this includes the costs associated with management, executive and marketing staff, staff training, overhead, rent, etc.
4. The CAPEX (capital expenditures) inputs require an estimate of all non-recurring investments and their amortization schedule; in the case of a space venture, this comprises all development costs as well as the cost of facilities and equipment, including all space elements.

These four types of required outputs lead the development of the integrated engineering and economic modeling approach.

Figure 3.1. Four primary input sheets drive the financial model.



3.3 INTEGRATING THE ENGINEERING AND ECONOMIC INPUT

This section describes the nine generalized analysis and modeling steps that can be applied to a candidate space resource case study to yield financial viability results. This modeling approach implies a constant interaction between the engineering and financial perspectives. At each point in the analysis, engineering factors (development and operations costs, schedule, performance, and risk assessments) have a direct impact on such issues as total investment requirements, the type and cost of financing likely to be used, the length of time to achieve positive cash flow, and venture operating margins and profitability. The nine steps are space resource definition, case study selection, demand modeling, engineering analysis, cost analysis, financial modeling, scenario optimization, sensitivity analysis, and conclusions.

3.3.1 SPACE RESOURCE DEFINITION

In the lunar propellant case study that will be studied, a raw resource from space (lunar water) is used by a private venture. However, the proposed modeling approach is not limited to space ventures that use material from space; serviced-based ventures such as on-orbit servicing or even remote sensing are very suited to the same approach. Even more that the availability of raw materials in space, what makes a space resource interesting from a financial viability standpoint is its potential for being of *direct* interest to customers. We will therefore use the following definition of a space resource:

A Space Resource:

- is a *Product* or *Service*
- has part of its supply chain and/or market in Space
- has a *direct* customer base on Earth or in Space
- is counted in units that reflect the *Pricing* structure that customers are willing to pay for the Resource.

For example in the case of lunar propellant, the space resource is defined as LEO-to-GEO transfer instead of water or propellant. It is counted in units of number of unit masses transferred to reflect the pricing structure both of competition (launch from Earth directly into GEO) and supply (lunar propellant production).

3.3.2 CASE STUDY SELECTION

At the present time, few potentially viable private ventures for Space Resource development have been identified and most of them are associated with conjectural markets, such as those listed in the Commercial Space Transportation Study (CSTS). With improving technologies, the number of opportunities for private space ventures will increase as space activities expand and in time. The approach used here to model a space transportation business will be useable with other opportunities, such as recovering precious metals from asteroids for use on Earth, or transporting raw materials from the Moon to Earth orbit to construct solar power satellites. Which of these case studies has the most potential?

Even propellant based on lunar water, which requires relatively simple processing, still must be extracted, purified, and liquefied before the customer can be expected to buy it. A similar set of processes, in some cases including manufacturing to meet specific functional requirements, will be needed to bring any Space Resource to its economic use. All steps in the process that lead to the ability to sell the product must be included in the analysis, which must demonstrate sufficient effectiveness to meet the market price constraints. So in principle, case studies will be selected when there is some preliminary indication that the processes exist that can produce a Space Resource at less cost to the customer than competition. In most ventures, there will be at least one competitor: providing the Space Resource from Earth.

Early case study validation should be may be made at a high level, with back-of-the-envelope estimates of engineering and financial parameters. A number of case study ideas can be ruled out from the get-go by considering a series of necessary conditions for viability. These conditions start with the need for a market and for a clear advantage over competition, and go on with quick payback ratio analyses at various levels, such as:

- Is the venture likely to consume more of the Space Resource than it produces?
- Is the venture likely to require more mass to be launched to LEO than it will save in customer launch mass?
- Is the venture marginal cost of production likely to be smaller than the price customers are willing to pay?
- etc.

Ruling out bad ideas early can only help pinpoint the venture of most financial viability potential.

3.3.3 DEMAND MODELING

Once a case study has cleared a high-level technical and financial feasibility check, a more detailed business case can be developed. This starts with a market or demand model that yields three main outputs: total market demand and projected growth rates; the market share that the venture expects to capture, and the price at which the venture can sell its product or service. Although the demand model will be specific to each case study, some general modeling rules apply to any commercial space market.

Annual market demand is the number of units of the product or service that are expected to be consumed each year. For example, several studies (CSTS, 1994; Smitherman, 2001) have forecasted the number of satellites to be launched as a function year, orbital regime, satellite type, and even satellite size. This type of analysis can be very useful starting points for any demand modeling. In addition, a thorough study should estimate the potential for new markets emerging from the availability of the space resource. For example, the availability of in-space refueling would see the emergence of new space missions such as maneuverable fleets of satellites.

Price forecast modeling involves an analysis of the maximum price each type of customer mission would be willing to pay for the space resource. For existing markets, the product or service must provide an advantage over the current way of doing business; quantification of this benefit readily provides an upper bound on the price that can be charged. For example, the price for "LEO-to-GEO transfer using lunar propellant" must first cost less than a traditional ELV or Shuttle staged launch to GEO, and second cost less than an OTV using Earth-based propellant. Similarly, the price for on-orbit servicing must be cheaper than satellite replacement, but also than designing a spacecraft with a longer mean mission duration. For potential new markets, a more involved analysis is required to estimate the maximum price that will allow the market to emerge; nested "private ventures in space" analyses might be required if the new market is itself a space venture (e.g. at what price of 'Commercial Service X' does 'Commercial Venture Y' become feasible?)

Finally, **market share growth** accounts for the rate at which the potential customers actually turn to the venture. This depends on several factors, such as the number of competitors, market differentiation, and customer perceptions of risk/confidence. As a necessarily highly uncertain parameter, market share growth is an important candidate for sensitivity analysis.

3.3.4 ENGINEERING ANALYSIS

The engineering model, or architecture design, combines the minimum set of system elements required to effectively deliver the Space Resource to its market. Although this design will be case-specific, a few simple rules of thumb apply:

1. **Focus on timelines and cost.** The venture expenses and its times to break-even are key to the financial viability of the venture. The basic model must capture technology, deployment, production, launch, and operational considerations with just enough definition to estimate timelines and costs.
2. **Favor scaling laws over point designs.** Rather than a static point design, what is helpful is a more general engineering model or tool that can accommodate a range of starting assumptions and their associated cost factors. Database-linked or analytical engineering scaling laws for example provide flexibility to meet the modeled demand. For example, the engineering model developed for the lunar propellant case study defined a unit-size architecture designed to meet a small amount of demand, and launches incremental units as demand increases. Beyond engineering scalability, this

approach has the advantage of decreasing the risk associated with uncertain demand growth.

3. **Start with a simple model** The same modeling approach applies to any level of detail, with the quality of the financial viability results depending only on the quality of the inputs. Starting with a very high level model can help carry out simple trade studies and identify scenarios that are worthwhile taking to the next level of detail. Preliminary modeling can begin with a technology list and mass breakdown for each primary system, while successive iterations will evolve more advanced technical descriptions for nested subsystem elements. The initial set of inputs defines the 'baseline scenario.'

3.3.5 COST ANALYSIS

The cost model must correctly anticipate technology level, design, development, production, launch, operations and maintenance costs. In addition, it must be scalable to adapt to scaling designs. Although not as accurate as grass roots or analogy-based estimates, cost models based on analytical Cost Estimating Relationships (CERs) are ideal for this application. CERs provide an estimate of cost and cost uncertainty based on a number of high-level engineering parameters that are readily available from the engineering model (such as type, mass and technology readiness level of each subsystem). This provides not only the required flexibility to quickly adapt to changing designs, but also the required inputs for cost risk analysis.

Similarly to engineering model, cost models can be developed at various levels of detail. For a first round of analysis, the cost model could be as simple as CERs based on total dry mass for development and production cost, wet mass for launch cost, and number of elements for operations cost.

It should be noted that the CERs typically available are derived primarily from government programs. It is conjectured, as space industrialization grows and technology becomes better understood, more reliable and more widely used, and particularly as commercial incentive structures replace government contracts, that costs could drop well below than those shown in current cost models. This is particularly true for mass production, and any private venture cost model should include learning curve effects.

3.3.6 FINANCIAL FEASIBILITY

The cost, performance and schedule outputs become inputs to the financial model, creating the initial assessment of financial viability. If the venture is not viable the financial model shows the main cost drivers, which in turn can be used to explore either alternative technologies or architectures, or to explore different versions of the baseline scenario by changing the primary assumptions or technologies. In addition, as all production processes used in space will have a startup cost and operational overhead, it will be desirable to know at what scale of production (and demand) the case study can be profitable.

3.3.7 FEEDBACK AND SCENARIO OPTIMIZATION

Preliminary investigation of the integrated model may identify areas in which the scenario may be improved. This can be done at the level of the cost model for the engineering system, in which the high-cost elements of the architecture can be analyzed and solutions found to reduce the scale or even eliminate an element of the architecture. For example, initial examination of the lunar ice architecture incorporated an all-propulsive approach to the transportation system, in which lunar propellants were utilized throughout. It was quickly determined that these architectures were economically infeasible, and architectures that involved aerobraking to low Earth orbit were introduced.

Analysis of the financial viability results from the first round of modeling can help guide refinements in engineering and financial assumptions. The use of new technologies, which have the potential to reduce key mass and cost drivers, can be traded against the additional cost and time associated with their development and validation. The impact of pricing strategy can be tested. The possible government incentives to release key hurdles can be identified.

The goal of this analysis step is to identify a scenario that combines realistic market assumptions, an efficient and feasible architecture design to meet this market, realistic cost estimates, and reasonable assumptions on government participation, into a close-to-financially viable private space venture.

3.3.8 SENSITIVITY ANALYSIS

Another tool that can be utilized is sensitivity analysis. This can be applied at the component level, such as comparing alternative ways of providing power for lunar surface systems. The sensitivity of the economic results to the grade of the resource will be important, as was shown in the lunar ice case. The model's economic assumptions can also be studied. For example, discount rates or the degree of sharing of public/private investment can be modeled. Finally, market assumptions can be tested, such as the size of the market or acceptable costs for the resource.

Once a good scenario has been identified, sensitivity analysis is key to test the impact of uncertain parameters and analyze the conditions for financial viability. A key metric to plot is the rate of return on investment in Year 10 for private investors in Year 1: this rate must exceed a given threshold to private investors to be interested (typically above 20% for risky ventures). Key parameters to test include (but are not restricted to):

- Market demand and market share growth. These parameters are typically very uncertain in any space venture, especially if the venture is launching a new product or service. The minimum demand and demand growth required for the venture to be viable can be compared with the expectations and their uncertainty.
- Discount factors. Private investors use discount rates to account for the perceived risk of the venture. The higher the perceived uncertainty, the higher the discount rate and the required return on investment. Since risk is always hard to quantify, it is important that the venture be viable for a range of discount rates.

- Launch cost from Earth. Whether a provider of service to the venture or a competitor, launch from Earth is bound to be a key player in any space venture's financial viability. The sensitivity of the venture to launch costs is particularly interesting as these costs are expected to drop in the coming decades.
- Key technological parameters. Testing the sensitivity of the venture to parameters such as propulsion system performance, specific masses of various components, or specific power of power sources, can help identify the key technical drivers and the areas of most interesting potential for technology development.
- Alternate government incentives, such as participation in development costs, tax rate, or guaranteed price and/or customer base. Another way to assess government incentives impacts is to assume the availability of technologies and/or assets in space at the start of the venture, which might reduce timelines and cost. This analysis can help identify the most efficient government incentives to foster private sector involvement.

3.3.9 CONCLUSIONS

After analysis using any or all of the above tools, a case can be made (or refuted) that a particular resource is economically viable for a particular market. It will be important at this stage to fully document all assumptions so that the reviewer can gauge the completeness and quality of the analysis.

The results of the sensitivity analyses described above can help draw a map of the conditions for financial viability of the space venture. The capabilities offered by such a modeling approach and the type of conclusions that can be drawn will be illustrated in the following sections on the lunar propellant case study.

Applying the same approach to a number of private venture cases studies can help draw a general map of the respective roles for the private sector and for the government in future solar system exploration.

4.0 CASE 1: LUNAR PROPELLANT FOR LEO-GEO TRANSFER

At the present time, few commercial activities that utilize known space resources have been identified, and none have been shown to be commercially feasible. The CSTS (1996) report and others suggest that water extracted from space resources may be the best candidate for commercial activity because of an existing market. The particular market or need that is identified for Case 1 is in-space transportation, specifically LEO-GEO transfer. The possibility that the need might be met using lunar resources, rather than bringing the required materials from Earth, has been extensively studied. Cryogenic propellant, as studied in the current model, requires relatively simple processing and water ice has been demonstrated to exist at both lunar poles. Steps in the process from resource extraction to utilization are described below.

The approach used here to model a space transportation business, specifically selling transportation services provided by an Orbital Transfer Vehicle (OTV). While others have demonstrated technical feasibility using the "mass payback" criteria (which compares the mass of equipment and propellant for production and delivery of the product to its place of use to the mass of the product that would have to be delivered from Earth - see Stancati, 1999; Rice, 2000), a positive mass-payback relationship does not guarantee an economic benefit. The approach used here is to step beyond the engineering modeling and create a foundation to show commercial benefits.

4.1 THE CASE 1 ENGINEERING MODEL

In the Case 1 model, lunar regolith is mined, the water removed by raising its temperature and condensing the water that is evolved, then the water electrolyzed and the product liquefied to produce liquid hydrogen (LH_2) and liquid oxygen (LOX) for propellant. A reusable space tanker that uses lunar LH_2/LOX transfers water to a space propellant depot at the Earth-Moon L1 point. This location has the advantage that it is always in the same position with respect to the Moon, providing anytime access back and forth, and is similarly placed with respect to Earth.

To correctly anticipate technology level, design and development factors, the Case 1 model limited itself to systems that have heritage (i.e., proven technologies). A spacecraft launched from L1 can enter any Earth orbit using about the same energy, although the trip must be timed properly to rendezvous with an object already in Earth orbit. Once the water has been delivered to L1 there are several options. In this study, two different options were considered. In the first option (Architecture 1, figure 4.1), a second propellant depot is established in LEO, presumably in equatorial orbit. Water is transferred from L1 to LEO, electrolyzed and liquefied in LEO, and used to fuel a reusable orbital transfer vehicle that transports payloads from LEO to GEO. The OTV then returns to LEO for refueling. In the second option (Architecture 2, figure 4.2), the reusable orbital transfer vehicle operates from L1, flies to LEO to rendezvous with a payload, takes the payload to GEO, then returns to L1 for fueling and another trip. This eliminates the need for a second refueling depot. Note that this section of the report is intended to present an overview of the development of the models for Case 1 Architectures 1 and 2. Details regarding specific technical assumptions can be found in Appendices 1-3.

Figure 4.1. Architecture 1 for Transporting Payloads from LEO-GEO Based on Lunar Propellants (Note: ΔV^2 close-up, scale: 1" = 4.25 Mj/Kg).

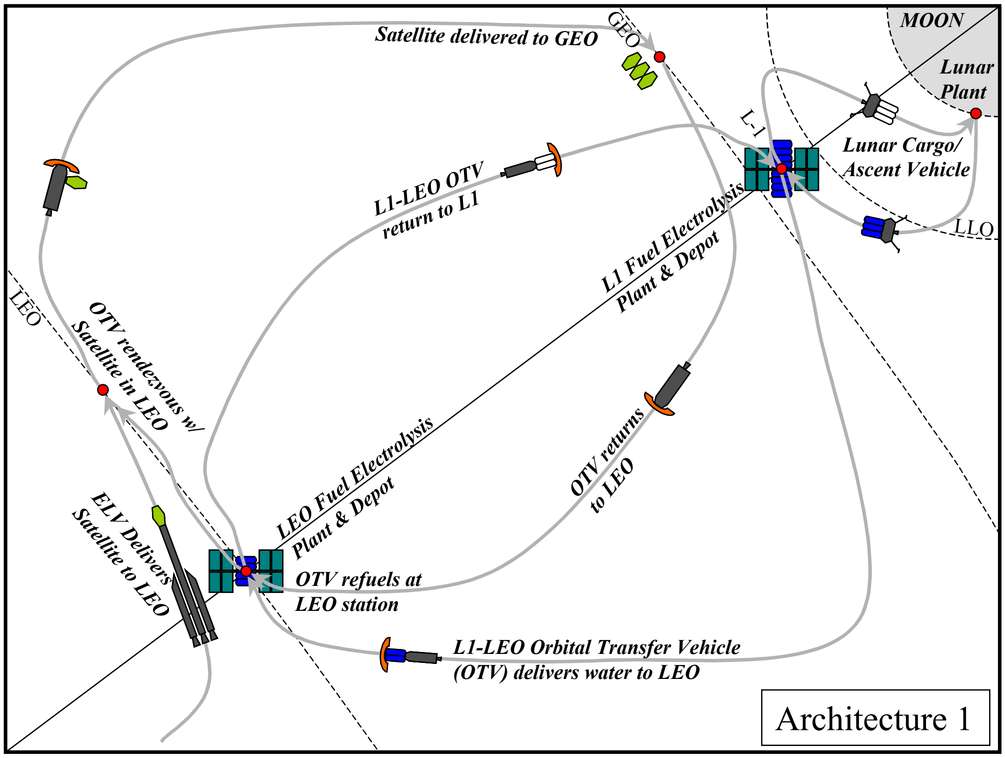
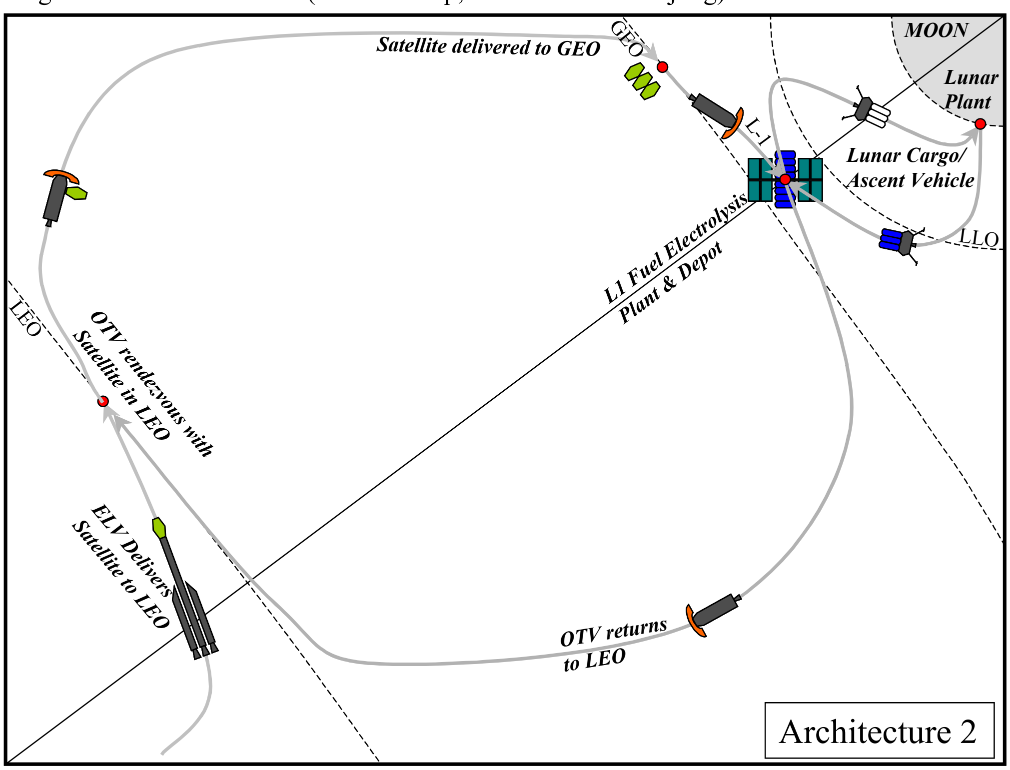


Figure 4.2. Architecture 2 (ΔV^2 close-up, scale: 1" = 4.25 Mj/Kg).



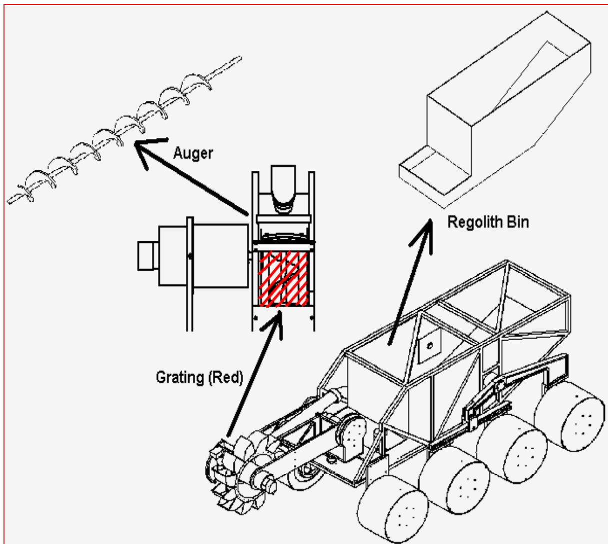
4.1.1 MINING AND PROCESSING SYSTEMS

The lunar surface mining and processing system consists of equipment to mine regolith, extract its water, electrolyze the water to produce gaseous hydrogen and oxygen, liquefaction equipment to liquefy the gases, and a storage capacity. Power must be provided for the facility. The surface system also must include a launch/landing facility with the capability of transferring the payload (water) and propellants (LOX, LH_2) to a tanker that will transport water to L1.

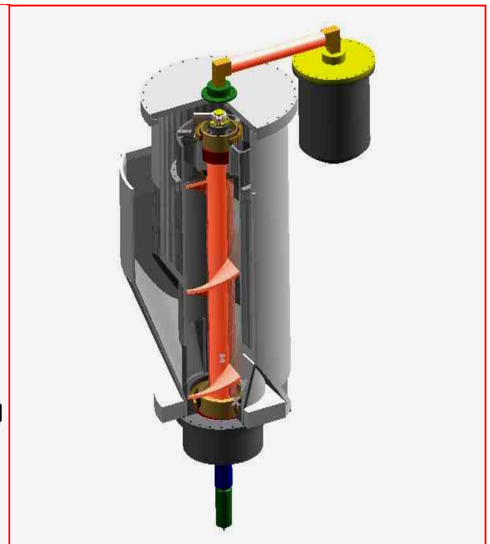
A baseline conservative assumption in the model is that the regolith contains 1% water by weight (note that the estimated value by Lunar Prospector is ~1.6%). It is assumed that all water and propellant production is carried out within the permanent shadow, although other options for the lunar system exist (see Duke et al, 1998) and should be investigated in further studies. A nuclear reactor is assumed to provide thermal and electrical energy for water extraction. The system extracts water by heating regolith from its ambient temperature (80K) to 200K under vacuum. Water is electrolyzed and the hydrogen and oxygen liquefied and stored for propellant. Liquid oxygen can be stored using passive thermal control techniques in the permanent shadow and the energy cost of storing liquid hydrogen is minimal. Water tanks must be insulated and heated to retain water in liquid form. The "specific mass" or "specific energy," which are defined as the mass or energy required to produce a given amount of product in a given amount of time, are provided for the major elements of the surface architecture in Table A1-4, along with other general assumptions utilized in the model. For costing purposes, it is assumed that 10 % of the system must be replaced each year of operations. The current architecture assumes that excess oxygen, which appears because the oxygen content of water is higher than that of the fuel mixture used in LH_2/LOX rockets, is lost to the system. Enough hydrogen and oxygen are stored on site to allow for continued operation of the system when a lunar water tanker is not present at the production facility. Otherwise, the product is stored in the tanker itself.

Data for the various elements of the lunar surface system have been extracted from Eagle Engineering (1988). Some of these data, particularly for excavation and extraction systems, have been under study at the Colorado School of Mines. A bucket wheel excavator modeling (Figure 4.3) has demonstrated the potential to excavate as much as 10 times the system's mass per hour. Therefore, excavator mass is not considered a major driver for the total plant mass on the lunar surface. Extraction systems tend to be more massive, with calculations suggesting that a system can process its own mass of regolith in one hour (the energy required to heat the regolith is modest, due to the low vapor pressure of water in vacuum). Indeed, the majority of electrical energy consumption is used to electrolyze the water and liquefy the propellants. Nuclear systems have been assumed in the current model; however, options exist for the use of solar energy, which can be collected in areas adjacent to the shadowed craters (where sunlit areas can be found more than 80% of the month). Solar systems will be less massive and less costly than nuclear systems, although the issue of intermittent power availability and channeling the energy from near-permanent sunlight into a permanently shadowed crater can create certain design complexities. Details regarding the complete list of assumptions for the lunar plant can be found in Appendix 1 and 2.

Figure 4.3. Mining and extraction systems under development at CSM.



Conceptual bucket wheel excavator under development at CSM



Conceptual design of CSM lunar ice extraction furnace

4.1.2 TRANSPORTATION ARCHITECTURES

The two architectures as depicted in Figures 4.2.1 and 4.2.2 have similar space transportation systems. In option 1, a reusable lunar tanker, which can land repeatedly at the production site on the Moon, is fueled with LH_2 and LOX, and carries a payload of water to L1. At the L1 depot, water is converted to propellant needed to return the lunar water tanker to the Moon and to send a separate water tanker spacecraft to a depot in LEO. This vehicle is reusable and flies to LEO using an aerobrake. At the LEO depot, the remaining water is converted to propellant and stored for delivery to reusable orbital transfer vehicles that deliver satellites from LEO to GEO, coming back empty to LEO using an aerobrake. A portion of the propellant also is utilized to return the water tanker to L1. Values for ΔV that are used in both architectures are reported in Table 4.1.

Table 4.1. ΔV assumptions used in transportation system modeling.

LEO-GEO	3800	m/sec
GEO-LEO with aerobraking	500	m/sec
GEO-L1 (assumption only)	800	m/sec
L1-LEO with aerobraking	500	m/sec
LEO-L1	3150	m/sec
L1-Moon's surface	2390	m/sec

An assumption is made that all vehicles use liquid oxygen and hydrogen fuel, with an Isp of 460 and a mixture ratio of 6.5:1. This mixture ratio is a matter for propellant system design, but perhaps represents a reasonable mixture for a highly reusable propulsion system, although it is a little higher than currently utilized in the Space Shuttle's main engines. Because the ratio is not stoichiometric for water, anywhere in the system that propellant is produced from water, excess oxygen is created. This excess oxygen is given no commercial value in our current models, although it is produced on the lunar surface, at L1 and, in the scenario for Architecture1, in LEO.

In addition to the production plant, both architectures share common elements as described below (although sizes differ slightly - detailed design parameters and vehicle sizes can be found in Appendix 1 and 2):

L1 Propellant Depot: At this depot, water is received and propellant is produced. The electrolysis and liquefaction systems are similar to those on the Moon. Excess oxygen produced at L1 is assumed lost to the system. Power for the propellant depot is provided by solar arrays.

Lunar Water Tanker. This vehicle is capable of landing near the propellant production plant (probably not in the permanent shadow), taking on a payload of water and cryogenic propellants and traveling from the Moon to the L1 propellant depot. The tanker is assumed to be highly reusable, with 10% per year hardware refurbishment.

In addition, each architecture has distinct elements. For Architecture 1, these include (detailed design parameters can be found in Appendix 1):

L1 to LEO Tanker. This system has an aerobrake for entry to LEO, assuming a mass fraction of 15% of the mass entering LEO (spacecraft and water payload). As Architecture 1 includes a depot in LEO, the tanker is sized for refueling in LEO. The LEO propellant depot is sized using the same assumptions as those for the L1 depot.

LEO Propellant Depot. At this depot, water is received from the L1 depot and propellant is produced for the LEO-GEO-LEO or LEO- L1 transfer system. The electrolysis and liquefaction systems are similar to those on the Moon. Excess oxygen produced at LEO is assumed lost to the system. Power for the propellant depot is provided by solar arrays.

LEO-GEO-LEO Orbital Transfer Vehicle: OTV for carrying payloads from LEO to GEO and returning to LEO with an aerobrake. This vehicle's mass is estimated using the same performance parameters ascribed to other tanker vehicles.

For Architecture 2, this includes (see Appendix 2 for detailed design parameters):

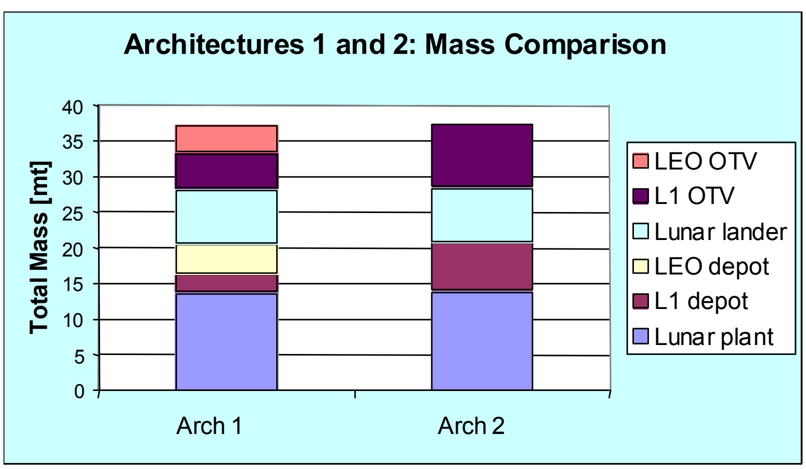
L1-LEO-GEO-L1 Orbital Transfer Vehicle. The transfer vehicle and tanker functions are combined and a single vehicle is fueled at L1, flies with a propellant load that is aerobraked into LEO where it performs a rendezvous maneuver with a satellite, then propels the satellite to GEO. Following the insertion, the vehicle flies back to L1 for refueling. This vehicle must carry to LEO the propellant needed for LEO-GEO-L1 as well as the aerobrake for entering LEO.

Architecture 1 has the advantage that the delivery of propellant from the LEO depot can be metered to the user in proportion to the needs of the LEO-GEO mission. Additional customers could be served by increasing the rate of water delivery to LEO with the water tankers and by increasing the propellant production capacity at the depot. The propellant depot would have to be in a fixed orbit and might not be suitable for the fueling of certain satellites; for example, a depot in equatorial orbit may not be amenable to fueling a mission requiring polar orbit. This architecture would allow the entity that delivers satellites to GEO to be a separate business from the one that produces propellant in LEO and from the entities that produce water on the Moon and transport it to LEO.

In Architecture 2, it is assumed that the only propellant depot is located at L1. For delivery of a satellite from LEO to GEO, an OTV is fueled at L1, aerobrakes to LEO, docks with the satellite that is to be delivered to GEO, flies to GEO and then returns to L1 for its next mission. This is similar to an architecture studied by Sercel et al (1999). The LEO propellant depot and the separate water tanker from L1 to LEO are not required. Because the OTV cannot be refueled in LEO, it must carry with it from L1 the propellant needed to get from LEO-GEO-L1. This architecture, as well as being somewhat simpler (it eliminates a LEO propellant depot and one of the types of OTV), has the advantage of allowing access to a variety of different Earth orbit inclinations with similar propellant requirements from L1. It is also amenable to an integrated business plan, in which the lunar mining and space transportation functions are provided by a single entity.

Sizing for each of the architectures starts with the total consumption of propellant per period. This is calculated by combining the transportation system assumptions (each vehicle uses propellant during its operation cycle) with annual market demand. Working back through the system, the amount of propellant required at each location in the system and the mass of lunar surface systems is calculated. Then, the specific mass and power data of each of the elements is used to determine the mass of hardware required at each location. For each additional increment of capability, a similar increment of hardware is added. The amount of propellant used at each node is shown in Appendices 1 and 2 for the unit plant size (note: ten production units are deployed the final year in each model for optimal phasing with market capture).

Figure 4.4. Mass comparison of architectures 1 and 2.



4.2 THE CASE 1 ECONOMIC MODEL

The economic model is affected by many assumptions outside the architectural assumptions. These include assumptions such as: (1) the technology level assumed at the start of development – The NASA-Air Force Cost Model (NAFCOM) assumes totally new development of all elements; (2) whether the commercial investor must pay for the development costs - as many of the systems are common to other space activities, the financial model assumes that DDT&E costs are absorbed by other government programs in Versions 2-4; (3) the size of the market - efficiencies are gained as the number of units that must be produced increases; And (4) primary business assumptions - such as the rate of market capture, expected rates of return to investors, discount rates and taxation.

While the launch energy from the Moon to LEO can be as low as 4% of that required from Earth (see Section 2.2), the question remains as to whether such a system can save the final customer money and still produce enough profit to reward investors.

4.2.1 CASE 1 COST MODELING

The NASA and Air Force Cost Model (NAFCOM99) cost estimation tool was utilized to estimate the costs of development and production at the systems level for elements of each of the architectures. The masses derived from the architecture analysis were input into NAFCOM along with analogies appropriate for the current level of analysis. Cost summaries for the two architectures are shown in Table 4. NAFCOM generates the cost estimates for design and development (D&D), system test hardware (STH), flight unit (FU) and production units (Prod). The cost model is responsive to the unit mass of the elements utilized. In general, smaller units cost more per kilogram than a single large unit. However, producing a series of small units generates up front savings due to a much lower design and development cost (which can be as high as four times the production cost) that is incurred only once. This is a significant consideration for the case where a number of identical systems are installed over time (to incrementally expand capacity) because it decreases up front capital expenditures. For the current studies, no attempt was made to optimize the size of individual elements, although a 'learning curve' was applied to the costing of multiple units. Note that the NAFCOM99 modeling approach, which was used for the current study, requires that separate estimates be built for each of the modeled scenarios, limiting the flexibility of sensitivity analysis.

Added to the hardware cost are launch costs, as each of the hardware components of the system must be delivered to its place of use. The model assumes that the cost of transportation from Earth to LEO is $10,000/kg (approximating the current launch costs of the Space Shuttle or Ariane 5). Transportation costs for initial delivery of payloads to L1 and the Moon are estimated as $35,000/kg and $90,000/kg respectively. Note that much of this cost is associated with transportation of propellant from the Earth into space.

Once the first propellant production unit is emplaced on the Moon, utilizing the lunar propellant and transportation vehicles reduces the cost of transportation of subsequent units of production. In our preliminary model, we assume that the first production unit, equivalent to that required to transport 3-5000 kg payloads a year from LEO to GEO, is installed and thereafter is utilized to provide propellant and transportation for new hardware for system expansion. After its installation, the cost of transportation of new hardware to L1 and the Moon is assumed to be equal to the cost of transportation to LEO, as system elements are 'handed to' OTVs operated by the enterprise. The model currently makes the following assumptions regarding the delivery of additional units to destinations beyond LEO:

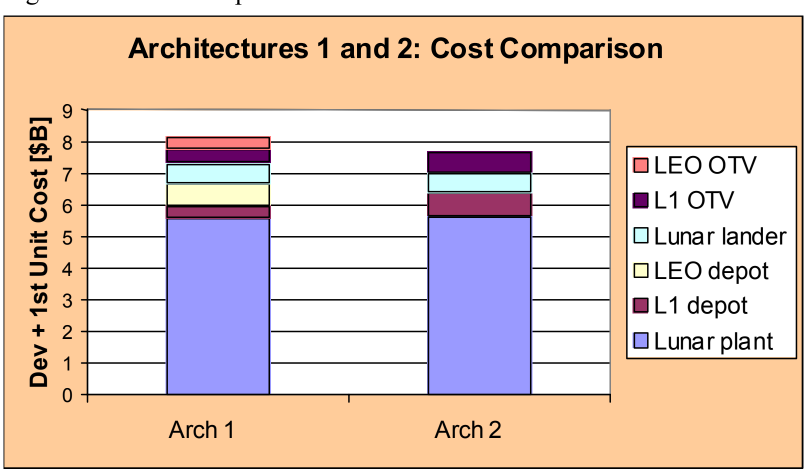
- Each year, the units required in the following year are launched
- For architecture 1, one unit is able to build up to 240 mt/yr (12 trips of the L1-LEO-L1 OTV and of the lunar lander, at 20 mt a trip)
- For architecture 2, one unit is able to build up to 117 mt/yr (12 trips of the OTV and at 9.7 mt a trip)
- Each vehicle can make up to 12 trips a year (for example in architecture 1, if demand increases from 15 mt/yr to 30 mt/yr, an additional lunar plant is required, but no additional LEO-L1-LEO OTV)

This assumption could be fine tuned by calculating the amount of propellant and vehicles in excess of the new hardware transportation requirement and incorporating the revenue from its sale into the economic analysis.

Operations costs are an important factor in commercial viability, and are modeled at the systems level using the Space Operations Cost Model (SOCM). It is assumed that all maintenance and repair is carried out by robotic systems and that on-site humans are not required for successful operation of the system. In fact, a one-ton maintenance facility is built into the architecture and cost estimates as part of each unit production plant deployed on the lunar surface. At a given level of activity, on-site humans for maintenance and repair may become economically desirable. However, circumstances under which that might become an effective approach have not been analyzed.

Finally, the economic model assumes that 10% of subsystems (and 1% of tanks) must be replaced each year. This provides a measure of replacement costs that is directly related to the mass of hardware being utilized in the system. The cost of producing the replacement hardware is scaled from the original NAFCOM estimates, and the transportation cost for the replacement hardware is included. Note that this places an increasing burden on later production years, comprising almost 1/3 of the capital cost in year 7 of system operation.

Figure 4.5. Cost comparison of architectures 1 and 2.



4.2.2 CASE 1 MARKET MODELING

Annual market demand is the number of units of the product or service consumed each year. Several studies have forecasted the number of satellites to be launched as a function year, orbital regime, satellite type, and even satellite size (CSTS, 1994; Smitherman, 2001). The launch of satellites from Earth to geosynchronous orbits (GEO) is an established and growing business. Each year, between 25 and 30 satellites are launched at a typical cost of $35,000 per kilogram of satellite. This comprises the primary candidate market for the case under examination. For purpose of early analysis, both architectures assumed that a constant number of satellites must be delivered from LEO to GEO annually. The 'unit system' is sized to provide the capacity to deliver 3 x 5000 kg satellites from LEO to GEO (for a total unit capacity of 15,000 kg). One unit is deployed in the first year, building to 10 in six years for a total capacity of 30 satellites per year (150 tons of total satellite mass). This simple satellite demand model is derived by combining the 2002 GSO launch forecast (AST, 2002) and a satellite mass growth model (AST, 1999) into market projections for the period of 2010-2016.

The price model is assumed to have an upper bound - taken as the minimum of a traditional ELV launch to GEO vs. an OTV using Earth-based propellant (both systems are considered to compete with lunar-based fuel supply). Demand is priced as a function of satellite mass (dollars per kilogram transported). Note that the demand model based on Smitherman (2001, developed for in-space water-based propellants provided from Earth) lacks the cost estimates or economic data required to derive a competing price. Because the main advantage for customers is savings in Earth launch cost, the maximum price that can be charged is the difference between the cost to launch to GEO ($35,000/kg) and the cost to launch to LEO ($10,000/kg), netting to $25,000 per kilogram of delivered satellite. A 20% 'discount' was assumed to be attractive to current customers, forming a simplified price function at a constant $20,000/kg. A market capture function was added to the model, starting with 10% market share in the first operational year, and ramping up to 100% after 7 years of successful operations. Market share growth accounts for the rate at which the potential customers actually turn to the venture. This can depend on several factors, such as the number of competitors, market differentiation, and customer perceptions of risk/confidence.

Consider a recent example of a 4,460 kg payload launched to GEO by an Ariane 44L. As it passed through LEO, the cryogenic third stage required more than twice as much propellant (11,900kg) as the final payload (see Figure 4.6). Besides highlighting the leverage that lunar resources hold over their terrestrial counterpart, the potential exists to refuel and reuse the upper stage for additional satellite delivery (or other uses such as satellite servicing). The existence of a fuel depot within reach of the empty vehicle (at L1) creates a commercial incentive for the owner of the vehicle to find additional customers, stimulating space commerce.

Figure 4.6. Performance specifications for Flight 113 of the Ariane 44L launch vehicle.

ELEMENT	MASS (kg)	
	DETAIL	RUNNING TOTAL
AfriStar	**2 739**	
GE-5	**1 720**	
• Adapter + SPELDA + Vehicle Equipment Bay (VEB) + residual fluids & performance reserve	1 137	
• 3rd stage dry mass	1 241	
Mass after end of 3rd stage propulsion		*6 836*
• 3rd stage propellant	11 720	
Mass after 2nd stage separation		*18 556*
• 2nd stage dry mass + 2/3 inter-stage	3 496	
• Fairing mass	745	
• 2nd stage propellants	35 453	
Mass after 1st stage separation		*58 250*
• 1st stage dry mass + 1/2 inter-stage	17 995	
• 1st stage propellants	231 173	
• Liquid strap-on boosters (dry mass + propellants)	174 655	
Total mass at liftoff		**482 073**

4.3 CASE 1 MODEL RESULTS

This section presents results obtained from the integrated modeling of Case 1, Architectures 1 and 2. Consistent assumptions are used in the baseline model for both architectures (the baseline has been labeled 'Version 0'). These assumptions are the most conservative, and are considered to be the most realistic – e.g., 'current' technology, 'standard' procurement and management, 'normal' investor behavior, etc. Iteration of the model to a financially feasible solution involved a process of changing progressive relaxation of assumptions (see Versions 1-5 in Table 4.2, below). The resulting feasible model (Version 5) indicates one set of possible conditions under which a commercial venture 'could' be profitable to private investors. The 'realism' of these feasibility conditions has been a subject of debate among team members. Note that while certain assumptions might be considered simplistic, and certain factors omitted (such as risk), the results are a good illustration of the analytic capabilities offered by the integrated modeling tool developed for this study.

4.3.1 BASELINE MODEL RESULTS

The baseline numerical assumptions for the case study included conservative demand, mass and cost estimates, and no government incentives apart from generic technology development. With these assumptions, the project Net Present Value (NPV) was quite negative (minus $5 Billion), as shown in Table 4.3.

4.3.2 MODEL VERSIONS: FINDING A FEASIBILE SOLUTION

Use of the integrated modeling tool makes it possible to explore in real time the conditions for financial viability. As an example, Table 4.2 identifies the manner in which the model was adjusted in each of the versions. Table 4.3 summarizes the results of several versions with incrementally 'less conservative' assumptions (for reference, the table also cites the traditional metrics: NPV and NPV-based rate of return). Table 4.4 shows the financial statements for the most feasible version for each of the architectures (Note: all model version calculations incorporate a discount rate of 10%, a cost of debt of 12% and an income tax rate of 40%). These results show how the model allows quick "what if" studies:

- What if the government pays for the upfront development and first unit costs? (Version 1)
- What if, in addition, the efficiency of commercial production reduces costs by 30% compared to the traditional NASA development and procurement approach? (Version 2)
- What if, in addition, the concentration of H2O in lunar regolith is twice our baseline (2% instead of 1%)? (Version 3)
- What if, in addition, the demand for LEO-to-GEO transport is twice as high as our conservative forecast? (Version 4)
- What if, in addition, the price charged for orbital transfer ($20,000/kg) is raised by 25% (to $25,000/kg) (Version 5)

Version 4 yields a venture with positive NPV, but the investor's return on equity (15.2%) is probably still insufficient to trigger investment (i.e. investors could probably achieve a similar rate of return in a more traditional investment). Therefore, Version 5 is considered to be the only version that achieves financial feasibility.

Table 4.2. Model versions relative to baseline.

Version	Description	Summary
0	Architecture 1&2 Baseline. All assumptions set to most conservative level.	Baseline
1	Baseline w/ No Non-Recurring Investments. (assumes that the public sector pays for design, development and first unit cost)	Remove DDT&E from Baseline
2	No Non-Rec. Investments + Reduce the production cost of all elements by 30%.	Add 30% Production Cost Reduction
3	No Non-Rec. Investments + Reduced production cost + Increase concentration of Water in Lunar Regolith from 1% to 2%.	Add 2x Lunar Water Concentration
4	No Non-Rec. Investments + Reduced production cost + Increase concentration of Water in Lunar Regolith + Double demand.	Add 2x Demand
5	No Non-Rec. Investments + Reduced production cost + Increase concentration of Water in Lunar Regolith + Double demand + Price Increase	Add 1.25x Price

Table 4.3. Model results (key financial metrics) by version for Architectures 1 and 2.

	Year 1 Return on Equity		Project Rate of Return		Net Present Value	
	Arch 1	Arch 2	Arch 1	Arch 2	Arch 1	Arch 2
Version 0	N/A	N/A	N/A	N/A	$ (5,275)	$ (5,006)
Version 1	-30.3%	-30.5%	-11.9%	-11.9%	$ (553)	$ (561)
Version 2	-9.8%	-10.1%	-5.0%	-5.2%	$ 255	$ 240
Version 3	-2.3%	1.6%	-1.7%	-0.3%	$ 593	$ 726
Version 4	15.0%	15.2%	6.2%	5.9%	$ 2,484	$ 2,461
Version 5	26.1%	26.3%	12.8%	12.6%	$ 4,156	$ 4,134

Table 4.4. Financial statements for Version 5 of Architectures 1 and 2.

Architecture 1 - Financial Statements

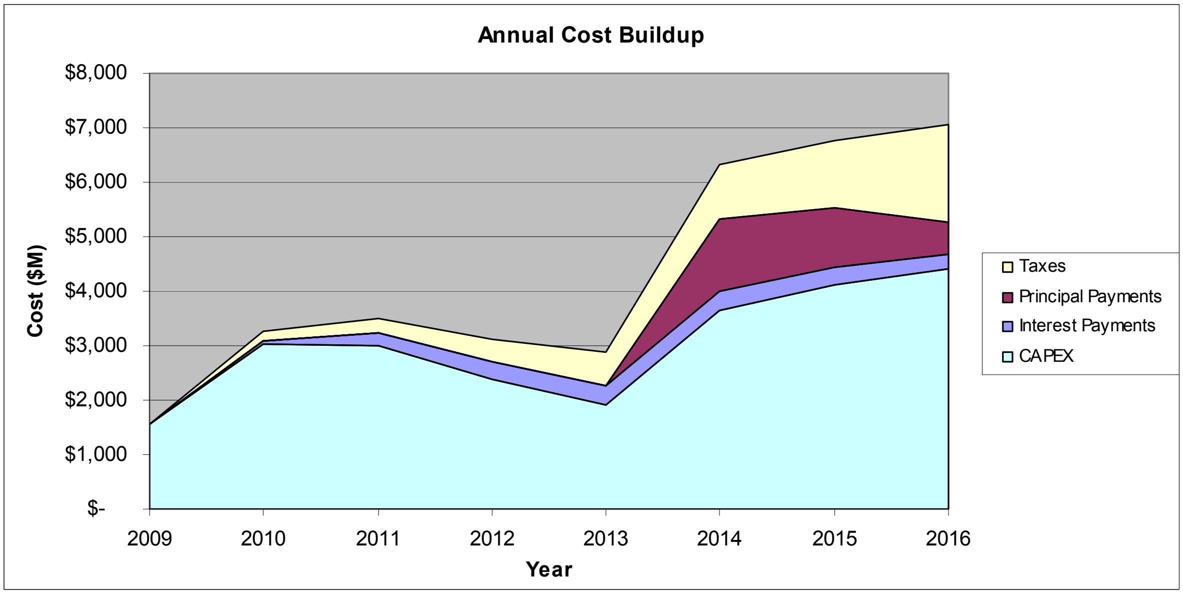
INCOME STATEMENT	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	Cumulative
Revenues	$ 0	$ 0	$ 0	$ 750	$ 1,500	$ 2,250	$ 3,000	$ 4,500	$ 6,000	$ 7,500	$ 25,501
Gross Profit	$ 0	$ 0	$ 0	$ 689	$ 1,378	$ 2,067	$ 2,755	$ 4,133	$ 5,511	$ 6,888	$ 23,421
EBITDA	$ (4)	$ (9)	$ (10)	$ 677	$ 1,365	$ 2,054	$ 2,742	$ 4,119	$ 5,496	$ 6,873	$ 23,305
EBIT	$ (4)	$ (9)	$ (10)	$ 520	$ 908	$ 1,357	$ 1,853	$ 2,864	$ 3,440	$ 4,817	$ 15,736
Net Income	$ (4)	$ (9)	$ (10)	$ 274	$ 411	$ 621	$ 895	$ 1,502	$ 1,867	$ 2,728	$ 8,275
CASH FLOW	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	Cumulative
Net Cash From Operations	$ (4)	$ (9)	$ (10)	$ 431	$ 868	$ 1,317	$ 1,783	$ 2,758	$ 3,924	$ 4,784	$ 15,844
Net Changes in Working Capital	$ 0	$ 0	$ 0	$ (57)	$ (57)	$ (57)	$ (57)	$ (115)	$ (115)	$ (115)	$ (573)
CAPEX/NRE	$ 0	$ 0	$ 1,587	$ 2,998	$ 2,993	$ 2,394	$ 1,923	$ 3,670	$ 4,127	$ 3,880	$ 23,571
Taxes	$ -	$ -	$ -	$ 167	$ 274	$ 414	$ 596	$ 1,002	$ 1,245	$ 1,819	$ 5,517
Annual Cash (Shortfall) Surplus	$ (4)	$ (8)	$ (1,596)	$ (2,624)	$ (2,182)	$ (1,134)	$ (197)	$ (2,338)	$ (1,409)	$ 222	$ (11,270)
Equity Financing	$ 104	$ 8	$ 1,596	$ 1,312	$ 1,091	$ 567	$ 98	$ 1,169	$ 705	$ -	$ 6,650
Debt Financing	$ -	$ -	$ -	$ 1,312	$ 1,091	$ 567	$ 98	$ 1,169	$ 705	$ -	$ 4,942
Principal and Interest Payments	$ -	$ -	$ -	$ 79	$ 223	$ 322	$ 362	$ 1,671	$ 1,419	$ 838	$ 4,914
BALANCE SHEET	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	
Total Assets	$ 100	$ 100	$ 1,686	$ 4,589	$ 7,187	$ 8,947	$ 10,043	$ 12,582	$ 14,778	$ 16,950	
Short and Long Term Liabilities	$ 0	$ 1	$ 1	$ 1,318	$ 2,414	$ 2,986	$ 3,089	$ 2,957	$ 2,581	$ 2,024	
Shareholder Equity	$ 104	$ 112	$ 1,708	$ 3,020	$ 4,111	$ 4,678	$ 4,776	$ 5,945	$ 6,650	$ 6,650	
Retained Earnings	$ (4)	$ (13)	$ (23)	$ 251	$ 662	$ 1,283	$ 2,178	$ 3,680	$ 5,547	$ 8,275	

Architecture 2 - Financial Statements

INCOME STATEMENT	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	Cumulative
Revenues	$ 0	$ 0	$ 0	$ 750	$ 1,500	$ 2,250	$ 3,000	$ 4,500	$ 6,000	$ 7,500	$ 25,501
Gross Profit	$ 0	$ 0	$ 0	$ 689	$ 1,378	$ 2,067	$ 2,755	$ 4,133	$ 5,511	$ 6,888	$ 23,421
EBITDA	$ (4)	$ (9)	$ (10)	$ 677	$ 1,365	$ 2,054	$ 2,742	$ 4,119	$ 5,496	$ 6,873	$ 23,305
EBIT	$ (4)	$ (9)	$ (10)	$ 523	$ 910	$ 1,360	$ 1,857	$ 2,870	$ 3,395	$ 4,772	$ 15,665
Net Income	$ (4)	$ (9)	$ (10)	$ 276	$ 411	$ 621	$ 896	$ 1,505	$ 1,841	$ 2,698	$ 8,225
CASH FLOW	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	Cumulative
Net Cash From Operations	$ (4)	$ (9)	$ (10)	$ 429	$ 866	$ 1,315	$ 1,781	$ 2,755	$ 3,942	$ 4,799	$ 15,865
Net Changes in Working Capital	$ 0	$ 0	$ 0	$ (57)	$ (57)	$ (57)	$ (57)	$ (115)	$ (115)	$ (115)	$ (573)
CAPEX/NRE	$ 0	$ 0	$ 1,548	$ 3,018	$ 3,013	$ 2,384	$ 1,910	$ 3,649	$ 4,105	$ 4,410	$ 24,039
Taxes	$ -	$ -	$ -	$ 168	$ 274	$ 414	$ 597	$ 1,004	$ 1,228	$ 1,798	$ 5,483
Annual Cash (Shortfall) Surplus	$ (4)	$ (8)	$ (1,557)	$ (2,646)	$ (2,204)	$ (1,127)	$ (187)	$ (2,332)	$ (1,379)	$ (290)	$ (11,735)
Equity Financing	$ 104	$ 8	$ 1,557	$ 1,323	$ 1,102	$ 564	$ 93	$ 1,166	$ 690	$ 145	$ 6,753
Debt Financing	$ -	$ -	$ -	$ 1,323	$ 1,102	$ 564	$ 93	$ 1,166	$ 690	$ 145	$ 5,083
Principal and Interest Payments	$ -	$ -	$ -	$ 79	$ 225	$ 325	$ 364	$ 1,684	$ 1,428	$ 840	$ 4,945
BALANCE SHEET	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	
Total Assets	$ 100	$ 100	$ 1,648	$ 4,575	$ 7,195	$ 8,949	$ 10,037	$ 12,561	$ 14,690	$ 17,124	
Short and Long Term Liabilities	$ 0	$ 1	$ 1	$ 1,329	$ 2,437	$ 3,005	$ 3,104	$ 2,957	$ 2,555	$ 2,146	
Shareholder Equity	$ 104	$ 112	$ 1,670	$ 2,993	$ 4,095	$ 4,659	$ 4,752	$ 5,918	$ 6,608	$ 6,753	
Retained Earnings	$ (4)	$ (13)	$ (23)	$ 253	$ 664	$ 1,285	$ 2,181	$ 3,686	$ 5,528	$ 8,225	

Note that the path of relaxed assumptions that was followed to improve the financial results of each successive version is not necessarily an optimal path. Numerous other variables could have been selected for relaxation, such as tax rates, hardware replacement rates, operations costs, discount rate, cost of debt and market capture rate. In addition, reduction factors could be applied to variables beyond production cost.

Figure 4.7. Cost buildup for Architecture 2, Version 5.



4.3.3 SENSITIVITY ANALYSIS

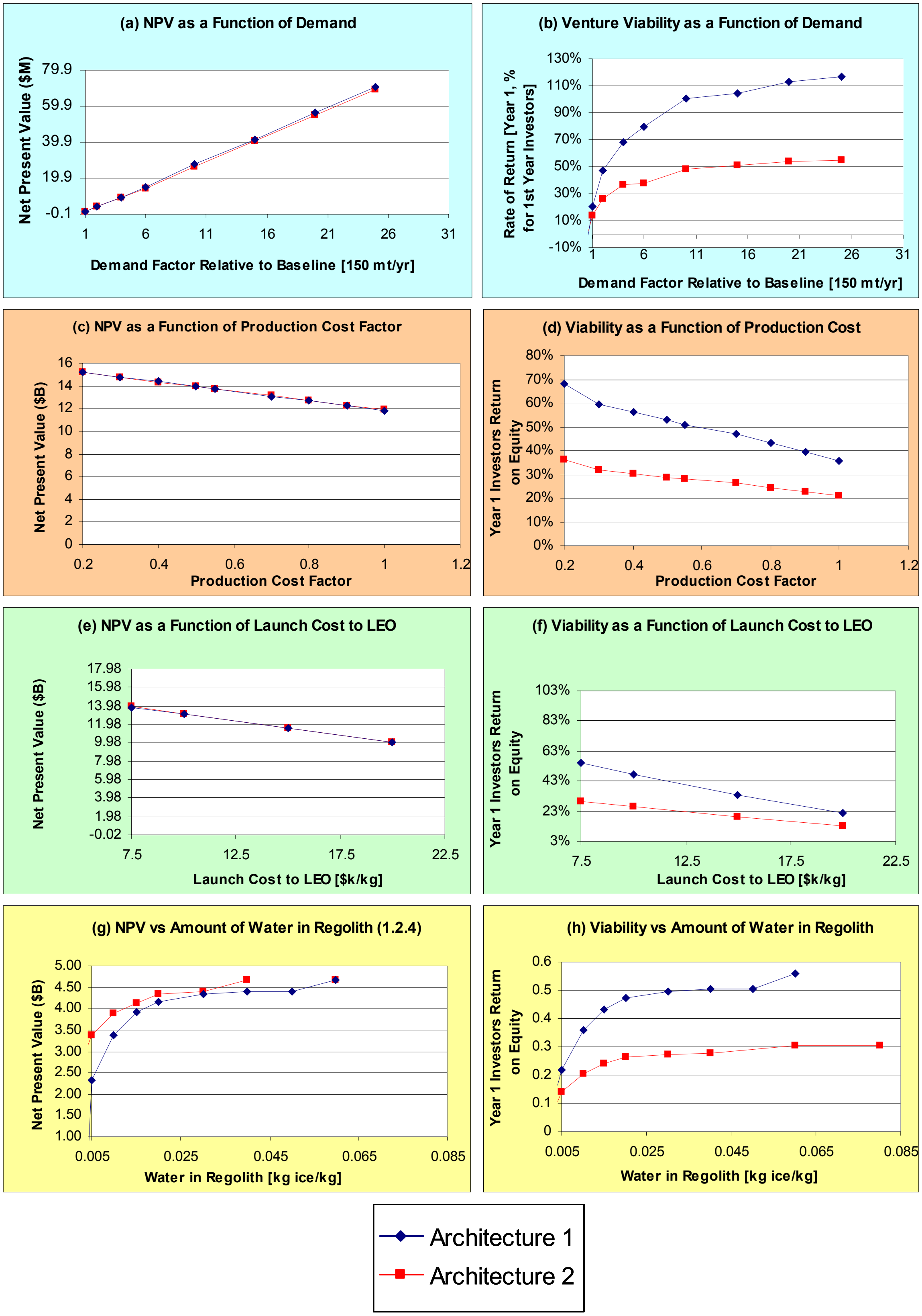
Sensitivity analysis was conducted on the Version 4 model, providing insight into the conditions under which the venture might be viewed as a good private sector investment. For example, the sensitivity to demand (Fig. 4.8a, b) shows that the venture would become viable for a fivefold increase in demand with respect to the baseline commercial LEO-to-GEO forecast. Other potential customers, such as military GEO satellites, solar system exploration missions by space agencies, and new markets such as orbital debris removal and/or avoidance, should be evaluated in future versions.

The sensitivity to production cost (Fig. 4.8c, d) can help identify target performance for technology development as well as production chain efficiency. In this case however, unrealistic improvements would be required to ensure financial viability. This can be interpreted in two ways: (1) Although they might help, production cost reduction efforts might not be the first priority for lunar resource development, or (2) A new scenario is required with much simpler design or break-through improvements in technology to enable a factor of five cost reduction.

The sensitivity to launch cost to LEO (Fig. 4.8e, f) shows how non-intuitive results can also be reached. "What if launch costs were much cheaper?" is a typical question when trying to improve the prospects for space business. However, the launch segment is not only a provider of service, but also a competitor. The net result is that financial viability actually decreases with decreasing launch cost to LEO.

Finally, Figs. 4.8g and h shows how the viability of the venture increases with water concentration in lunar regolith. This shows how the modeling approach can be used to provide a justification for exploration missions, and more generally the value of potential NASA's actions to mitigate sources of uncertainty.

Figure 4.8. Sensitivity analysis of Version 5 of Architectures 1 and 2.



4.4 IMPLICATIONS FOR HUMAN EXPLORATION AND TECHNOLOGY

One metric that may be of interest to the human exploration community is the expected unit cost for fuel at the various production points. The unit costs presented in Figures 4.9 and 4.10 represent an *upper bound* on the expected cost of one unit of the resource at each destination (this is because the metric shown is total unit cost - fixed plus variable costs). Economic theory of natural resources predicts that a firm will continue to sell a product at a price just above the marginal costs (which can be approximated by variable costs alone), which are substantially lower than shown below. Note also that the unit costs below carry a heavy capital burden due to expanding capacity by increasing the size of the plant each year. Therefore, it is a reasonable expectation that a human exploration mission arriving at the L1 point could purchase fuel at a cost ranging between $15 and $5 Million per ton of fuel, depending on the 'maturity' (year of operation) of the commercial enterprise (note that the current expected cost is roughly $35 Million per ton). Note that the marginal cost has not been calculated in the current model.

Figure 4.9. Unit costs at the Moon and L1 for Architecture 1, Version 5.

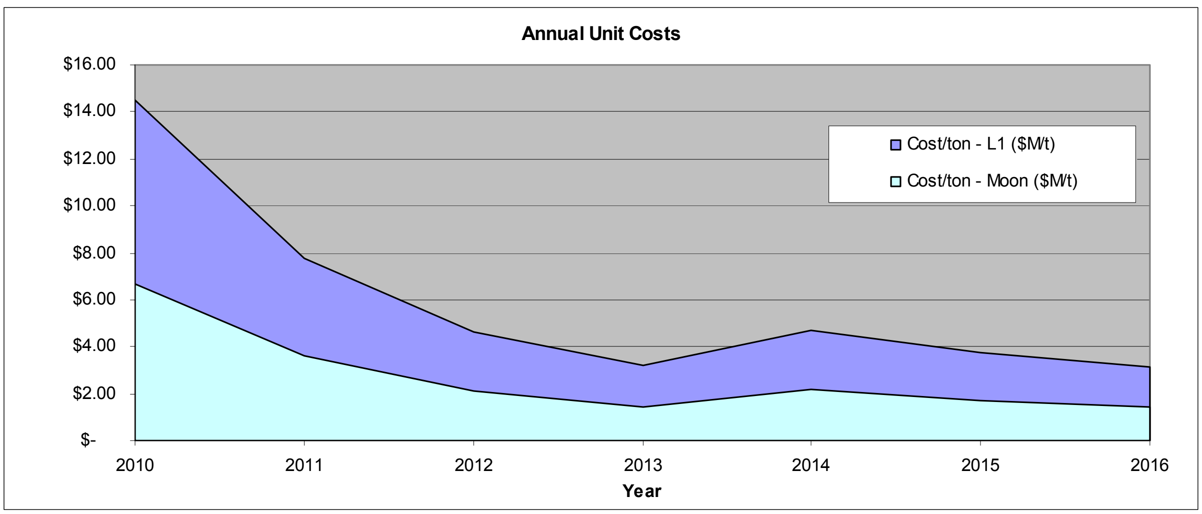
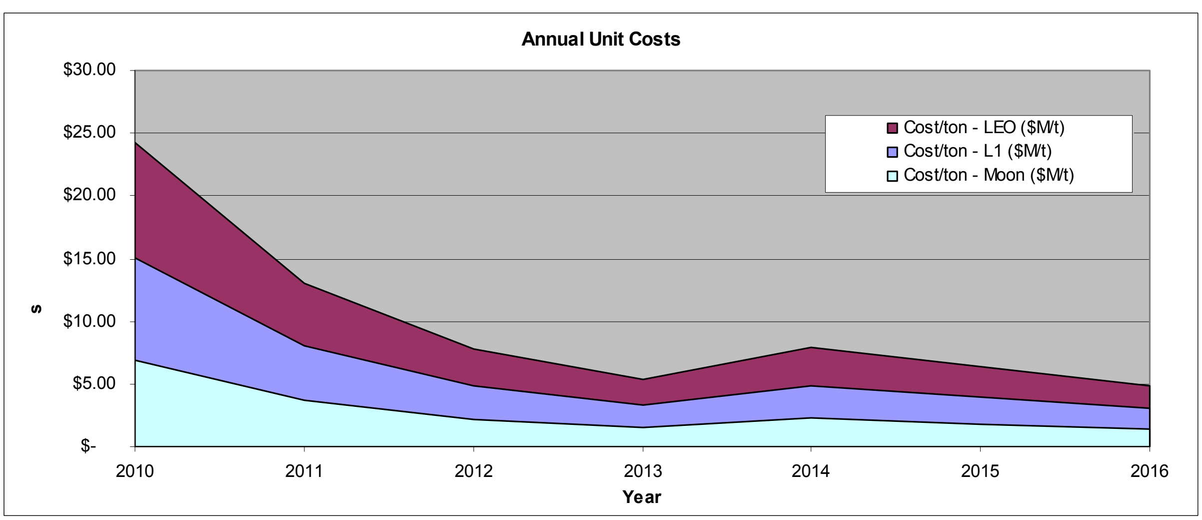


Figure 4.10. Unit costs at the Moon, L1 and LEO for Architecture 2, Version 5.



From a cursory inspection of the integrated financial model for each of the two architectures, several additional variables can be identified that have strong implications with respect to commercial viability, technology investment and human exploration:

1. The abundance of ice in the lunar regolith. The baseline case assumes that there is 1% ice in the regolith. If the ice concentration is higher in local areas, the amount of regolith that must be excavated and processed is proportionally less, and the amount of thermal energy required for its extraction is reduced. However, the power required for electrolysis and liquefaction remains the same because the total amount of water produced would remain constant. Figure 4.8(g) compares the net present value derived from the economic model for Architecture 2 Version 5. This comparison provides a prima facie case for the potential economic importance of further lunar exploration.
2. The mass of the lunar excavators and extractors. The designs for these elements that must work in the lunar shadowed craters are poorly understood. The current model may underestimate the effect of operating under extreme conditions (this could be corrected by modeling risk and reliability factors).
3. Power system architecture. The current baseline model assumes nuclear power systems, which currently are estimated to have specific masses of about 30 kg/kW. However, recent designs of thin film solar cell arrays have specific masses in the range of 1kg/kW. An architecture that utilizes solar energy could be reasonable for the polar application. Within relatively short distances of areas that apparently contain ice, high points with access to power most of the time exist (Bussey et al., 1999). Choices must be made as to the surface configuration of the power systems (they must be erected vertically because the sunlight is coming horizontally to the surface near the poles) and the means of transporting energy from sunlit areas into the shadow. If the specific mass of the total power system could be reduced to 5 kg/kW, significant reductions in transportation costs could result. In addition, NAFCOM costs nuclear systems at relatively high price/kg. Thin film solar arrays would have significantly lower costs if carried from Earth, and might even potentially be produced on the Moon.
4. The space transportation system. Masses for transportation elements have been derived from various literature sources, and are based on past designs. These may not reflect the best materials or technologies in the current application. The mass fraction of propellant that can be carried by a vehicle in space is quite sensitive to the dry mass of the spacecraft. If turning to new materials or technology can reduce structure, tanks, or other subsystem mass the effectiveness and profitability of a commercial architecture will improve.
5. Assumptions of system lifetime are also important for the space transportation elements. 10% per year refurbishment for all systems (e.g., mining plant, depot and spacecraft) has been assumed in this model, and each OTV is assumed to fly a mission once per month. This is approximately equivalent to an assumption that each vehicle can fly 120 times before being fully replaced (the validity of this assumption remains to be proven). Note that in Year 10 of

both models, refurbishment mass has risen to 1/3 of the total launch mass, and has become a significant cost factor.

6. Cost model assumptions. The NAFCOM cost model may have overestimated the development and production costs for the hardware, especially if a commercial development and procurement paradigm is assumed. Most of the analogies used in the current architectures are for single spacecraft or systems, principally built for government programs and therefore may not be applicable. This has been modeled by assuming that development and operations costs are some fraction of the NAFCOM costs (e. g. 70% - see integrated models Versions 2, 3, 4 and 5, for both architectures).
7. Cost optimization for the unit size of system elements in each architecture could minimize total costs by balancing up front (design and development) expenditures with long-run hardware costs. This kind of optimization was not conducted, and would require 'NAFCOM-like' parametric cost equations in optimization-friendly software (such as MS Excel). Due to the lack of transparency for NAFCOM cost engineering relationships, costs were estimated individually for each architectural variant in the current model.
8. The current model does not include any cost reduction associated with the possible commonality between elements used in different applications. For example, an OTV used for L1-LEO-L1 may have much in common with a lunar water tanker, in that the delta V requirements are similar and the systems might be very similar, with the exception of the landing gear on the lunar lander. Although differences will exist in the design of electrolysis units for lunar surface and 0-g applications, common development might lead to lower costs.
9. The current architecture was built to test a specific commercial market application. Additional markets, including government markets could be included and would raise the net present value of the operation. In particular, sales of propellant on the Moon or in L1 to Moon and Mars human exploration programs could provide significant benefits to those programs and an early human exploration program could choose to develop most of the systems identified in these architectures, allowing a later commercial opportunity to be developed at much lower cost.

5.0 CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

We have developed and are improving an integrated engineering and financial modeling approach to enable rapid analysis of the financial viability of any space resource development venture. The approach consists in starting from a customer's point of view and a demand analysis, developing initial architectural concepts and modeling their scaling laws, and optimizing the scenario for the metrics of interest to private sector investors. We illustrated the advantages of this approach on a high-level lunar-propellant-based transportation service case study. "What if?" studies and sensitivity analysis help yield conclusions on the value of exploration missions and technology development, the optimal technical and business strategies, as well as the best public incentives to foster private sector involvement.

This modeling approach can be applied to other case studies, such as lunar mining for precious minerals, power production, solar cell production, and tourism; asteroid mining for water or precious minerals; in-space manufacturing for high-value materials or support of space endeavors; in-space transport using nuclear or solar electric propulsion; on-orbit servicing in Earth orbit and beyond; remote-sensing data commercialization; space tourism, and more. Application on such a wide space of possible ventures, and on different time scales can help draw a global map of the possible space resource development pathways for an integrated public and private sector space exploration strategy.

6.0 REFERENCES

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LIST OF ACRONYMS

AST – Administrator for Space Transportation, Federal Aviation Administration
CAPEX – Capital Expenditures
CCACS – Center for Commercial Applications of Combustion in Space
CER – Cost Engineering Relationship
CSM – Colorado School of Mines
CSP – Center for Space Policy, Inc.
CSTS – Commercial Space Transportation System Study
D&D – Design and Development (cost)
EEI – Eagle Engineering, Inc.
EBIT – Earnings before interest and tax
EBITDA – Earnings before interest, tax, depreciation and amortization
ELV – Expendable Launch Vehicle
FU – Functional Unit (cost)
GEO – Geosynchronous Earth Orbit
GSO – Geosynchronous Orbit
H_2 – Hydrogen (gas)
H_2O - Water
JPL – Jet Propulsion Laboratory
K – Degrees Kelvin (temperature)
L1 – (First) Earth-Moon Lagrangian Point
LEO – Low Earth Orbit
LH_2 – Liquid Hydrogen
LOX – Liquid Oxygen
NAFCOM – NASA and Air Force Cost Model (software)
NASA – National Aeronautics and Space Administration
NExT – NASA Exploration Team
NPV – Net Present Value
O_2 – Oxygen (gas)
OTV – Orbital Transfer Vehicle
R&D – Research and Development
ROR – Rate of Return (%)
SG&A – Sales, General and Administrative (expense)
SOCM – Space Operations Cost Model (spreadsheet)
SRD – Space Resource Development
STH – Systems Test Hardware (cost)
ΔV – Change in Velocity (typically km/sec/kg)
ΔV^2 – Change in Velocity squared ($km^2/sec^2/kg^2$ = mega-joules per kilogram)

SRD Appendix 1

Case 1, Architecture 1 Assumptions, Model Development and Cost Modeling

A1.1 DEVELOPMENT OF ARCHITECTURE 1 SYSTEM ELEMENTS

LEO-GEO-LEO Orbital Transfer Vehicle: OTV for carrying payloads from LEO to GEO and returning to LEO with an aerobrake.

Calculation method

Definitions:

- m_{pp}: mass of propellant required from LEO to GEO
- m_i: inert mass
- m_{ab}: aerobrake mass
- m_{sg}: mass of payload to transfer to GEO
- m_f: mass of propellant to maneuver from GEO to LEO
- $\alpha = m_i / m_{pp}$
- $r = (m_i + m_p + mpp + m_{ab}) / (m_i + m_p + m_{ab})$
- rt: (initial/final) mass ratio for GEO-LEO transport with aerobraking

Method:

An iterative process on m_{pp} has been designed and programmed into an excel user-defined function, based on the following equations:

- Propulsion system mass = $(64.77+0.0745*m_{pp}+1.004*m_{pp}^{\wedge(2/3)})$ [Sercel et all, 1999]
- Structure mass = 30% propulsion system mass + 15% m_{pp}
- m_i = Constant base mass (telecom, C&DH and power) + Propulsion system mass + Structure mass
- $m_{ab} = 0.15*(m_i + m_{pp})$
- $m_f = (m_i + m_{ab})*(rf-1)$
- $m_{pp} = (m_i + m_{ab} + m_f + m_{sg})*(r-1)$

Finally, the total propellant to be refueled at the LEO station is $m_{pp}+m_f$

Results are provided in Table A1.1.

TABLE A1.1. Orbital Transfer Vehicle (Architecture 1).

Parameter	Value	Unit	Comment
R	2.2		Using 3800 m/sec for LEO-GEO delta-V
Rf	1.1		Assume 500 m/sec for L1-LEO propulsive with aerobraking
Telecomm system mass	10.0	kg	Assume constant
C&DH system mass	3.0	kg	Assume constant
Power system mass	15.0	kg	Assume constant
Msg	5000.0	kg	From Demand Model
mpp	10859.6	kg	Use "OTVModelRough" function
Propulsion system mass	1366.2	kg	64.77+0.0745*mpp+1.004*mpp^(2/3)
Structure mass	2034.3	kg	Add .15X payload to TLALOC assumption
Inert mass mi	3428.7	kg	Total inert mass without mab
a(a)	0.3		mi/mpp
Aerobrake mass	514.3	kg	mab=0.15*(mi+mpp)
Propellant for GEO-LEO	394.3	kg	mf=(mi+mab)*(rf-1)
Total propellant in LEO	11225.5	kg	To be refueled in L1 before each trip

L1 to LEO Tanker. This system has an aerobrake for entry to LEO, assuming a mass fraction of 15% of the mass entering LEO (spacecraft and water payload). As Architecture 1 includes a depot in LEO, the tanker is sized for refueling in LEO. The LEO propellant depot is sized using the same assumptions as those for the L1 depot. This architecture also provides a separate OTV for carrying payloads from LEO to GEO and returning to LEO with an aerobrake. That vehicle's mass is estimated using the same performance parameters ascribed to the tanker vehicles.

Calculation method

Definitions:

- m_{pp}: mass of propellant required from L1 to LEO
- m_i: inert mass
- m_{ab}: aerobrake mass
- m_{sg}: mass of payload to transfer to LEO (water)
- m_f: mass of propellant to maneuver from LEO to L1
- $\alpha = m_i / m_{pp}$
- $r = (m_i + m_p + mpp + m_{ab}) / (m_i + m_p + m_{ab})$
- rt: (initial/final) mass ratio for GEO-LEO transport with aerobraking

Method:

An iterative process on m_{pp} has been designed and programmed into an excel user-defined function, based on the following equations:

- Propulsion system mass = $(64.77+0.0745*m_{pp}+1.004*m_{pp}{}^{\wedge(2/3)})$ [Sercel et all, 1999]
- Structure mass = 30% propulsion system mass + 15% m_{pp}

- m_i = Constant base mass (telecom, C&DH and power) + Propulsion system mass + Structure mass
- $m_{ab} = 0.15*(m_i + m_{pp})$
- $m_f = (m_i + m_{ab})*(rf-1)$
- $m_{pp} = (m_i + m_{ab} + m_f + m_{sg})*(r-1)$

Finally, the total propellant to be refueled at the L1 station is m_{pp}, and the total propellant to be refueled at the LEO station is m_f

Results are provided in Table A1.2.

TABLE A1.2. L1-LEO Tanker parameters.

Parameter	Value	Unit	Comment
R	2.1		Using 3800 m/sec for LEO-GEO delta-V
Rf	2.3		Assume 4100 m/sec for LEO-L1 propulsive
Telecomm system mass	10.0	kg	Assume constant
C&DH system mass	3.0	kg	Assume constant
Power system mass	15.0	kg	Assume constant
Msg	20000.0	kg	From Demand Model
Mpp	2504.8	kg	Use "OTVModelRough" function
Propulsion system mass	905.6	kg	64.77+0.0745*mpp+1.004*mpp^(2/3)
Structure mass	647.4	kg	Add .15X payload to TLALOC assumption
Inert mass mi	1781.0	kg	Total inert mass without mab
a(a)	0.3		mi/mpp
Aerobrake mass	3267.2	kg	mab=0.15*(mi+mpp)
Propellant for LEO-L1	6562.6	kg	mf=(mi+mab)*(rf-1)
Total propellant in LEO	2504.8	kg	To be refueled in LEO
Total propellant in L1	6562.6	kg	To be refueled in L1 before each trip

<u>Lunar water tanker</u>. This vehicle is capable of landing near the propellant production plant (probably not in the permanent shadow), taking on a payload of water and cryogenic propellants and traveling from the Moon to the L1 propellant depot. Delta V's for each of the legs of the scenarios are given in Table 2. The mass of the lunar water tanker was estimated from scaling equations based on the Apollo lunar lander (Eckart, 1999). The tanker is assumed to be highly reusable, with 10% per year hardware refurbishment.

Calculation method

- Setting the mpp: mass of propellant required from LEO to GEO
- Calculation of the tanker total gross mass from the mpp, using the rocket equation
- Vehicle inert mass calculation using Apollo equation:

  Lander dry mass = $0.064*mgross+59.1*(m_{pp} /dbL_{H2}L_{OX})+390$, being db=bulk density
- Finally, the amount of water the can deliver to the L1 station is calculating as follows:

  Moon-L1 vehicle load capacity = mgross - Lander dry mass - m_{pp}

Table A1.3 shows the results of those calculations.

TABLE A1.3. Lunar Water Tanker vehicle parameters.

Parameter	Value	Unit	Comment
Total propellant available to ship	23427.2	kg	
Lander total mass	55034.5	kg	Calculated from the available propellant mass
Moon-L1 vehicle load capacity	23859.9	kg	
O2/H2 mixture ratio	6.5		
Engine Isp	460.0	sec	
Delta V	2500.0	m/sec	One-way delta V from the Moon surface to the L1 station
delta V/Isp g ratio	0.6		
Mi/Mf ratio	1.7		
dbLH2Lox	361.0		propellant bulk density
Dry weight of vehicle	7747.5	kg	Lander dry mass

Lunar surface water extraction and propellant production plant. This system produces water for export from the Moon and sufficient propellant to launch it to space. The baseline assumption in the model is that the regolith contains 2% water by weight. It is assumed that all water and propellant production is carried out within the permanent shadow, although other options for the lunar system exist (Duke et al, 1998) and should be investigated in further studies. A nuclear reactor is assumed to provide thermal and electrical energy for water extraction. The system extracts water by heating regolith from its ambient temperature (80K) to 200K under vacuum. Water is electrolyzed and the hydrogen and oxygen liquefied and stored for propellant. Liquid oxygen can be stored using passive thermal control techniques in the permanent shadow and the energy cost of storing liquid hydrogen is minimal. Water tanks must be insulated and heated to retain water in liquid form. The "specific mass" or "specific energy," which are defined as the mass or energy required to produce a given amount of product in a given amount of time, are provided for the major elements of the surface architecture in Table 1, along with other general assumptions utilized in the model. For costing purposes, it is assumed that 10 % of the system must be replaced each year of operations. The current architecture assumes that the excess oxygen is lost to the system. Enough hydrogen and oxygen are stored on site to allow for continued operation of the system when a lunar water tanker is not present at the production facility. Otherwise, the product is stored in the tanker itself.

TABLE A1.4. Generalized mining plant input assumptions.

ELEMENT	Performance	ELEMENT	Performance
Specific mass		***Specific Power***	
Excavator (kg/kg regolith/hr)	0.10	Excavator (kW/kg regolith/hr)	0.01
Hauler (kg/kg/hr)	0.13	Hauler (kW/kg/hr)	0.013
Extractor (kg/kg/hr)	1	Extractor (kW/kg/hr)	138
Electrolyzer (kg/kg/hr)	50	Electrolyzer (kW/kg H_2O/hr)	4.5
H_2 Liquefier (kg/kg/hr)	15	H_2 liquefier (kW/kg H_2/hr)	14.9
Liquefier radiator (kg/kg/hr)	260	O_2 liquefier (kW/kg O_2/hr)	0.95
O_2 Liquefier (kg/kg/hr)	7	Thermal efficiency of nuclear plant (kWt/kWe)	4

O_2 radiator (kg/kg/hr)	7	***General assumptions***	
H_2 storage tank (kg/kg H_2)	0.15	Lunar surface structure specific mass (kg/kg components)	0.25
O_2 storage tank (kg/kg O_2)	0.08	Space facility structure specific mass (kg/kg components)	0.1
H_2O storage tank (kg/kg H_2O)	0.01	Component refurbishment (kg/kg components/yr)	0.05
Specific mass of nuclear power system (kg/kWe)	30	Duty cycle for lunar surface activities (hr/year)	8760
Specific mass of photovoltaic power systems (kg/kWe)	8	Duty cycle at L1 (hr/yr)	8760
Specific mass of thermal power associated with nuclear reactor	1	Duty cycle in LEO (hr/yr)	4500

L1 Propellant Depot. At this depot, water is received from the Moon and propellant is produced for the L1-LEO or L1-LEO-GEO-L1 transfer system as well as for returning the lunar water tanker to the Moon. The electrolysis and liquefaction systems are similar to those on the Moon. Excess oxygen produced at L1 is assumed lost to the system. Power for the propellant depot is provided by solar arrays.

LEO Propellant Depot. At this depot, water is received from the L1 depot and propellant is produced for the LEO-GEO-LEO or LEO- L1 transfer system. The electrolysis and liquefaction systems are similar to those on the Moon. Excess oxygen produced at LEO is assumed lost to the system. Power for the propellant depot is provided by solar arrays.

Starting with the market assumptions, the amount of propellant needed in each of the architectures is calculated from the transportation system assumptions, determining the required amount of propellant at each node of the architecture. For architecture 1, a roundtrip Moon-L1-Moon transfer delivers water to L1 and uses propellant produced at L1 to return an empty transfer vehicle to the Moon. The L1 propellant depot must also produce propellant for the orbital transfer vehicle to travel to LEO, transfer a satellite to GEO and travel back to L1. An aerobrake is used for LEO orbit insertion. Working back through the system, the amount of propellant required at each location in the system is calculated as follows:

- The amount of propellant required in LEO is given.
- The payload capacity of the L1-LEO-L1 vehicle is also given, as are the vehicle performance data
- The useful payload provided to LEO by one flight of the tanker vehicle is calculated (the difference between the vehicle payload and the amount of propellant required to return the vehicle to L1)
- The amount of propellant required in L1 to deliver the payload to LEO is calculated
- The payload capacity of the Moon-L1-Moon vehicle is given, and a similar calculation is made to determine the number of trips that the Moon-L1-Moon vehicle must make to support each delivery from L1 to LEO
- A similar calculation is made for the production of water on the Moon to support the Moon-L1 transportation leg

For all previous calculations, is important to remember that the mixture ratio for engines is 6.5:1 whereas the electrolysis ratio is 9:1, so we are going to have an excess of O2, that we assume can throw away without any penalty. Results are available in Table A1.5.

TABLE A1.5. Transportation Model (Architecture 1).

Parameter	**Value**	**Unit**	**Comment**
Water produced on the Moon	235126.0	kg	Scales extraction system on Moon
Mass of water electrolyzed on the Moon for propellant	127089.0	kg	Scales propellant production system on the
Excess O2 available on Moon	21182.0	kg	
Water electrolyzed at L1 for sending tanker to LEO	10045.0	kg	Scales propellant production system at L1
Water electrolyzed at L1 for sending LADV back to Moon	31153.0	kg	
Excess O2 available at L1	11946.0	kg	
Mass of water electrolyzed in LEO	66839	kg	
Excess O2 in LEO available for fuel	11140	kg	
Satellite Payload Mass	5000.0	kg	From User-defined INPUTS
Propellant required in LEO	11256.0	kg	Assumes aerobraking into LEO
Number of trips per year	3,0		
Requirement for propellant in LEO (annual)	33768.0	kg	
Propellant required in LEO for satellite delivery (per trip)	11256.0	kg	
H_2 requirement in LEO for satellite delivery (per trip)	1500.8	kg	
O_2 required in LEO for satellite delivery (per trip)	9755.2	kg	
Total water required in L1 for each trip of L1-LEO-L1	13507.2	kg	
Annual shipment of water to LEO for LEO-GEO-LEO OTV	40521.6	kg	
Excess O2	6753.6	kg	
Moon-L1-Moon Payload (water)	23859	kg	
Propellant required - Moon - L1	23388.8	kg	
H_2 required - Moon - L1	3118.5	kg	
Equivalent Water required - Moon - L1	28066.5	kg	
Excess O_2 - Moon - L1	4677.7	kg	
Propellant used for return to Moon	5733.1	kg	
H_2 required for return to Moon	764.4	kg	
Equivalent Water required for return to Moon	6879.7	kg	
Excess O_2 for return to Moon	1146.63	kg	
Useful payload in L1 for each flight of Moon-L1-Moon	16979.2	kg	
No. of flights of Moon-L1-Moon vehicle required annually	4.5		
L1-LEO-L1 Payload (water)	20000	kg	
Propellant required - L1 -LEO	2504.8	kg	
H_2 required - L1 -LEO	333.9	kg	
Equivalent water required - L1 -LEO	3005.7	kg	
Excess O_2 required - L1 -LEO	500.9	kg	
Propellant used for return to L1	6562.4	kg	
H_2 in propellant	874.9	kg	
Equivalent water	7874.8	kg	
Excess O_2	1312.4	kg	
Useful payload in LEO for each flight of L1-LEO-L1	12125.12	kg	
No. of flights of L1-LEO-L1 vehicle required annually	3.3		

Then, the specific mass and power data of each of the elements is used to determine the mass of hardware required at each location. For each additional increment of capability, a similar increment of hardware is added. Space does not permit the depiction of the complete architecture.

A1.2 ARCHITECTURE 1 COST MODEL

Tables A1.6-A1.8 provide the analysis for the lunar surface, L1 and LEO elements in Architecture 1, showing the general application of the cost model. Figures A1.1 shows the full cost model for Architecture 1, with details regarding systems integration costs shown in Figure A1.2.

TABLE A1.6. Architecture 1, Lunar Surface System.

Lunar Surface Mining & Processing Equipment	**Mass**	**D&D**	**STH**	**FU**	**Prod**	**Total**
HARDWARE TOTAL	13769.7	1843.3	741.3	570.2	570.2	3154.8
Regolith Excavator	268.0	19.3	17.4	13.4	13.4	50.1
Regolith Hauler	348.0	27.3	25.2	19.3	19.3	71.8
Thermal Extraction	2677.9	595.1	23.7	18.3	18.3	637.1
Water Electrolysis	724.0	89.6	37.7	29.0	29.0	156.4
Hydrogen Liquefier	24.0	2.8	0.5	0.4	0.4	3.8
Hydrogen Liquefier Radiators	419.0	26.7	1.6	1.2	1.2	29.6
Oxygen Liquefier	90.0	5.5	1.6	1.2	1.2	8.3
Oxygen Liquefier Radiators	129.0	14.8	0.6	0.5	0.5	15.9
Water Tanks	520.0	7.0	1	0.8	0.8	8.7
Hydrogen Tanks	469.0	6.6	0.9	0.7	0.7	8.2
Oxygen Tanks	1999.0	14.6	2.2	1.7	1.7	18.6
Power System (Nuclear)	3347.9	557.2	435.6	335.1	335.1	1327.8
Maintenance Facility	1000.0	374.1	152.6	117.4	117.4	644
Ancillary Equipment	1754.0	102.5	40.6	31.2	31.2	174.3
SYSTEM INTEGRATION		2088.1			345.5	2433.6
TOTAL	13769.7	3931.4	741.3	915.7	915.7	5588.4

TABLE A1.7. Architecture1, L1 Depot.

L1 Depot	**Mass**	**D&D**	**STH**	**FU**	**Prod**	**Total**
HARDWARE TOTAL	2601.9	157.6	35.9	27.6	27.6	221
Water Electrolysis	257.0	81.1	23.1	17.8	17.8	122.1
Hydrogen Liquefier	23.0	2.8	0.5	0.4	0.4	3.7
Hydrogen Liquefier Radiators	407.0	26.3	1.6	1.2	1.2	29.1
Oxygen Liquefier	88.0	5.5	1.5	1.2	1.2	8.2
Oxygen Liquefier Radiators	88.0	12.2	0.5	0.4	0.4	13.1
Water Tanks	323.0	5.4	0.7	0.6	0.6	6.7
Hydrogen Tanks	206.0	4.2	0.6	0.4	0.4	5.2
Oxygen Tanks	878.0	9.3	1.4	1.0	1.0	11.7
Power System (solar)	95.0	1.4	2.5	2.0	2.0	5.9
Ancillary Equipment	237.0	9.4	3.4	2.6	2.6	15.4
SYSTEM INTEGRATION		159.1		18.1	18.1	195.4
TOTAL	2601.9	316.7	35.9	45.7	45.7	398.3

TABLE A1.8. Architecture 1, LEO Depot.

LEO Depot	**Mass**	**D&D**	**STH**	**FU**	**Prod**	**Total**
HARDWARE TOTAL	4214.9	261.8	71.5	55.0	55.0	388.3
Water Electrolysis	832.0	174.1	55.9	43.0	43.0	272.9
Hydrogen Liquefier	28.0	3.1	0.6	0.5	0.5	4.2
Hydrogen Liquefier Radiators	481.0	28.6	1.8	1.4	1.4	31.8
Oxygen Liquefier	104.0	5.9	1.8	1.3	1.3	9
Oxygen Liquefier Radiators	104.0	13.3	0.5	0.4	0.4	14.3
Water Tanks	222.0	4.4	0.6	0.5	0.5	5.4
Hydrogen Tanks	370.0	5.8	0.8	0.6	0.6	7.2
Oxygen Tanks	1579.0	12.8	1.9	1.5	1.5	16.3

Power System (solar)	112.0	1.6	2.9	2.2	2.2	6.7
Ancillary Equipment	383.0	12.2	4.7	3.7	3.7	20.6
SYSTEM INTEGRATION		271.8		35.4	35.4	342.7
TOTAL	4214.9	533.6	71.5	90.5	90.5	695.6

FIGURE A1.1. The complete NAFCOM99 cost estimate for Architecture 1, showing analogies.

SRD Architecture 1c NAFCOM 99 Cost Estimate							
Brad R.Blair, Colorado School of Mines	**Mass (kg)**	**D&D**	**STH**	**FU**	**Prod**	**Total Cost**	**Analogy**
GRAND TOTAL	37317.2	5764.4	1063.8	1323.8	1323.8	**8151.9**	
SYSTEM 1: Lunar Surface Mining & Procesing Equipment	13769.7	3931.4	741.3	915.7	915.7	**5588.4**	
HARDWARE TOTAL	13769.7	1843.3	741.3	570.2	570.2	**3154.8**	
Regolith Excavator	268.0	19.3	17.4	13.4	13.4	**50.1**	
Structure	67.0	8.1	5.6	4.3	4.3	**18**	Mars Pathfinder!Structural/Mechanical Group!0.4733!0.1195!
Mobility	67.0	3.9	6.3	4.8	4.8	**15**	Mars Pathfinder!Mechanisms Subsystem!0.2281!0.1338!
Excavation	67.0	0.8	1.4	1.1	1.1	**3.3**	DSCS-IIIA!Wheel, Reaction!0.0462!0.0495!
Soil Handling	64.0	6.0	3.6	2.8	2.8	**12.4**	Mars Pathfinder!Structural/Mechanical Group!0.4733!0.1195!Viking
CC&DH	3.0	0.5	0.4	0.3	0.3	**1.3**	Lunar Prospector!CC&DH Group!0.0840!0.0696!
Regolith Hauler	348.0	27.3	25.2	19.3	19.3	**71.8**	
Structure	115.0	9.9	6.6	5.1	5.1	**21.6**	Mars Pathfinder!Structures Subsystem!0.4309!0.0965!
Mobility	115.0	5.2	9.2	7.1	7.1	**21.5**	Mars Pathfinder!Mechanisms Subsystem!0.2281!0.1338!
Soil Handling	115.0	10.9	8.2	6.3	6.3	**25.4**	Mars Pathfinder!Structural/Mechanical Group!0.4733!0.1195!
CC&DH	3.0	1.3	1.1	0.9	0.9	**3.3**	ATS-6!CC&DH Group!0.2316!0.1768!
Thermal Extraction	2677.9	595.1	23.7	18.3	18.3	**637.1**	Centaur-D!Propulsion Subsystem!4.5779!0.0910!
Water Electrolysis	724.0	89.6	37.7	29.0	29.0	**156.4**	Shuttle Orbiter!Generation, Electrical Power!0.6770!0.1049!
Hydrogen Liquefier	24.0	2.8	0.5	0.4	0.4	**3.8**	OMV!Heat Pipes/Cold Plate!0.3571!0.0159!
Hydrogen Liquefier Radiators	419.0	26.7	1.6	1.2	1.2	**29.6**	Centaur-D!Thermal Control Subsystem!0.8024!0.0048!
Oxygen Liquefier	90.0	5.5	1.6	1.2	1.2	**8.3**	OMV!Heat Pipes/Cold Plate!0.3571!0.0159!
Oxygen Liquefier Radiators	129.0	14.8	0.6	0.5	0.5	**15.9**	Centaur-D!Thermal Control Subsystem!0.8024!0.0048!
Water Tanks	520.0	7.0	1	0.8	0.8	**8.7**	Centaur-G'!Tank!0.1321!0.0102!
Hydrogen Tanks	469.0	6.6	0.9	0.7	0.7	**8.2**	Centaur-G'!Tank!0.1321!0.0102!
Oxygen Tanks	1999.0	14.6	2.2	1.7	1.7	**18.6**	Centaur-G'!Tank!0.1321!0.0102!
Power System (Nuclear)	3347.9	557.2	435.6	335.1	335.1	**1327.8**	Galileo Orbiter!Electrical Power and Distribution Group!2.2209!0.32
Maintenanace Facility	1000.0	374.1	152.6	117.4	117.4	**644**	
Mobility	200.0	78.9	10.4	8.0	8.0	**97.3**	Lunar Rover!Mobility Subsystem!3.4282!0.1031!
Sensors	200.0	140.2	51.7	39.8	39.8	**231.6**	Mars Pathfinder!Avionics!0.5333!0.2781!
Manipulators	200.0	7.1	13.5	10.4	10.4	**31.1**	Mars Pathfinder!Mechanisms Subsystem!0.2281!0.1338!
CC&DH	200.0	108.6	61.3	47.1	47.1	**217**	Mars Pathfinder!CC&DH Group!0.5600!0.3296!
Spare Parts	200.0	39.4	15.6	12.0	12.0	**67**	Electrical Power and Distribution Group!9.140!0.6863!0.1141!
Ancillary Equipment	1754.0	102.5	40.6	31.2	31.2	**174.3**	Structural/Mechanical Group!8.447!0.9953!0.0878!
SYSTEM INTEGRATION		2088.1		345.5	345.5	**2779.1**	Mars Pathfinder!0.0538!0.2393!0.0254!0.1608!0.1024!0.0409!0.0170!0
SYSTEM 2: L1 Depot	2601.9	316.7	35.9	45.7	45.7	**398.3**	
HARDWARE TOTAL	2601.9	157.6	35.9	27.6	27.6	**221**	
Water Electrolysis	257.0	81.1	23.1	17.8	17.8	**122.1**	Shuttle Orbiter!Electrical Power Subsystem!1.2013!0.1399!
Hydrogen Liquefier	23.0	2.8	0.5	0.4	0.4	**3.7**	OMV!Heat Pipes/Cold Plate!0.3571!0.0159!
Hydrogen Liquefier Radiators	407.0	26.3	1.6	1.2	1.2	**29.1**	Centaur-D!Thermal Control Subsystem!0.8024!0.0048!
Oxygen Liquefier	88.0	5.5	1.5	1.2	1.2	**8.2**	OMV!Heat Pipes/Cold Plate!0.3571!0.0159!
Oxygen Liquefier Radiators	88.0	12.2	0.5	0.4	0.4	**13.1**	Centaur-D!Thermal Control Subsystem!0.8024!0.0048!
Water Tanks	323.0	5.4	0.7	0.6	0.6	**6.7**	Centaur-G'!Tank!0.1321!0.0102!
Hydrogen Tanks	206.0	4.2	0.6	0.4	0.4	**5.2**	Centaur-G'!Tank!0.1321!0.0102!
Oxygen Tanks	878.0	9.3	1.4	1.0	1.0	**11.7**	Centaur-G'!Tank!0.1321!0.0102!
Power System (solar)	95.0	1.4	2.5	2.0	2.0	**5.9**	Lunar Prospector!Solar Array!0.0406!0.0324!
Ancillary Equipment	237.0	9.4	3.4	2.6	2.6	**15.4**	Structural/Mechanical Group!7.689!0.2732!0.0298!
SYSTEM INTEGRATION		159.1		18.1	18.1	**195.4**	Mars Pathfinder!0.0538!0.2393!0.0254!0.1608!0.1024!0.0409!0.0170!0
SYSTEM 3: LEO Depot	4214.9	533.6	71.5	90.5	90.5	**695.6**	
HARDWARE TOTAL	4214.9	261.8	71.5	55.0	55.0	**388.3**	
Water Electrolysis	832.0	174.1	55.9	43.0	43.0	**272.9**	Shuttle Orbiter!Electrical Power Subsystem!1.2013!0.1399!
Hydrogen Liquefier	28.0	3.1	0.6	0.5	0.5	**4.2**	OMV!Heat Pipes/Cold Plate!0.3571!0.0159!
Hydrogen Liquefier Radiators	481.0	28.6	1.8	1.4	1.4	**31.8**	Centaur-D!Thermal Control Subsystem!0.8024!0.0048!
Oxygen Liquefier	104.0	5.9	1.8	1.3	1.3	**9**	OMV!Heat Pipes/Cold Plate!0.3571!0.0159!
Oxygen Liquefier Radiators	104.0	13.3	0.5	0.4	0.4	**14.3**	Centaur-D!Thermal Control Subsystem!0.8024!0.0048!
Water Tanks	222.0	4.4	0.6	0.5	0.5	**5.4**	Centaur-G'!Tank!0.1321!0.0102!
Hydrogen Tanks	370.0	5.8	0.8	0.6	0.6	**7.2**	Centaur-G'!Tank!0.1321!0.0102!
Oxygen Tanks	1579.0	12.8	1.9	1.5	1.5	**16.3**	Centaur-G'!Tank!0.1321!0.0102!
Power System (solar)	112.0	1.6	2.9	2.2	2.2	**6.7**	Lunar Prospector!Solar Array!0.0406!0.0324!
Ancillary Equipment	383.0	12.2	4.7	3.7	3.7	**20.6**	Structural/Mechanical Group!7.689!0.2732!0.0298!
SYSTEM INTEGRATION		271.8		35.4	35.4	**342.7**	Mars Pathfinder!0.0538!0.2393!0.0254!0.1608!0.1024!0.0409!0.0170!0
SYSTEM 4: OTV (LEO-L1)	5047.9	269.9	70.9	89.6	89.6	**430.4**	
HARDWARE TOTAL	5047.9	115.7	70.9	54.5	54.5	**241.1**	
Propulsion System	906.0	34.8	14.7	11.3	11.3	**60.8**	Centaur-G'!Propulsion Subsystem!0.4858!0.1080!
Water Tanks	200.0	4.1	0.6	0.4	0.4	**5.1**	Centaur-G'!Tank!0.1321!0.0102!
CC&DH	13.0	1.6	1.5	1.1	1.1	**4.2**	Lunar Prospector!CC&DH Group!0.0840!0.0696!
Structure	647.0	27.3	13	10.0	10.0	**50.3**	Centaur-G'!Structural/Mechanical Group!0.4582!0.0567!
Power	15.0	7.2	0.2	0.1	0.1	**7.5**	Centaur-D!Electrical Power Subsystem!0.6713!0.0089!
Aerobrake	3266.9	40.8	40.9	31.5	31.5	**113.2**	Mars Pathfinder!Entry Heat Shield & Backshell!0.2811!0.0573!
SYSTEM INTEGRATION		154.2		35.1	35.1	**224.4**	Mars Pathfinder!0.0538!0.2393!0.0254!0.1608!0.1024!0.0409!0.0170!0
SYSTEM 5: Lunar Lander	7747.8	446.8	83.5	105.4	105.4	**635.7**	
HARDWARE TOTAL	7747.8	208.1	83.5	64.2	64.2	**355.9**	
Propulsion System	2180.0	56.4	24.9	19.2	19.2	**100.5**	Centaur-G'!Propulsion Subsystem!0.4858!0.1080!
Water Tanks	239.0	4.5	0.6	0.5	0.5	**5.7**	Centaur-G'!Tank!0.1321!0.0102!
CC&DH	15.0	1.8	1.6	1.3	1.3	**4.7**	Lunar Prospector!CC&DH Group!0.0840!0.0696!
Structure	3481.9	68.8	42.4	32.6	32.6	**143.8**	Centaur-G'!Structural/Mechanical Group!0.4582!0.0567!
Power	15.0	7.2	0.2	0.1	0.1	**7.5**	Centaur-D!Electrical Power Subsystem!0.6713!0.0089!
Landing System	1819.0	69.6	14	10.8	10.8	**94.4**	Apollo LM!Landing Gear!0.6626!0.0295!
SYSTEM INTEGRATION		238.6		41.2	41.2	**321.0**	Mars Pathfinder!0.0538!0.2393!0.0254!0.1608!0.1024!0.0409!0.0170!0
SYSTEM 6: OTV (LEO-GEO)	3934.9	266.0	60.7	76.9	76.9	**403.5**	
HARDWARE TOTAL	3934.9	118.2	60.7	46.7	46.7	**225.5**	
Propulsion System	1362.0	43.5	18.8	14.4	14.4	**76.8**	Centaur-G'!Propulsion Subsystem!0.4858!0.1080!
CC&DH	13.0	1.6	1.5	1.1	1.1	**4.2**	Lunar Prospector!CC&DH Group!0.0840!0.0696!
Structure	2032.0	51.2	29.1	22.3	22.3	**102.6**	Centaur-G'!Structural/Mechanical Group!0.4582!0.0567!
Power	15.0	7.2	0.2	0.1	0.1	**7.5**	Centaur-D!Electrical Power Subsystem!0.6713!0.0089!
Aerobrake	513.0	14.7	11.2	8.6	8.6	**34.5**	Mars Pathfinder!Entry Heat Shield & Backshell!0.2811!0.0573!
SYSTEM INTEGRATION		147.8		30.2	30.2	**208.2**	Mars Pathfinder!0.0538!0.2393!0.0254!0.1608!0.1024!0.0409!0.0170!0

FIGURE A1.2. Detail showing the NAFCOM99 systems integration cost estimates for Architecture 1.

SRD Architecture 1c - Systems Engineering Cost Details (NAFCOM 99 Estimate)															
Brad R.Blair, Colorado School of Mines, 19-Dec-02	**Wt - lbs**		IACO	STO	GSE	Tooling	M/E	SEI	PM	LOOS	Sub	Cont	ProSupp	Fee	Total
GRAND TOTAL	73596														
SYSTEM 1: Lunar Surface Mining & Procesing Equipment	30357	DDT&E	5.6	18.8	65.6	6.6	59.1	415.6	38.0	229.8	773.5	503.7	386.2	424.8	2088.1
		FU	2.0	0.0	0.0	0.0	0.0	74.7	11.2	0.0	87.9	98.7	75.7	83.2	345.5
		Prod	2.0	0.0	0.0	0.0	0.0	74.7	11.2	0.0	87.9	98.7	75.7	83.2	345.5
SYSTEM 2: L1 Depot	5736	DDT&E	0.7	4.5	4.9	0.5	4.4	31.1	5.4	13.3	59.9	38.0	29.1	32.1	159.1
		FU	0.2	0.0	0.0	0.0	0.0	4.2	0.9	0.0	5.3	4.9	3.8	4.2	18.1
		Prod	0.2	0.0	0.0	0.0	0.0	4.2	0.9	0.0	5.3	4.9	3.8	4.2	18.1
SYSTEM 3: LEO Depot	9292	DDT&E	1.1	6.1	8.5	0.8	7.6	53.6	8.2	24.1	101.6	65.2	50.0	55.0	271.8
		FU	0.4	0.0	0.0	0.0	0.0	8.1	1.5	0.0	10.0	9.8	7.5	8.2	35.4
		Prod	0.4	0.0	0.0	0.0	0.0	8.1	1.5	0.0	10.0	9.8	7.5	8.2	35.4
SYSTEM 4: OTV (LEO-L1)	11129	DDT&E	1.1	4.4	4.7	0.5	4.3	30.0	5.3	12.8	58.3	36.7	28.2	31.0	154.2
		FU	0.3	0.0	0.0	0.0	0.0	8.0	1.5	0.0	9.9	9.7	7.4	8.1	35.1
		Prod	0.3	0.0	0.0	0.0	0.0	8.0	1.5	0.0	9.9	9.7	7.4	8.1	35.1
SYSTEM 5: Lunar Lander	17081	DDT&E	1.2	5.7	7.4	0.7	6.7	46.9	7.4	20.8	89.4	57.2	43.8	48.2	238.6
		FU	0.4	0.0	0.0	0.0	0.0	9.4	1.7	0.0	11.5	11.4	8.7	9.6	41.2
		Prod	0.4	0.0	0.0	0.0	0.0	9.4	1.7	0.0	11.5	11.4	8.7	9.6	41.2
SYSTEM 6: OTV (LEO-GEO)	8675	DDT&E	1.0	4.3	4.5	0.5	4.1	28.8	5.1	12.2	55.9	35.2	27.0	29.7	147.8
		FU	0.3	0.0	0.0	0.0	0.0	6.9	1.3	0.0	8.6	8.3	6.4	7.0	30.2
		Prod	0.3	0.0	0.0	0.0	0.0	6.9	1.3	0.0	8.6	8.3	6.4	7.0	30.2

SRD Appendix 2

Case 1, Architecture 2 Development and Cost Model

A2.1 DEVELOPMENT OF ARCHITECTURE 2 SYSTEM ELEMENTS

L1-LEO-GEO-L1 Orbital Transfer Vehicle. The transfer vehicle and tanker functions are combined and a single vehicle is fueled at L1, flies with a propellant load that is aerobraked into LEO where it performs a rendezvous maneuver with a satellite, then propels the satellite to GEO. Following the insertion, the vehicle flies back to L1 for refueling. This vehicle must carry to LEO the propellant needed for LEO-GEO-L1 as well as the aerobrake for entering LEO.

Calculation method

Definitions:

- m_{pp}: mass of propellant required from LEO to GEO
- m_i: inert mass
- m_{ab}: aerobrake mass
- m_{sg}: mass of payload to transfer to GEO
- m_{pf}: mass of propellant to maneuver from GEO to L1
- m_{pt}: mass of propellant to maneuver from L1 to LEO
- $\alpha = m_i / m_{pp}$
- $r = (m_i + m_p + mpp + m_{ab}) / (m_i + m_p + m_{ab})$
- rt: (initial/final) mass ratio for L1-LEO transport with aerobraking
- rf: (initial/final) mass ratio for GEO-L1 transport

Method:

An iterative process on m_{pp} has been designed and programmed into an excel user-defined function, based on the following equations:

- Propulsion system mass = $(64.77+0.0745*m_{pp}+1.004*m_{pp}{}^{\wedge(2/3)})$ [Sercel et all, 1999]
- Structure mass = 30% propulsion system mass + 15% m_{pp}
- m_i = Constant base mass (telecom, C&DH and power) + Propulsion system mass + Structure mass
- $m_{ab} = 0.15*(m_i + m_{pp})$
- $m_{pf} = (m_i + m_{ab})*(rf-1)$
- $m_{pt}=(m_i+m_{ab}+m_{pf}+m_{pp}) \times (rt-1)$
- $m_{pp} = (m_i + m_{ab}+m_{pf}+m_{sg})*(r-1)$

Finally, the total propellant to be refueled at the L1 station is $m_{pp}+m_{pf}+m_{pt}$

Results are provided in Table A2.1.

TABLE A2.1. Orbital Transfer Vehicle (Architecture 2).

Parameter	Value	Unit	Comment
R	2.16		Using 3800 m/sec for LEO-GEO delta-V
Rt	1.10		Assume 500 m/sec for L1-LEO propulsive with aerobraking
Rf	1.17		Assume 800 m/sec for GEO-L1 propulsive
Telecomm system mass	10.00	kg	Assume constant
C&DH system mass	3.00	kg	Assume constant
Power system mass	15.00	kg	Assume constant
Msg	5000.00	kg	From Demand Model
Mpp	17926.89	kg	Use "OTVModelRough" function
Propulsion system mass	2088.03	kg	64.77+0.0745*mpp+1.004*mpp^(2/3)
Structure mass	3315.44	kg	Add .15X payload to TLALOC assumption
Inert mass mi	5431.47	kg	Total inert mass without mab
a(a)	0.30		mi/mpp
Aerobrake mass	3503.75	kg	mab=0.15*(mi+mpp)
Propellant for GEO-L1	1518.99	kg	mpf=(mi+mab)*(rf-1)
Propellant for L1-LEO	2838.11	kg	mpt=(mi+mab+mpp+mpf)*(rt-1)
Total propellant in L1	22283.97	kg	To be refueled in L1 before each trip

Lunar water tanker: This vehicle is capable of landing near the propellant production plant (probably not in the permanent shadow), taking on a payload of water and cryogenic propellants and traveling from the Moon to the L1 propellant depot. Delta V's for each of the legs of the scenarios are given in Table X. The mass of the lunar water tanker was estimated from scaling equations based on the Apollo lunar lander (Eckart, 1999). The tanker is assumed to be highly reusable, with 10% per year hardware refurbishment.

Calculation method

- Setting the mpp: mass of propellant required from LEO to GEO
- Calculation of the tanker total gross mass from the mpp, using the rocket equation
- Vehicle inert mass calculation using Apollo equation:

  Lander dry mass = 0.064*mgross+59.1*(m_{pp} /db$L_{H2}L_{OX}$)+390, being db=bulk density
- Finally, the amount of water the can deliver to the L1 station is calculating as follows:

  Moon-L1 vehicle load capacity = mgross - Lander dry mass - m_{pp}

Table A2.2 shows the results of those calculations.

TABLE A2.2. Lunar Water Tanker Vehicle (Architecture 2).

Parameter	Value	Unit	Comment
Total propellant available to ship	23427.2	kg	
Lander total mass	55034.5	kg	Calculated from the available propellant mass
Moon-L1 vehicle load capacity	23859.9	kg	
O2/H2 mixture ratio	6.5		
Engine Isp	460.0	sec	
Delta V	2500.0	m/sec	One-way delta V from the Moon surface to the L1 station
delta V/Isp g ratio	0.6		
Mi/Mf ratio	1.7		
dbLH2Lox	361.0		propellant bulk density
Dry weight of vehicle	7747.5	kg	Lander dry mass

Lunar surface water extraction and propellant production. This system produces water for export from the Moon and sufficient propellant to launch it to space. The baseline assumption in the model is that the regolith contains 2% water by weight. It is assumed that all water and propellant production is carried out within the permanent shadow, although other options for the lunar system exist (Duke et al, 1998) and should be investigated in further studies. A nuclear reactor is assumed to provide thermal and electrical energy for water extraction. The system extracts water by heating regolith from its ambient temperature (80K) to 200K under vacuum. Water is electrolyzed and the hydrogen and oxygen liquefied and stored for propellant. Liquid oxygen can be stored using passive thermal control techniques in the permanent shadow and the energy cost of storing liquid hydrogen is minimal. Water tanks must be insulated and heated to retain water in liquid form. The “specific mass” or “specific energy,” which are defined as the mass or energy required to produce a given amount of product in a given amount of time, are provided for the major elements of the surface architecture in Table 1, along with other general assumptions utilized in the model. For costing purposes, it is assumed that 10 % of the system must be replaced each year of operations. The current architecture assumes that the excess oxygen is lost to the system. Enough hydrogen and oxygen are stored on site to allow for continued operation of the system when a lunar water tanker is not present at the production facility. Otherwise, the product is stored in the tanker itself.

A propellant depot in L1. At this depot, water is received from the Moon and propellant is produced for the L1-LEO or L1-LEO-GEO-L1 transfer system as well as for returning the lunar water tanker to the Moon. The electrolysis and liquefaction systems are similar to those on the Moon. Excess oxygen produced at L1 is assumed lost to the system. Power for the propellant depot is provided by solar arrays.

Starting with the market assumptions, the amount of propellant needed in each of the architectures is calculated from the transportation system assumptions, determining the required amount of propellant at each node of the architecture.. For architecture 2, a roundtrip Moon-L1-Moon transfer delivers water to L1 and uses propellant produced at L1 to return an empty transfer vehicle to the Moon. The L1 propellant depot must also produce propellant for the an orbital transfer vehicle to travel to LEO, transfer a satellite to GEO and travel back to L1. An aerobrake is used for LEO orbit insertion. Working back through the system, the amount of propellant required at each location in the system is calculated as follows:

- The amount of propellant required in L1 for the L1-LEO-GEO-L1 OTV is given
- The payload capacity of the Moon-L1-Moon vehicle is given

- The useful payload provided to L1 by one flight of the tanker is calculated (the difference between the vehicle payload and the amount of propellant required to return the vehicle to the moon) is made to determine the number of trips that the Moon-L1-Moon vehicle must make to support each delivery from L1 to GEO
- Finally, the amount of water to be produced on the moon and the amount of water to be electrolyzed on the moon in order to produce propellant for Moon-L1-Moon vehicle are calculated from previous data

For all previous calculations, is important to remember that the mixture ratio for engines is 6.5:1 whereas the electrolysis ratio is 9:1, so we are going to have an excess of O2, that we assume can throw away without any penalty. Results are available in Table

TABLE A2.3. Transportation Model (Architecture 2).

Parameter	Value	Unit	Comment
Water produced on the Moon	245329	kg	Scales extraction system on Moon
Mass of water electrolyzed on the Moon for	132604	kg	Scales propellant production system on the Moon
Excess O2 available on Moon	22101	kg	
Mass of water electrolyzed at L1 for sending OTV	80222	kg	Scales propellant production system at L1
Mass of water electrolyzed at L1 for sending LADV	32503	kg	
Excess O2 available at L1	18788	kg	
Satellite Payload Mass	5000.0	kg	From User-defined INPUTS
Propellant required in L1	22284.0	kg	Assumes aerobraking into LEO
Number of trips per year	3.0		
Requirement for propellant in L1 (annual)	66851.9	kg	
Propellant required in L1 (per trip)	22284.0	kg	
H_2 requirement in L1 for satellite delivery (per trip),	2971.2	kg	
O_2 required in L1 for satellite delivery (per trip), O2	19312.8	kg	
Total water required in L1 for each trip of OTV	26740.8	kg	
Annual shipment of water to L1 for OTV	80222.3	kg	
Excess O2 in L1	13370.4	kg	
Payload (water) on LADV	23437.2	kg	
Dry mass of LADV	7747.5	kg	
Mi/Mf for LADV	1.7		
Propellant mixture ratio	6.5		
Propellant required for Moon to L1 trip, total	23389.5	kg	
Propellant required for Moon to L1 trip, H2	3118.6	kg	
Propellant required for Moon to L1 trip, water	28067.4	kg	
Excess O2 from Moon to L1 trip	4677.9	kg	
Annual water production required for Moon-L1 trip	132603.6	kg	
Propellant used for return to the Moon	5733.1	kg	
Propellant used for return to the Moon, H2	764.4	kg	
Propellant used for return to the Moon, water	6879.7	kg	
Excess O2 from return to the Moon	1146.6	kg	
Useful water delivered to L1 for each LADV round-	16980.2	kg	
Number of flights of the LADV required annually	4.7		

Then, the specific mass and power data of each of the elements is used to determine the mass of hardware required at each location. For each additional increment of capability, a similar increment of hardware is added. Space does not permit the depiction of the complete architecture.

A2.2 ARCHITECTURE 2 COST MODEL

Tables A2.4 and A2.5 provide the analysis for the lunar surface and L1 elements in Architecture 2 that shows the general application of the cost model. Figures A2.1 shows the full cost model for Architecture 1, with details regarding systems integration costs shown in Figure A2.2.

TABLE A2.4. Architecture 2, Lunar Surface System.

Lunar Surface Mining & Processing Equipment	**Mass**	**D&D**	**STH**	**FU**	**Prod**	**Total**
HARDWARE TOTAL	13980.7	1861.6	750.5	577.3	577.3	3189.5
Regolith Excavator	274.0	19.5	17.7	13.6	13.6	50.8
Regolith Hauler	356.0	27.7	25.5	19.6	19.6	72.8
Thermal Extraction	2736.9	602.3	24.1	18.5	18.5	644.8
Water Electrolysis	736.0	90.6	38.2	29.4	29.4	158.2
Hydrogen Liquefier	25.0	2.9	0.6	0.4	0.4	3.9
Hydrogen Liquefier Radiators	425.0	26.9	1.6	1.3	1.3	29.8
Oxygen Liquefier	92.0	5.6	1.6	1.2	1.2	8.4
Oxygen Liquefier Radiators	131.0	14.9	0.6	0.5	0.5	16.1
Water Tanks	520.0	7.0	1	0.8	0.8	8.7
Hydrogen Tanks	469.0	6.6	0.9	0.7	0.7	8.2
Oxygen Tanks	1999.0	14.6	2.2	1.7	1.7	18.6
Power System (Nuclear)	3420.9	565.1	442.7	340.5	340.5	1348.3
Maintenance Facility	1000.0	374.1	152.6	117.4	117.4	644
Ancillary Equipment	1796.0	103.9	41.3	31.7	31.7	176.9
SYSTEM INTEGRATION		2110.5		349.7	349.7	2809.9
TOTAL	13980.7	3972.1	750.5	927.1	927.1	5649.7

TABLE A2.5. Architecture 2, L1 Depot.

L1 Depot	**Mass**	**D&D**	**STH**	**FU**	**Prod**	**Total**
HARDWARE TOTAL	6806.8	280.3	74.2	57.1	57.1	411.6
Water Electrolysis	692.0	154.4	48.7	37.4	37.4	240.5
Hydrogen Liquefier	63.0	4.6	1.2	0.9	0.9	6.7
Hydrogen Liquefier Radiators	1096.0	43.2	3.5	2.7	2.7	49.4
Oxygen Liquefier	236.0	8.9	3.4	2.6	2.6	14.9
Oxygen Liquefier Radiators	236.0	20.1	1	0.8	0.8	21.9
Water Tanks	369.0	5.8	0.8	0.6	0.6	7.2
Hydrogen Tanks	615.0	7.6	1.1	0.8	0.8	9.6
Oxygen Tanks	2624.9	17.0	2.6	2.0	2.0	21.6
Power System (solar)	256.0	2.7	5.3	4.1	4.1	12.2
Ancillary Equipment	619.0	15.9	6.6	5.1	5.1	27.6
SYSTEM INTEGRATION		288.8		36.7	36.7	362.3
TOTAL	6806.8	569.1	74.2	93.8	93.8	737.1

FIGURE A2.1. The complete NAFCOM99 cost estimate for Architecture 2, showing analogies.

SRD Architecture 2 NAFCOM 99 Cost Estimate							
Brad R.Blair, Colorado School of Mines	Mass (kg)	D&D	STH	FU	Prod	Total Cost	Analogy
GRAND TOTAL	37470.2	5393.2	1018.1	1264.5	1264.5	**7675.8**	
SYSTEM 1: Lunar Surface Mining & Pro	13980.7	3972.1	750.5	927.1	927.1	**5649.7**	
HARDWARE TOTAL	13980.7	1861.6	750.5	577.3	577.3	**3189.5**	
Regolith Excavator	274.0	19.5	17.7	13.6	13.6	**50.8**	
Structure	68.5	8.2	5.7	4.4	4.4	**18.3**	Mars Pathfinder!Structural/Mechanical Group!0.4733!0.1195!
Mobility	68.5	3.9	6.4	4.9	4.9	**15.3**	Mars Pathfinder!Mechanisms Subsystem!0.2281!0.1338!
Excavation	68.5	0.8	1.4	1.1	1.1	**3.3**	DSCS-IIIA!Wheel, Reaction!0.0462!0.0495!
Soil Handling	65.5	6.1	3.7	2.8	2.8	**12.6**	Mars Pathfinder!Structural/Mechanical Group!0.4733!0.1195!Viking I
CC&DH	3.0	0.5	0.4	0.3	0.3	**1.3**	Lunar Prospector!CC&DH Group!0.0840!0.0696!
Regolith Hauler	356.0	27.7	25.5	19.6	19.6	**72.8**	
Structure	117.7	10.0	6.7	5.2	5.2	**22**	Mars Pathfinder!Structures Subsystem!0.4309!0.0965!
Mobility	117.7	5.3	9.3	7.2	7.2	**21.8**	Mars Pathfinder!Mechanisms Subsystem!0.2281!0.1338!
Soil Handling	117.6	11.0	8.3	6.4	6.4	**25.8**	Mars Pathfinder!Structural/Mechanical Group!0.4733!0.1195!
CC&DH	3.0	1.3	1.1	0.9	0.9	**3.3**	ATS-6!CC&DH Group!0.2316!0.1768!
Thermal Extraction	2736.9	602.3	24.1	18.5	18.5	**644.8**	Centaur-D!Propulsion Subsystem!4.5779!0.0910!
Water Electrolysis	736.0	90.6	38.2	29.4	29.4	**158.2**	Shuttle Orbiter!Generation, Electrical Power!0.6770!0.1049!
Hydrogen Liquefier	25.0	2.9	0.6	0.4	0.4	**3.9**	OMV!Heat Pipes/Cold Plate!0.3571!0.0159!
Hydrogen Liquefier Radiators	425.0	26.9	1.6	1.3	1.3	**29.8**	Centaur-D!Thermal Control Subsystem!0.8024!0.0048!
Oxygen Liquefier	92.0	5.6	1.6	1.2	1.2	**8.4**	OMV!Heat Pipes/Cold Plate!0.3571!0.0159!
Oxygen Liquefier Radiators	131.0	14.9	0.6	0.5	0.5	**16.1**	Centaur-D!Thermal Control Subsystem!0.8024!0.0048!
Water Tanks	520.0	7.0	1	0.8	0.8	**8.7**	Centaur-G'!Tank!0.1321!0.0102!
Hydrogen Tanks	469.0	6.6	0.9	0.7	0.7	**8.2**	Centaur-G'!Tank!0.1321!0.0102!
Oxygen Tanks	1999.0	14.6	2.2	1.7	1.7	**18.6**	Centaur-G'!Tank!0.1321!0.0102!
Power System (Nuclear)	3420.9	565.1	442.7	340.5	340.5	**1348.3**	Galileo Orbiter!Electrical Power and Distribution Group!2.2209!0.3272
Maintenanace Facility	1000.0	374.1	152.6	117.4	117.4	**644**	Mars Pathfinder!CC&DH Group!0.5600!0.3296!
Mobility	200.0	78.9	10.4	8.0	8.0	**97.3**	Lunar Rover!Mobility Subsystem!3.4282!0.1031!
Sensors	200.0	140.2	51.7	39.8	39.8	**231.6**	Mars Pathfinder!Avionics!0.5333!0.2781!
Manipulators	200.0	7.1	13.5	10.4	10.4	**31.1**	Mars Pathfinder!Mechanisms Subsystem!0.2281!0.1338!
CC&DH	200.0	108.6	61.3	47.1	47.1	**217**	Mars Pathfinder!CC&DH Group!0.5600!0.3296!
Spare Parts	200.0	39.4	15.6	12.0	12.0	**67**	Electrical Power and Distribution Group!9.140!0.6863!0.1141!
Ancillary Equipment	1796.0	103.9	41.3	31.7	31.7	**176.9**	Structural/Mechanical Group!8.447!0.9953!0.0878!
SYSTEM INTEGRATION		2110.5		349.7	349.7	**2809.9**	Mars Pathfinder!0.0538!0.2393!0.0254!0.1608!0.1024!0.0409!0.0170!0.1
SYSTEM 2: L1 Depot	6806.8	569.1	74.2	93.8	93.8	**737.1**	
HARDWARE TOTAL	6806.8	280.3	74.2	57.1	57.1	**411.6**	
Water Electrolysis	692.0	154.4	48.7	37.4	37.4	**240.5**	Shuttle Orbiter!Electrical Power Subsystem!1.2013!0.1399!
Hydrogen Liquefier	63.0	4.6	1.2	0.9	0.9	**6.7**	OMV!Heat Pipes/Cold Plate!0.3571!0.0159!
Hydrogen Liquefier Radiators	1096.0	43.2	3.5	2.7	2.7	**49.4**	Centaur-D!Thermal Control Subsystem!0.8024!0.0048!
Oxygen Liquefier	236.0	8.9	3.4	2.6	2.6	**14.9**	OMV!Heat Pipes/Cold Plate!0.3571!0.0159!
Oxygen Liquefier Radiators	236.0	20.1	1	0.8	0.8	**21.9**	Centaur-D!Thermal Control Subsystem!0.8024!0.0048!
Water Tanks	369.0	5.8	0.8	0.6	0.6	**7.2**	Centaur-G'!Tank!0.1321!0.0102!
Hydrogen Tanks	615.0	7.6	1.1	0.8	0.8	**9.6**	Centaur-G'!Tank!0.1321!0.0102!
Oxygen Tanks	2624.9	17.0	2.6	2.0	2.0	**21.6**	Centaur-G'!Tank!0.1321!0.0102!
Power System (solar)	256.0	2.7	5.3	4.1	4.1	**12.2**	Lunar Prospector!Solar Array!0.0406!0.0324!
Ancillary Equipment	619.0	15.9	6.6	5.1	5.1	**27.6**	Structural/Mechanical Group!7.689!0.2732!0.0298!
SYSTEM INTEGRATION		288.8		36.7	36.7	**362.3**	Mars Pathfinder!0.0538!0.2393!0.0254!0.1608!0.1024!0.0409!0.0170!0.1
SYSTEM 3: Lunar Lander	7747.8	446.8	83.5	105.4	105.4	**635.7**	
HARDWARE TOTAL	7747.8	208.1	83.5	64.2	64.2	**355.9**	
Propulsion System	2180.0	56.4	24.9	19.2	19.2	**100.5**	Centaur-G'!Propulsion Subsystem!0.4858!0.1080!
Water Tanks	239.0	4.5	0.6	0.5	0.5	**5.7**	Centaur-G'!Tank!0.1321!0.0102!
CC&DH	13.0	1.6	1.5	1.1	1.1	**4.2**	Lunar Prospector!CC&DH Group!0.0840!0.0696!
Structure	3481.9	68.8	42.4	32.6	32.6	**143.8**	Centaur-G'!Structural/Mechanical Group!0.4582!0.0567!
Power	15.0	7.2	0.2	0.1	0.1	**7.5**	Centaur-D!Electrical Power Subsystem!0.6713!0.0089!
Landing System	1819.0	69.6	14	10.8	10.8	**94.4**	Apollo LM!Landing Gear!0.6626!0.0295!
SYSTEM INTEGRATION		238.6		41.2	41.2	**321.0**	Mars Pathfinder!0.0538!0.2393!0.0254!0.1608!0.1024!0.0409!0.0170!0.1
SYSTEM 4: OTV (LEO-GEO-L1)	8934.8	405.2	109.8	138.2	138.2	**653.2**	
HARDWARE TOTAL	8934.8	173.2	109.8	84.5	84.5	**367.5**	
Propulsion System	2088.0	55.1	24.3	18.7	18.7	**98**	Centaur-G'!Propulsion Subsystem!0.4858!0.1080!
CC&DH	13.0	1.6	1.5	1.1	1.1	**4.2**	Lunar Prospector!CC&DH Group!0.0840!0.0696!
Structure	3314.9	67.0	40.9	31.5	31.5	**139.4**	Centaur-G'!Structural/Mechanical Group!0.4582!0.0567!
Power	15.0	7.2	0.2	0.1	0.1	**7.5**	Centaur-D!Electrical Power Subsystem!0.6713!0.0089!
Aerobrake	3503.9	42.4	43	33.1	33.1	**118.4**	Mars Pathfinder!Entry Heat Shield & Backshell!0.2811!0.0573!
SYSTEM INTEGRATION		232.0		53.7	53.7	**339.5**	Mars Pathfinder!0.0538!0.2393!0.0254!0.1608!0.1024!0.0409!0.0170!0.1

FIGURE A2.2. Detail showing the NAFCOM99 systems integration cost estimates for Architecture 2.

SRD Architecture 2 - Systems Engineering Cost Details (NAFCOM 99 Estimate)															
Brad R.Blair, Colorado School of Mines, 19-Dec-02	Wt - lbs		IACO	STO	GSE	Tooling	M/E	SEI	PM	LOOS	Sub	Cont	ProSupp	Fee	Total
GRAND TOTAL	82608														
SYSTEM 1: Lunar Surface Mining & Procesing Equipment	30822	DDT&E	5.7	18.9	66.3	6.6	59.7	420.0	38.3	232.5	781.8	509.1	390.3	429.3	2110.5
		FU	2.0	0.0	0.0	0.0	0.0	75.5	11.3	0.0	88.9	99.9	76.6	84.3	349.7
		Prod	2.0	0.0	0.0	0.0	0.0	75.5	11.3	0.0	88.9	99.9	76.6	84.3	349.7
SYSTEM 2: L1 Depot	15007	DDT&E	1.1	6.3	9.0	0.9	8.1	57.0	8.6	25.8	107.8	69.3	53.2	58.5	288.8
		FU	0.4	0.0	0.0	0.0	0.0	8.4	1.6	0.0	10.3	10.1	7.8	8.5	36.7
		Prod	0.4	0.0	0.0	0.0	0.0	8.4	1.6	0.0	10.3	10.1	7.8	8.5	36.7
SYSTEM 3: Lunar Lander	17081	DDT&E	1.2	5.7	7.4	0.7	6.7	46.9	7.4	20.8	89.4	57.2	43.8	48.2	238.6
		FU	0.4	0.0	0.0	0.0	0.0	9.4	1.7	0.0	11.5	11.4	8.7	9.6	41.2
		Prod	0.4	0.0	0.0	0.0	0.0	9.4	1.7	0.0	11.5	11.4	8.7	9.6	41.2
SYSTEM 4: OTV (LEO-GEO-L1)	19698	DDT&E	1.5	5.6	7.2	0.7	6.5	45.5	7.2	20.2	87.1	55.5	42.6	46.8	232.0
		FU	0.5	0.0	0.0	0.0	0.0	12.2	2.2	0.0	14.9	14.9	11.4	12.6	53.7
		Prod	0.5	0.0	0.0	0.0	0.0	12.2	2.2	0.0	14.9	14.9	11.4	12.6	53.7

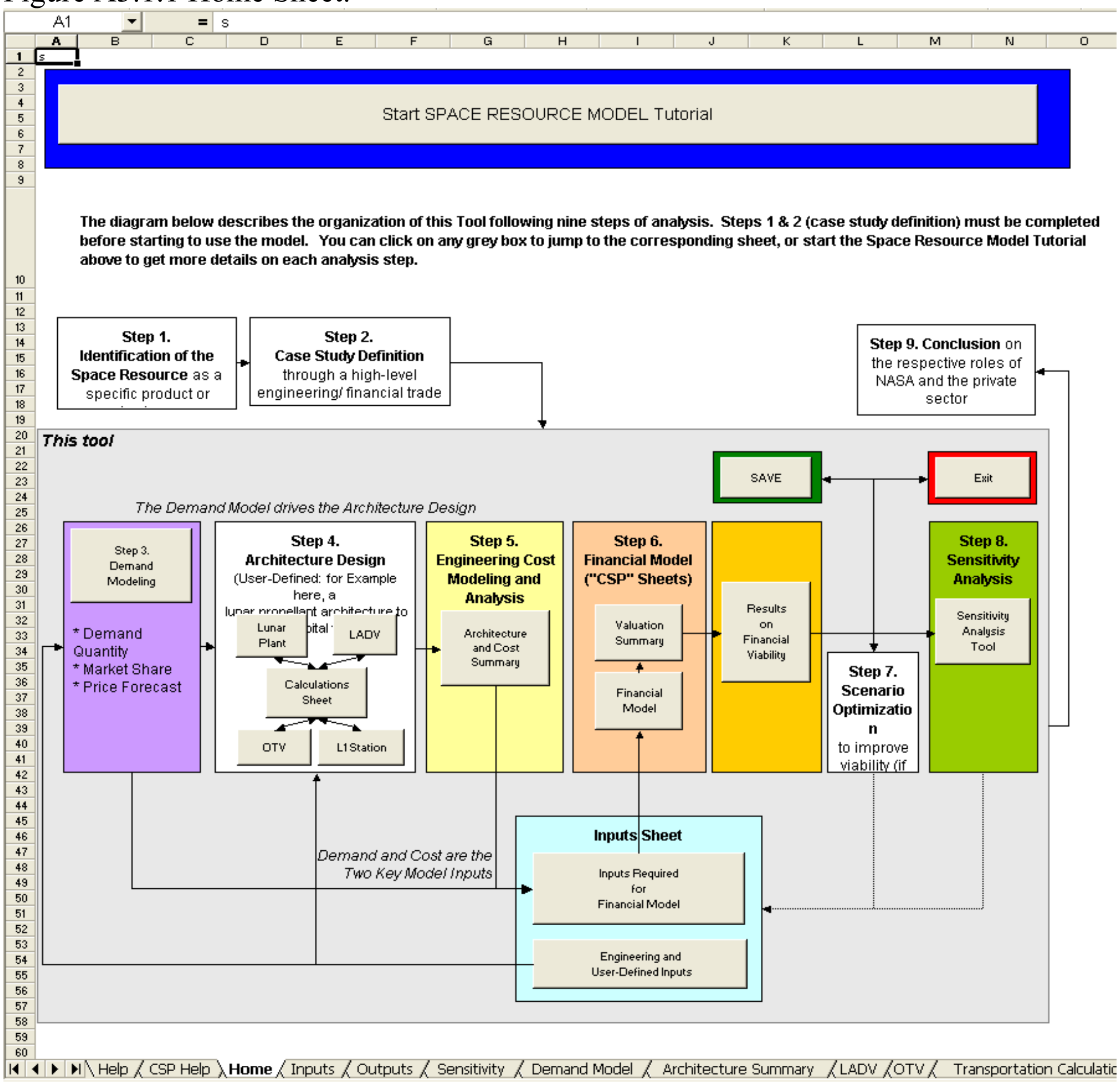
SRD Appendix 3

Financial Toolkit Primer

A3.1 OVERVIEW

A Software Tool has been developed in Microsoft Excel in order to help to calculate and/or modify any possible scenario related with the economic and financial analysis of a space resource development project. The process starts from a baseline containing all the assumptions and calculations described before in this paper. The diagram below describes the organization of this Tool following nine steps of analysis. Steps 1 & 2 (case study definition) must be completed before starting to use the model. You can click on any gray box to jump to the corresponding sheet, or start the Space Resource Model Tutorial above to get more details on each analysis step. At any time in the process, changes can be saved.

Figure A3.1.1 Home Sheet.



A3.2 STEP 1: IDENTIFICATION OF THE SPACE RESOURCE

The first step of analysis consists in defining the space resource to be studied. A space resource is defined as any product or service that can be made available for a certain price in space, including products from raw materials, such as asteroid metals, as well as services, such as transfer from LEO to GEO. The space resource defined should be of direct interest to potential customers. Thus, the resource in the example case study is not "lunar propellant" but rather "transfer from LEO to GEO".

A3.2 STEP 2: CASE STUDY DEFINITION

The second step of analysis consists in a high-level case study definition. A case study is defined by the determination of a specified space resource to be sold to specific customers in a specific set of orbital locations. The selection of the case study begins with a combination of engineering and financial "common sense":

First, there must be an identifiable, predictable market. For example, the market for orbital transfer can be derived from projections of government and commercial launch demand.

Second, there must be good potential for market capture, i.e. a potential for providing the resource cheaper than direct or functionally equivalent competitors. For example, for LEO-to-GEO transfer based on lunar propellant, two already-established competitors are direct launch into GEO and use of Earth-based propellants.

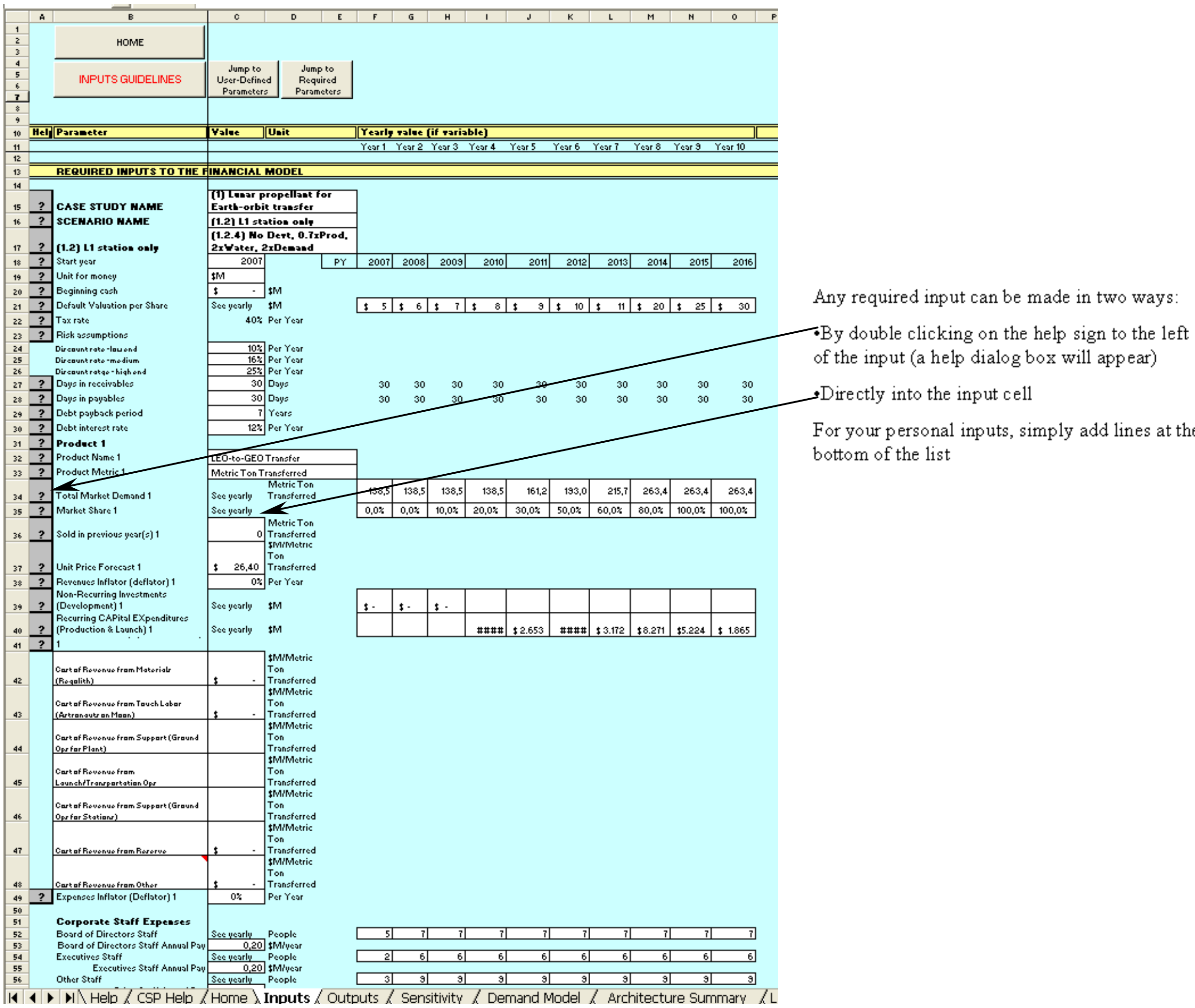
If any one of these conditions is not met at a back-of-the-envelope level, further analysis is not necessary: the venture cannot be viable. If both conditions are met, then this tool can be used to determine the conditions under which such a venture is viable. You can start filling in this *Inputs Sheet* with your case study name and space resource name. This sheet lists all the inputs to the global model. It includes also example inputs for a baseline case study. The process of updating this baseline for your case study is as follows:

First, the minimum inputs required to run the financial model have to be entered.

Second, you can also start defining your own parameters on this sheet (i.e. for new defined products).

Third, all the parameters needed for the engineering models have to be entered.

Figure A3.2.1 Input Sheet.



A3.3 STEP 3: DEMAND MODELING

Every space resource case study starts with a model of the demand. Since it is case-specific, a new demand model must be developed for each case study.

The required outputs from any demand model are:

(1) The number of units of the resource (product or service) expected to be purchased over the years of the case study,

(2) The market share, i.e. the percentage of these units that will be purchased from the modeled venture, and

(3) The forecast price per unit sold.

This sheet shows an example demand model for LEO-to-GEO transfer: the model is based on GEO launch predictions. You can use this demand sheet and this example to build your own customized demand model and generate the required outputs.

Figure A3.3.1 Demand Model Sheet.

B13 =

HOME

Inputs (from Inputs Sheet)

Demand Factor wrt Model	1
Market Share Growth Factor wrt Model	1
Launch cost to LEO ($/kg)	2,00E+03
Launch cost to GEO ($/kg)	3,50E+04

REQUIRED OUTPUTS (linked back to inputs sheet)

DEMAND RESULTS (including sensitivity factors)		2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Quantity	Metric Ton	139	139	139	139	161	193	216	263	263	263
Market Share		0,0%	0,0%	10,0%	20,0%	30,0%	50,0%	60,0%	80,0%	100,0%	100,0%

PRICE ($M/Metric Ton) 26,4

Demand Quantity and Market Share Model

BASELINE MODEL RESULTS		2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Quantity	Metric Ton	139	139	139	139	161	193	216	263	263	263
Market Share		0,0%	0,0%	10,0%	20,0%	30,0%	50,0%	60,0%	80,0%	100,0%	100,0%

CALCULATIONS

Source: Futron Corporation "An Analysis of Potential Markets and their Fuel Requirements for an In-Space Propellant Depot", NAS8-99134

Commercial	Mass (kg)	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Microsat	45,4	0	0	0	0	0	0	0	0	0	0
Small	908	0	0	0	0	0	0	0	0	0	0
Medium	2270	2	1	1	0	0	1	1	1	0	0
Intermediate	4540	15	11	14	18	23	31	29	35	30	26
Large	9080	0	0	0	0	1	1	2	3	3	3
Heavy	25000	0	0	0	0	0	0	0	0	0	0

Government	Mass (kg)	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Microsat	45,4	0	0	0	0	0	0	0	0	0	0
Small	908	0	0	0	0	0	0	0	0	0	0
Medium	2270	6	6	5	7	5	6	5	6	5	7
Intermediate	4540	6	6	5	5	6	6	6	6	6	6
Large	9080	0	1	0	0	1	0	0	1	0	0
Heavy	25000	1	1	0	0	0	0	1	1	0	1

Total	Mass (kg)	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Microsat	45,4	0	0	0	0	0	0	0	0	0	0
Small	908	0	0	0	0	0	0	0	0	0	0
Medium	2270	8	7	6	7	5	7	6	7	5	7
Intermediate	4540	21	17	19	23	29	37	35	41	36	32
Large	9080	0	1	0	0	2	1	2	4	3	3
Heavy	25000	1	1	0	0	0	0	1	1	0	1
Total Sat		30	26	25	30	36	45	44	53	44	43
Total Mass (kg)		138500	127150	99880	120310	161170	192950	215680	263350	202030	213410
Average Mass (kg)	4613										

Pricing Model

The pricing model is simple: the service provided must be cheaper than the cost savings in launching into LEO instead of GEO.
Therefore the price is a fraction of that difference, here chosen to be 0.8

Savings Fraction	80,00%
Resulting Price ($M/mt)	26,4

Home / Inputs / Outputs / Sensitivity / Demand Model / Architecture Summary / LADV / OTV /

A3.4 STEP 4: ARCHITECTURE DESIGN

Together with demand forecast, venture costs are key to the financial viability of the venture. Therefore the fourth analysis step consists in designing a space architecture that meets the demand requirements, with just enough definition to generate a cost estimate.

Various designs are usually possible for a given demand: we call each architecture design a "Scenario" of a given Case Study. A new design model must be developed for each scenario. The tool can be used at any level of design detail.

As an example, this sheet gives the design of a lunar plant to extract and electrolyze water. Important aspects of this model include:

* The amount of demand is an input to the architecture design model. The model should be scalable with demand so as to run sensitivity analyses and trades studies.

* In this example, the design model defines "architecture units" designed to meet a fixed amount of demand; this allows to build up the architecture as demand grows.

* Many technology performance metrics (specific masses, specific powers, etc) are kept as parameters in the Inputs sheet. This allows running sensitivity analysis on technological performance.

This tool includes all architectural sheets for the lunar propellant case study example (LADV, OTV, L1 Station, Lunar Plant, Calculations sheet). You can use these sheets as baseline/example to develop your own design sheets.

Figure A3.4.1 LADV Sheet

B7 = Lunar Ascent/Descent Vehicle (LADV) Model

HOME | Architecture Summary

Lunar Ascent/Descent Vehicle (LADV) Model

Model Description [Author: Javier Diaz, Colorado School of Mines]
A vehicle for transporting propellant from the Moon to L1 and returning to the Moon is defined. This vehicle will transport water.

Calculation Method
This LADV is based on a scaled modelof the Apollo lander.
The vehicle is sized to use the same amount of fuel (I.e. the same tanks) as the OTV --??
That fuel amount and the Apollo sizing together determine the size of the vehicle and the amount of water it can deliver to the L1 station.

	Parameter	Value	Unit	Comment
14	Total propellant available to ship	23437,2	kg	
15	Lander total mass	55100,1	kg	Calculated from the available propellant mass
16	Moon-L1 vehicle load capacity	23909,6	kg	
17	O2/H2 mixture ratio	6,5		
18	Engine Isp	460.0	sec	
19	Delta V	2500.0	m/sec	One-way delta V from the Moon surface to the L1 station
20	delta V/Isp g ratio	0,6		
21	Mi/Mf ratio	1,7		
22	db	361.0		
23	Dry weight of vehicle	7753.3	kg	Lander dry mass = 0.064*Mgross+59.1*(MpropellantfdbLH2Lox)+390

Figure A3.4.2 L1 Sheet

B7 = L1 STATION Model

	Parameter	Value	Unit	Comment
14	Amount of water electrolyzed at L1	113604,5	kg	From transportation calculations
15	L1 station duty cycle	8000,0	hours/year	From User-Defined Inputs
16	Water electrolyzis rate	14,2	kg/hr	From water electroluzed and duty cycle
17	Lunar Plant duty cycle	2920,0	hours/year	From User-Defined Inputs
18	Hydogen production rate	4,3	kg/hr	From water electroluzed and duty cycle
19	Oxygen production rate	34,6	kg/hr	From water electroluzed and duty cycle
20	Water storage	37868,2	kg	From transportation calculations
21	Hydrogen storage	4207,6	kg	From water storage
22	Oxygen storage	33660,6	kg	From water storage
23	Electrolyzer specific mass	50,0	kg/kg/hour	From User-Defined Inputs
24	Electrolyzer mass	710,0	kg	From specific mass and electrolysis rate
25	Specific mass for H2 liquefier	15,0	kg/kg/hour	From User-Defined Inputs
26	Mass of H2 liquefier	64,8	kg	From specific mass and liquefaction rate
27	Specific mass of liquefier radiator	200,0	kg/kg/hour	From User-Defined Inputs
28	Mass of H2 liquefier radiator	864,6	kg	From specific mass and liquefaction rate
29	Specific mass of O2 liquefier	7,0	kg/kg/hour	From User-Defined Inputs
30	Mass of O2 liquefier	242,1	kg	From specific mass and liquefaction rate
31	Specific mass of O2 liquefier radiator	7,0	kg/kg/hour	From User-Defined Inputs
32	Mass of O2 liquiefier radiator	242,1	kg	From specific mass and liquefaction rate
33	Hydrogen storage tank specific mass	0,2	kg/kg	From User-Defined Inputs
34	Hydrogen storage tank mass	631,1	kg	
35	Oxygen storage tank specific mass	0,1	kg/kg	From User-Defined Inputs
36	Oxygen storage tank mass	2692,8	kg	
37	Water tank storage specific mass	0,0	kg/kg	From User-Defined Inputs
38	Water tank mass	378,7	kg	
39	Specific power of electrolyzer	4,5	kW/kg/hour	From User-Defined Inputs
40	Power for electrolyzer	63,9	kW	
41	Specific power for H2 liquefier	14,9	kW/kg/hour	From User-Defined Inputs
42	Power for H2 liquefier	64,4	kW	
43	Specific power for O2 liquefier	1,0	kW/kg/hour	From User-Defined Inputs
44	Power for O2 liquefier	32,9	kW	
45	Power system specific mass	8,0	kg/kW	From User-Defined Inputs
46	Power system mass	1289,3	kg	
47	Total system mass	7115,6	kg	

Figure A3.4.3 OTV Sheet.

B7 = Orbital Transfer Vehicle (O

HOME | Architecture Summary

Orbital Transfer Vehicle (OTV) Model

Model Description [Author: Javier Diaz, Colorado School of Mines]

A vehicle is required to be stationed at L1 for transportating payloads from LEO to GEO. This vehicle performs the following maneuvers:
(1) Depart from Earth-Moon Lagrange point L1 with full propellant load,
(2) Aerobrake into Low Earth Orbit (LEO),
(3) Rendezvous and capture customer satellite,
(4) Transfer customer satellite to geostationnary (GEO) orbit,
(5) Leave satellite in GEO and maneuver back to L1, and
(6) Dock with L1 station for refueling.
The architecture is scaled from of a point design done separately. A storage and processing faciilty is required at L1, but no facilities are required in LEO.

Calculation Method

Define mpp as the mass of propellant required from LEO to GEO, mi as the inert mass, mab as the aerobrake mass, and msg as the mass of payload to transfer to GEO. Define the ratios alpha = mi/mpp, r = (mi+mp+mpp+mab)/(mi+mp+mab), rt the (initial/final) mass ratui for L1-LEO transport with aerobraking, and rf the (initial/final) mass ratio for GEO-L1 transport.

The design results from the following iteration loop on mpp, programmed into the user-defined "OTVModel13" function:
Propulsion system mass = (64.77+0.0745*mpp+1.004*mpp^(2/3)) [from literature]
Structure mass = 30% propulsion system mass + 15% mpp
Inert mass mi = Constant base mass (telecom, C&DH and power) + Propulsion system mass + Structure mass
Aerobrake mass mab = 0.15*(mi + mpp)
Mass to maneuver from GEO to L1 is mpf = (mi+mab)*(rf-1)
Propellant for GEO-LEO maneuver is mpp = (mi+mab+mpf+msg)*(r-1)

Finally, the total propellant to be refueled at the L1 station is mpp+mpf+mpt where:
Propellant for L1-LEO maneuver is mpt = (mi+mab+mpf+mpp)*(Rt-1)

Parameter	Value	Unit	Comment
r	2,16		Using 3800 m/sec for LEO-GEO delta-V
rt	1,10		Assume 500 m/sec for L1-LEO propulsive with aerobraking
rf	1,17		Assume 800 m/sec for GEO-L1 propulsive
Telecomm system mass	10,00	kg	Assume constant
C&DH system mass	3,00	kg	Assume constant
Power system mass	15,00	kg	Assume constant
msg	5000,00	kg	From Demand Model
mpp	17926,89	kg	Use "OTVModelRough" function
Propulsion system mass	2088,03	kg	64.77+0.0745*mpp+1.004*mpp^(2/3)
Structure mass	3315,44	kg	Add .15X payload to TLALOC assumption
Inert mass mi	5431,47	kg	Total inert mass without mab
a(a)	0,30		mi/mpp
Aerobrake mass	3503,75	kg	mab=0.15*(mi+mpp)
Propellant for GEO-L1	1518,99	kg	mpf=(mi+mab)*(rf-1)
Propellant for L1-LEO	2838,11	kg	mpt=(mi+mab+mpp+mpf)*(rt-1)
Total propellant in L1	22283,97	kg	To be refueled in L1 before each trip

Figure A3.4.4 Lunar Plant Sheet.

B7 = LUNAR PLANT Model

HOME | Architecture Summary

LUNAR PLANT Model

Mass of miners	0,84895774	mt	From total regolith and specific mass
Specific mass of hauler	0,13	kg/kg/hour	From User-Defined Inputs
Mass of haulers	1,10364506	mt	From total regolith and specific mass
Specific mass of reactors	1	kg/kg/hour	Input
Mass of reactor(s)	8,48957736	mt	From total regolith and specific mass
Specific heat of regolith	1,00	kJ/kg/o	Constant
Heating range	600,00	o	Constant assumption
Thermal power required	0,00141493	kWt	From heating range, specific heat and total regolith
Electrolysis rate	45,9901382	kg/hour	From total water to electrolyze, and duty cycle
Specific mass for electrolysis	50	kg/kg/hour	From User-Defined Inputs
Mass of electrolyzer(s)	2,29950691	mt	From electrolysis rate and specific mass
Hydrogen liquefaction rate	5,6	kg/hour	From electrolysis rate
Specific mass for H2 liquefier	15	kg/kg/hour	From User-Defined Inputs
Mass of H2 liquefier	0,1	mt	From liquefaction rate and specific mass
Specific mass of liquefier radiator	200	kg/kg/hour	From User-Defined Inputs
Mass of H2 liquefier radiator	1,1	mt	From liquefaction rate and specific mass
O2 liquefaction rate	40,8801228	kg/hour	From electrolysis rate
Specific mass of O2 liquefier	7	kg/kg/hour	From User-Defined Inputs
Mass of O2 liquefier	0,28616086	mt	From liquefaction rate and specific mass
Specific mass of O2 liquefier radiator	7	kg/kg/hour	From User-Defined Inputs
Mass of O2 liquiefier radiator	0,28616086	mt	From liquefaction rate and specific mass
Water storage for propellant	27704,9383	kg	Input from Transportation Calculations
Total water storage	51142,0983	kg	Input from Transportation Calculations
Hydrogen storage	5682,45536	kg	From water storage
Oxygen storage	45459,6429	kg	From water storage
Hydrogen storage tank specific mass	0,15	kg/kg	From User-Defined Inputs
Hydrogen storage tank mass	258322,392	mt	From total storage and specific mass
Oxygen storage tank specific mass	0,08	kg/kg	From User-Defined Inputs
Oxygen storage tank mass	3,63677143	mt	From total storage and specific mass
Water tank storage specific mass	0,01	kg/kg	From User-Defined Inputs
Water tank mass	0,51142098	mt	From total storage and specific mass
Total storage tank mass	258326,54	mt	From H2, O2, and H2O storage tank masses
Specific power of electrolyzer	4,5	kW/kg/hour	From User-Defined Inputs
Power for electrolyzer	206,955622	kW	From electrolysis rate and specific power
Specific power for H2 liquefier	14,9	kW/kg/hour	From User-Defined Inputs
Power for H2 liquefier	82,8	kW	From liquefaction rate and specific power
Specific power for O2 liquefier	0,95	kW/kg/hour	From User-Defined Inputs
Power for O2 liquefier	38,8361167	kW	From liquefaction rate and specific power
Specific mass of thermal power system	1	kg/kWt	From User-Defined Inputs
Mass of thermal power system (plumbing)	0,00141493	mt	From thermal power required and specific mass
Thermal efficiency of nuclear plant	4	kWt/kWe	From User-Defined Inputs
Electrical energy available	0,00035373	kWe	From thermal power and efficiency
Specific mass of power system	30	kg/kW	From User-Defined Inputs
Mass of electrical power system	1,0612E-05	mt	From electrical power and specific mass
Total system mass	283128,318	mt	From sum of mass elements

Figure A3.4.5 Transportation Calculations Sheet.

B7 = Transportation Model: Calc

HOME | Architecture Summary

Transportation Model: Calculations Sheet

	Parameter	Value	Unit	Comment
14	Water produced on the Moon	247895,7	kg	Scales extraction system on Moon
15	Mass of water electrolyzed on the Moon for propellant	134291,2	kg	Scales propellant production system on the Moon
16	Excess O2 available on Moon	22381,9	kg	
17	Mass of water electrolyzed at L1 for sending OTV to LEO	80222,3	kg	Scales propellant production system at L1
18	Mass of water electrolyzed at L1 for sending LADV back to Moon	33382,2	kg	
19	Excess O2 available at L1	18934,1	kg	
20	Mass of facilities on the Moon			
21	Satellite Payload Mass	5000,0	kg	From User-defined INPUTS
22	Propellant required in L1	22284,0	kg	Assumes aerobraking into LEO
23	Number of trips per year	3,0		
24	Requirement for propellant in L1 (annual)	66851,9	kg	
25	Propellant required in L1 for satellite delivery (per trip)	22284,0	kg	
26	Propellant requirement in L1 for satellite delivery (per trip), H2	2971,2	kg	
27	Propellant required in L1 for satellite delivery (per trip), O2	19312,8	kg	
28	Total water required in L1 for each trip of OTV	26740,8	kg	
29	Annual shipment of water to L1 for OTV	80222,3	kg	
30	Excess O2 in L1	13370,4	kg	
31	Payload (water) on LADV	23437,2	kg	
32	Dry mass of LADV	7753,3	kg	
33	Mi/Mf for LADV	1,7		
34	Propellant mixture ratio	6,5		
35	Propellant required for Moon to L1 trip, total	23087,4	kg	
36	Propellant required for Moon to L1 trip, H2	3078,3	kg	
37	Propellant required for Moon to L1 trip, water	27704,9	kg	
38	Excess O2 from Moon to L1 trip	4617,5	kg	
39	Annual water production required for Moon-L1 trip	134291,2	kg	
40	Propellant used for return to the Moon	5739,1	kg	
41	Propellant used for return to the Moon, H2	765,2	kg	
42	Propellant used for return to the Moon, water equivalent	6886,9	kg	
43	Excess O2 from return to the Moon	1147,8	kg	
44	Useful water delivered to L1 for each LADV round-trip	16550,3	kg	
45	Number of flights of the LADV required annually	4,8		

A3.5 STEP 5: ENGINEERING COST MODELING AND ANALYSIS

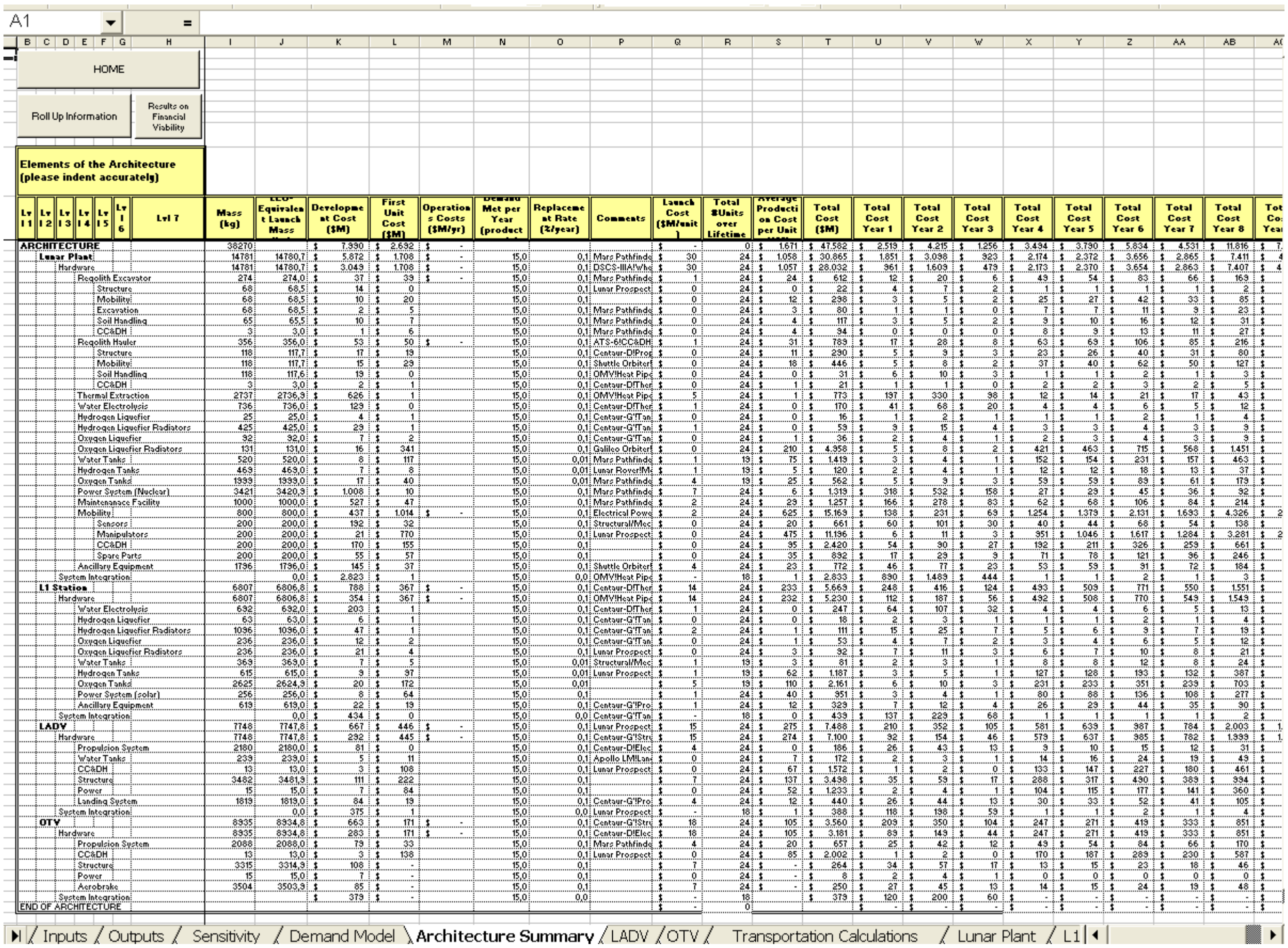
Due to lack of time and variety of possible approaches, this tool doesn't include a cost model. Instead, the users must develop their own cost model for each of the architecture elements. It is best to have models as Cost Estimating Relationships (CERs) that depend on design parameters: thus the cost estimate automatically scales with input parameters, such as demand.

Once engineering cost estimates are developed, this "Architecture Summary" sheet provides an optional tool to summarize the architecture and generate the total cost numbers required as inputs to the financial model. On the basis of an elements list with mass, cost, replacement rate and demand met information; the tool calculates the total number of units launched each year to meet demand growth, and the total cost per year.

This flexible approach allows to study sensitivity to demand, demand growth, launch cost, replacement rate, or even technology parameters affecting mass or cost.

An alternative is to directly input the total costs per year in the *Inputs Sheet*.

Figure A3.5.1 Architecture Summary Sheet.



A3.6 STEP 6: FINANCIAL MODEL

CSP Associates, Inc. developed a generic financial model to translate engineering cost numbers and demand forecasts into the financial parameters of interest to private investors: Enterprise Value (EV), Price-Earnings (P:E), investors return on equity, breakeven analysis.

For that purpose, the tool models in a very generic way the three principal financial accounting documents used to calculate the performance of a private sector enterprise and yield the desired valuation metrics: an income statement, a balance sheet and a cash flow statement.

CSP Associates, Inc. developed a generic financial model to translate engineering cost numbers and demand forecasts into the financial parameters of interest to private investors.

As can be seen on this navigation diagram, the financial model consists of three types of sheets:

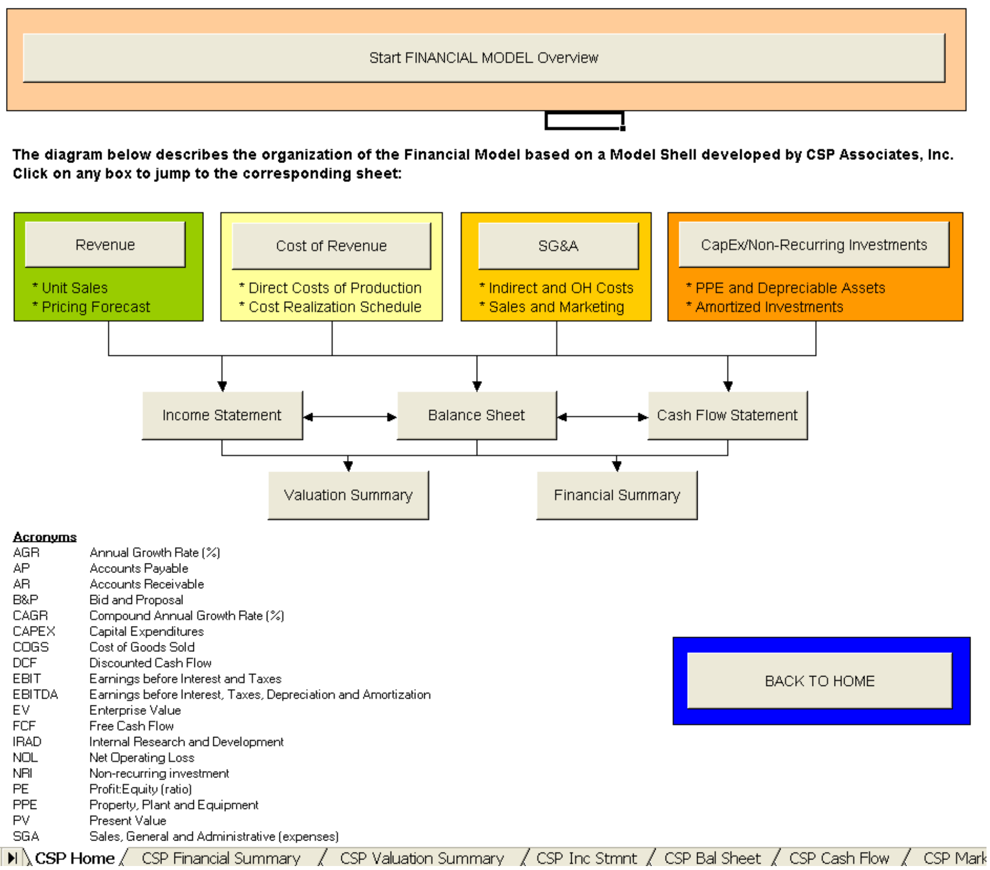
1. Four Inputs sheets (revenues, cost of revenue, SG&A, CAPEX) translate the engineering inputs into accounting terms. All inputs originate from the Inputs sheet.

2. Three Pro Forma sheets (income statement, balance sheet and cash flow statement) model in a very generic way the three principal financial accounting documents used to calculate the performance of a private sector enterprise and yield the desired valuation metrics.

3. Finally, the financial and valuation summary sheets summarize the expected financial state and viability of the venture.

You can click on any grey box to navigate through the financial sheets, or run the financial model overview to learn more about the financial model.

Figure A3.6.1 Architecture Summary Sheet.



A3.6.1 INPUTS: REVENUE

The Revenue sheet translates the demand forecast (demand quantity, market share and forecast price) into expected revenue in each year of the venture. Note that the model accepts up to 6 possible space resources (products or services)

Figure A3.6.1.1 CSP Revenue Model Sheet.

	A	B	C	D	E	F	G	H	I	J	K	L	M
2	HOME	Financial Model HOME											
7	(1) Lunar propellant for Earth-orbit tra		PY	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
8	(1.2.4) No Devt, 0.7xProd, 2xWater, 2xDemand												
9	**REVENUE MODEL**												
10		$M											
12	**Revenue Forecast**		$ -	$ -	$ -	$ 366	$ 731	$ 1.276	$ 2.547	$ 3.416	$ 5.562	$ 6.952	$ 6.952
13	LEO-to-GEO Transfer		$ -	$ -	$ -	$ 366	$ 731	$ 1.276	$ 2.547	$ 3.416	$ 5.562	$ 6.952	$ 6.952
14	LEO-to-GEO Transfer		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
15	N/A		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
16	N/A		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
17	N/A		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
18	N/A		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
21	**Unit Sales Forecast**												
22	LEO-to-GEO Transfer	ı Transferred	0,00	0,00	0,00	13,85	27,70	48,35	96,48	129,41	210,68	263,35	263,35
23	LEO-to-GEO Transfer	N/A	0,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
24	N/A	Metric Tons	0,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
25	N/A	Metric Tons	0,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
26	N/A	Metric Tons	0,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
27	N/A	Metric Tons	0,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
30	**Unit Pricing Forecast**	**Unit Price**											
31	LEO-to-GEO Transfer	$ 26,40	$ 26,4	$ 26,40	$ 26,40	$ 26,40	$ 26,40	$ 26,40	$ 26,40	$ 26,40	$ 26,40	$ 26,40	$ 26,40
32	*Inflator (Deflator)*	*0%*											
33	LEO-to-GEO Transfer	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
34	*Inflator (Deflator)*	*0%*											
35	N/A	$0,00	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
36	*Inflator (Deflator)*	*0%*											
37	N/A	$0,00	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
38	*Inflator (Deflator)*	*0%*											
39	N/A	$0,00	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
40	*Inflator (Deflator)*	*0%*											
41	N/A	$0,00	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
42	*Inflator (Deflator)*	*0%*											

A3.6.2 INPUTS: COST OF REVENUE

The Cost of Revenue inputs describe the direct marginal cost of producing each additional unit, each year; for a space venture, these typically include manufacturing, operations and delivery costs.

Figure A3.6.2.1 CSP Cost of Revenue Sheet.

1	HOME	Financial Model HOME										
2												
3												
4	(1) Lunar propellant for Earth-	PY	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
5	(1.2.4) No Debt, 0.7xProd, 2xWater, 2xDemand											
6	COST OF REVENUE	$M										
10												
11	Total Cost of Goods Sold	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
12												
13	LEO-to-GEO Transfer	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
14	LEO-to-GEO Transfer	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
15	N/A	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
16	N/A	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
17	N/A	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
18	N/A	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
19												
20												
21												
22	OST OF REVENUE BY PRODUCT/SERVIC											
23												
24	LEO-to-GEO Transfer	$	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
25	Cost of Revenue from Materials (Reg	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
26	Cost of Revenue from Touch Labor (A	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
27	Cost of Revenue from Support (Grou	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
28	Cost of Revenue from Launch/Transpo	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
29	Cost of Revenue from Support (Grou	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
30	Cost of Revenue from Reserve	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
31	Cost of Revenue from Other	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
32	Expenses Inflator (Deflator) 1	0%										
33	COGS	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
34												
35												
36	LEO-to-GEO Transfer	$	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
37	Cost of Revenue from Materials (Reg	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
38	Cost of Revenue from Touch Labor (A	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
39	Cost of Revenue from Support (Grou	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
40	Cost of Revenue from Launch/Transpo	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
41	Cost of Revenue from Support (Grou	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
42	Cost of Revenue from Reserve	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
43	Cost of Revenue from Other	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
44	Inflator (Deflator)	0%										
45	COGS	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
46												
47												
48	N/A	$	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
49	Cost of Revenue from Materials (Reg	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
50	Cost of Revenue from Touch Labor (A	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
51	Cost of Revenue from Support (Grou	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
52	Cost of Revenue from Launch/Transpo	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
53	Cost of Revenue from Support (Grou	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
54	Cost of Revenue from Reserve	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
55	Cost of Revenue from Other	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
56	Inflator (Deflator)	0%										
57	COGS	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
58												
59												
60	N/A	$	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
61	Cost of Revenue from Materials (Reg	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
62	Cost of Revenue from Touch Labor (A	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
63	Cost of Revenue from Support (Grou	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
64	Cost of Revenue from Launch/Transpo	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
65	Cost of Revenue from Support (Grou	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
66	Cost of Revenue from Reserve	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
67	Cost of Revenue from Other	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
68	Inflator (Deflator)	0%										
69	COGS	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
70												
71												
72	N/A	$	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
73	Cost of Revenue from Materials (Reg	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
74	Cost of Revenue from Touch Labor (A	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
75	Cost of Revenue from Support (Grou	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
76	Cost of Revenue from Launch/Transpo	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
77	Cost of Revenue from Support (Grou	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -

A3.6.3 INPUTS: SG&A

The Sales, General and Administrative (SG&A) inputs describe the indirect business operations costs, including management, executive and marketing staff, staff training, overhead, rent, etc

Figure A3.6.3.1 CSP SG&A Sheet.

	A	B	C	D	E	F	G	H	I	J	K	L	M
1													
2	HOME	Financial Model HOME											
3													
4	(1) Lunar propellant for Earth-orbit transfer		PY	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
8	**Total Sales, General & Administrative**	$K		$ 3	$ 6	$ 7	$ 9	$ 9	$ 10	$ 10	$ 10	$ 11	$ 11
9	Payroll			$ 2	$ 4	$ 5	$ 6	$ 6	$ 6	$ 7	$ 7	$ 7	$ 7
10	Rent-Utilities/Overhead			$ 1	$ 2	$ 2	$ 3	$ 3	$ 3	$ 3	$ 3	$ 4	$ 4
11	Startup/Nonrecurring			$ 0	$ 0	$ 0	$ 1	$ 1	$ 1	$ 1	$ 1	$ 1	$ 1
12	Total Headcount			13	29	31	37	38	38	38	38	38	38
13													
14													
15	**Corporate Expenses**			$ 3	$ 5	$ 5	$ 5	$ 5	$ 6	$ 6	$ 6	$ 6	$ 7
16													
17	Headcount			10	22	22	22	22	22	22	22	22	22
18	Board of Directors Staff			5	7	7	7	7	7	7	7	7	7
19	Executives Staff			2	6	6	6	6	6	6	6	6	6
20	Other Staff			3	9	9	9	9	9	9	9	9	9
21													
22	Total Payroll	Annual		$ 2	$ 3	$ 3	$ 4	$ 4	$ 4	$ 4	$ 4	$ 4	$ 4
23	Board of Directors Staff	$/Yr	$ 0	$ 1	$ 1	$ 2	$ 2	$ 2	$ 2	$ 2	$ 2	$ 2	$ 2
24	Executives Staff	$/Yr	$ 0	$ 0	$ 1	$ 1	$ 1	$ 1	$ 1	$ 2	$ 2	$ 2	$ 2
25	Other Staff	$/Yr	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
26	Benefit Load	%	20%	$ 0	$ 1	$ 1	$ 1	$ 1	$ 1	$ 1	$ 1	$ 1	$ 1
27	Inflator (Deflator)	%	4%										
28													
29	Rent-Utilities-Overhead			$ 1	$ 2	$ 2	$ 2	$ 2	$ 2	$ 2	$ 2	$ 2	$ 2
30	Rent	$/Sq Ft	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
31		Sq Ft/Emp.	200										
32	Utilities and Communications	% Rent	15%	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
33	Other Overhead	% Labor	50%	$ 1	$ 2	$ 2	$ 2	$ 2	$ 2	$ 2	$ 2	$ 2	$ 2
34	Inflator (Deflator)	%	4%										
35													
36													
37	**Sales and Marketing/CRM Expenses**			$ 1	$ 1	$ 2	$ 3	$ 4	$ 4	$ 4	$ 4	$ 4	$ 4
38													
39	Headcount			3	7	9	15	16	16	16	16	16	16
40	Sales Staff			1	2	4	5	6	6	6	6	6	6
41	Marketing Staff			2	5	5	5	5	5	5	5	5	5
42	Customer Support Staff			0	0	0	5	5	5	5	5	5	5
43													
44	Total Payroll	Annual		$ 0	$ 1	$ 1	$ 2	$ 2	$ 3	$ 3	$ 3	$ 3	$ 3
45	Sales Staff	$/Yr	$ 0	$ 0	$ 0	$ 1	$ 1	$ 1	$ 1	$ 1	$ 1	$ 1	$ 1
46	Marketing Staff	$/Yr	$ 0	$ 0	$ 1	$ 1	$ 1	$ 1	$ 1	$ 1	$ 1	$ 1	$ 1
47	Customer Support Staff	$/Yr	$ 0	$ -	$ -	$ -	$ 1	$ 1	$ 1	$ 1	$ 1	$ 1	$ 1
48	Benefit Load	%	20%	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
49	Inflator (Deflator)	%	4%										
50													
51	Rent-Utilities-Overhead			$ 0	$ 0	$ 1	$ 1	$ 1	$ 1	$ 1	$ 1	$ 1	$ 1
52	Rent	$/Sq Ft	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
53		Sq Ft/Emp.	100										
54	Utilities and Communications	% Rent	15%	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
55	Other Overhead	% Labor	30%	$ 0	$ 0	$ 1	$ 1	$ 1	$ 1	$ 1	$ 1	$ 1	$ 1
56	Inflator (Deflator)	%	4%										
57													
58													
59	**Field Engineers/Personnel Expenses**			$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
60													
61	Headcount			0	0	0	0	0	0	0	0	0	0
62	Astronauts - Lunar Plant			0	0	0	0	0	0	0	0	0	0
63	Astronauts - In-space Stations			0	0	0	0	0	0	0	0	0	0
64	Astronauts - Transportation			0	0	0	0	0	0	0	0	0	0
65	Ground Support - Lunar Plant			0	0	0	0	0	0	0	0	0	0
66	Ground Support - In-space Stations			0	0	0	0	0	0	0	0	0	0
67	Ground Support - Transportation			0	0	0	0	0	0	0	0	0	0
68	Ground Support - Delivery			0	0	0	0	0	0	0	0	0	0
69													
70	Total Payroll	Annual		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
71	Astronauts - Lunar Plant	$/Yr	$ 0	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
72	Astronauts - In-space Stations	$/Yr	$ 0	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
73	Astronauts - Transportation	$/Yr	$ 0	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
74	Ground Support - Lunar Plant	$/Yr	$ 0	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
75	Ground Support - In-space Stations	$/Yr	$ 0	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
76	Ground Support - Transportation	$/Yr	$ 0	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -

A3.6.4 INPUTS: CAPEX

The Capital Expenditures (CAPEX) inputs are an estimate of non-recurring investments and their amortization schedule; this comprises costs for development, facilities and equipment, including all space elements.

Figure A3.6.4.1 CSP CAPEX-D&A Sheet.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	HOME	Financial Model HOME													
2															
3															
4	(1) Lunar propellant for Earth-orbit transfer			PY	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	
5	(1.2.4) No Devt, 0.7xProd, 2xWater, 2xDemand														
6	CAPEX & DEP/AMORT SCHEDULE														
7															
8	PPE and Amortized NRI Summary	$M													
9															
10	Prior Venture PPE	$ -													
11															
12	Beginning Balance			$ -	$ -	$ -	$ 0	$ 2.461	$ 4.874	$ 7.017	$ 10.182	$ 12.117	$ 18.325	$ 20.777	
13	PPE			$ -	$ -	$ 0	$ 2.461	$ 2.658	$ 2.653	$ 4.084	$ 3.172	$ 8.271	$ 5.224	$ 1.866	$ 30.389
14	Capitalized NRI			$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
15	Less Depreciation			$ (0)	$ (0)	$ (0)	$ (0)	$ (245)	$ (511)	$ (919)	$ (1.236)	$ (2.063)	$ (2.772)	$ (2.772)	$ (10.519)
16	Less Amortization			$ (0)	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ (0)	$ (0)	$ -
17	Ending Balance			$ -	$ -	$ 0	$ 2.461	$ 4.874	$ 7.017	$ 10.182	$ 12.117	$ 18.325	$ 20.777	$ 19.870	$ 19.870
18															
19	DEPRECIATION SCHEDULE														
20															
21	IT/Support Equipment (4 Year Useful Life)														
22	PY	$ -	4	$ -	$ -	$ -									
23	2007	$ -	4		$ -	$ -	$ -	$ -							
24	2008	$ 0	4			$ 0	$ 0	$ 0	$ 0						
25	2009	$ 0	4				$ 0	$ 0	$ 0	$ 0					
26	2010	$ 0	4					$ 0	$ 0	$ 0	$ 0				
27	2011	$ 0	4						$ 0	$ 0	$ 0	$ 0			
28	2012	$ 0	4							$ 0	$ 0	$ 0	$ 0		
29	2013	$ 0	4								$ 0	$ 0	$ 0	$ 0	
30	2014	$ 0	4									$ 0	$ 0	$ 0	
31	2015	$ 0	4										$ 0	$ 0	
32	2016	$ 0	4											$ 0	
33	Subtotal IT Equipment Depreciation			$ -	$ -	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	
34															
35	Furniture, Machinery & Equipment (10 Year Useful Life)														
36															
37	PY	$ -	10	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -		
38	2007	$ -	10		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	
39	2008	$ -	10			$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	
40	2009	$ -	10				$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	
41	2010	$ 2.446	10					$ 245	$ 245	$ 245	$ 245	$ 245	$ 245	$ 245	
42	2011	$ 2.653	10						$ 265	$ 265	$ 265	$ 265	$ 265	$ 265	
43	2012	$ 4.084	10							$ 408	$ 408	$ 408	$ 408	$ 408	
44	2013	$ 3.172	10								$ 317	$ 317	$ 317	$ 317	
45	2014	$ 8.271	10									$ 827	$ 827	$ 827	
46	2015	$ 5.224	10										$ 522	$ 522	
47	2016	$ 1.865	10										$ 187	$ 187	
48	Subtotal Furniture, Machinery Depreciation			$ -	$ -	$ -	$ -	$ 245	$ 510	$ 918	$ 1.235	$ 2.063	$ 2.771	$ 2.771	
49															
50	Real Estate/Buildings (40 Year Useful Life)														
51															
52	PY	$ -	40	0,0	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	
53	2007	$ -	40		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	
54	2008	$ -	40			$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	
55	2009	$ 15	40				$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	
56	2010	$ 5	40					$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	
57	2011	$ -	40						$ -	$ -	$ -	$ -	$ -	$ -	
58	2012	$ -	40							$ -	$ -	$ -	$ -	$ -	
59	2013	$ -	40								$ -	$ -	$ -	$ -	
60	2014	$ -	40									$ -	$ -	$ -	
61	2015	$ -	40										$ -	$ -	
62	2016	$ -	40											$ -	
63	Subtotal Real Estate/Buildings			0	0	0	0	1	1	1	1	1	1	1	
64															
65	Total Depreciation			$ -	$ -	$ 0	$ 0	$ 245	$ 511	$ 919	####	####	####	####	
66															
67															
68	AMORTIZATION														
69															
70	Development Costs (Non-recurring)	Total		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	
71	LEO-to-GEO Transfer	$ -		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	
72	LEO-to-GEO Transfer	$ -		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	
73	N/A	$ -		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	
74	N/A	$ -		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	
75	N/A	$ -		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	
76	N/A	$ -		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	
77															
78	Amoritization of Development Costs	Total	Recov	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	
79	LEO-to-GEO Transfer	$ -	3	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -			
80	LEO-to-GEO Transfer	$ -	3	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -			
81	N/A	$ -	3	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -			
82	N/A	$ -	6	$ -	$ -	$ -	$ -	$ -	$ -	$ -					
83	N/A	$ -	4	$ -	$ -	$ -	$ -	$ -							
84	N/A	$ -	4	$ -	$ -	$ -	$ -	$ -							
85															
86															
87															
88	TOTAL INVESTING														
89	PPE			$ -	$ -	$ 0	$ 2.461	$ 2.658	$ 2.653	$ 4.084	$ 3.172	$ 8.271	$ 5.224	$ 1.866	
90	Non-Recurring Investments			$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	

A3.6.5 PRO-FORMAS: INCOME STATEMENT

The Income Statement documents the profits and losses of the venture. Starting with the generated revenues, it substracts first the cost of goods sold, then sales, general and administrative (SG&A) costs, estimated depreciation and amortization, debt interest payments, and calculates taxes, to finally yield a net income.

Figure A3.6.5.1 CSP Inc Stmnt Sheet.

	A	B	C	D	Orden descendente	G	H	I	J	K	L	M
1												
2	HOME	Financial Model HOME										
3												
4	(1) Lunar propellant for Earth-orbit tran	PY	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	Cumulative
5	(1.2.4) No Devt, 0.7xProd, 2xWater, 2xDemand												
6	**INCOME STATEMENT**												
7													
8	**Total Revenue**	$ -	$ -	$ -	$ 366	$ 731	$ 1.276	$ 2.547	$ 3.416	$ 5.562	$ 6.952	$ 6.952	$ 27.804
9													
10	LEO-to-GEO Transfer	$ -	$ -	$ -	$ 366	$ 731	$ 1.276	$ 2.547	$ 3.416	$ 5.562	$ 6.952	$ 6.952	$ 27.804
11	LEO-to-GEO Transfer	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
12	N/A	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
13	N/A	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
14	N/A	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
15	N/A	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
16													
17													
37	**Cost of Goods Sold**	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
38													
39	LEO-to-GEO Transfer	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
40	LEO-to-GEO Transfer	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
41	N/A	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
42	N/A	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
43	N/A	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
44	N/A	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
45													
46	**Gross Margin**		$ -	$ -	$ 366	$ 731	$ 1.276	$ 2.547	$ 3.416	$ 5.562	$ 6.952	$ 6.952	$ 27.804
47	*Gross Margin %*		#¡DIV/0!	#¡DIV/0!	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%
48													
49	**SGA & Other**		$ 3	$ 7	$ 7	$ 9	$ 10	$ 10	$ 11	$ 11	$ 11	$ 12	$ 91
50	Payroll	$ -	$ 2	$ 4	$ 5	$ 6	$ 6	$ 6	$ 7	$ 7	$ 7	$ 7	$ 57
51	Rent-Utilities/Overhead	$ -	$ 1	$ 2	$ 2	$ 3	$ 3	$ 3	$ 3	$ 3	$ 4	$ 4	$ 29
52	Startup/Nonrecurring	$ -	$ 0	$ 0	$ 0	$ 1	$ 1	$ 1	$ 1	$ 1	$ 1	$ 1	$ 6
53													
54	**Operating Profit (EBITDA)**		$ (3)	$ (7)	$ 358	$ 722	$ 1.267	$ 2.537	$ 3.406	$ 5.551	$ 6.941	$ 6.941	$ 27.712
55	*EBITDA %*		#¡DIV/0!	#¡DIV/0!	98,0%	98,8%	99,2%	99,6%	99,7%	99,8%	99,8%	99,8%	99,7%
56													
57	**Depreciation and Amortization**		$ -	$ 0	$ 0	$ 245	$ 511	$ 919	$ 1.236	$ 2.063	$ 2.772	$ 2.772	$ 10.519
58	Depreciation (PPE)	$ -	$ -	$ 0	$ 0	$ 245	$ 511	$ 919	$ 1.236	$ 2.063	$ 2.772	$ 2.772	$ 10.519
59	Amortization (NRI)	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
60													
61													
62	**EBIT**		$ (3)	$ (7)	$ 358	$ 477	$ 756	$ 1.618	$ 2.170	$ 3.488	$ 4.169	$ 4.168	$ 17.194
63	*EBIT %*		#¡DIV/0!	#¡DIV/0!	97,8%	65,2%	59,2%	63,5%	63,5%	62,7%	60,0%	60,0%	61,8%
64													
65	**Interest**		$ -	$ -	$ -	$ 66	$ 187	$ 317	$ 421	$ 555	$ 647	$ 558	$ 2.752
66													
67	**Income Before Taxes**		$ (3)	$ (7)	$ 358	$ 411	$ 569	$ 1.301	$ 1.749	$ 2.932	$ 3.522	$ 3.610	$ 14.441
68													
69	*NOL*		$ (3)	$ (10)	$ 348	$ -	$ -	$ -	$ -	$ -	$ -	$ -	
70	*Taxable Income*		$ (3)	$ (10)	$ 348	$ 411	$ 569	$ 1.301	$ 1.749	$ 2.932	$ 3.522	$ 3.610	$ 14.441
71	**Taxes**	40%	$ -	$ -	$ 139	$ 164	$ 228	$ 520	$ 700	$ 1.173	$ 1.409	$ 1.444	$ 5.776
72													
73	**Net Income**		$ (3)	$ (7)	$ 219	$ 247	$ 341	$ 780	$ 1.049	$ 1.759	$ 2.113	$ 2.166	$ 8.665
74	*Net%*		#¡DIV/0!	#¡DIV/0!	60%	34%	27%	31%	31%	32%	30%	31%	31%
75													
76	**Cumulative Net**		$ (3)	$ (10)	$ 209	$ 455	$ 797	$ 1.577	$ 2.626	$ 4.386	$ 6.499	$ 8.665	
77													
78	Discounted Net Income	10%	$ (3)	$ (6)	$ 181	$ 185	$ 233	$ 485	$ 592	$ 903	$ 986	$ 919	$ 4.474
79		16%	$ (3)	$ (6)	$ 162	$ 158	$ 189	$ 372	$ 431	$ 623	$ 645	$ 570	$ 3.139
80		25%	$ (3)	$ (5)	$ 140	$ 126	$ 140	$ 256	$ 275	$ 369	$ 355	$ 291	$ 1.942
81													

CSP Home / CSP Financial Summary / CSP Valuation Summary / **CSP Inc Stmnt** / CSP Bal Sheet / CSP Cash Flow / CSP Market Assum

A3.6.6 PRO-FORMAS: BALANCE SHEET

The Balance Sheet provides an annual snapshot of the firm's year-end assets (sum of current assets such as cash and receivables, plus long-term assets such as the value of any physical plant) versus its liabilities (sum of current payments owed by the company, long term debt, investor's equity and retained earnings/losses).

Figure A3.6.6.1 CSP Bal Sheet.

HOME	Financial Model HOME									
(1) Lunar propellant for Earth	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
(1.2.4) No Devt, 0.7xProd, 2xWater, 2xDemand										
BALANCE SHEET	$K									
Assets										
Cash	$ 100	$ 100	$ 100	$ 100	$ 100	$ 100	$ 100	$ 100	$ 100	$ 1.927
Accounts Receivable	$ -	$ -	$ 30	$ 61	$ 106	$ 212	$ 285	$ 463	$ 579	$ 579
Current Assets	$ 100	$ 100	$ 130	$ 161	$ 206	$ 312	$ 385	$ 563	$ 679	$ 2.507
Net PPE	$ -	$ 0	$ 2.461	$ 4.874	$ 7.017	$ 10.182	$ 12.117	$ 18.325	$ 20.777	$ 19.870
Other										
Longterm Assets	$ -	$ 0	$ 2.461	$ 4.874	$ 7.017	$ 10.182	$ 12.117	$ 18.325	$ 20.777	$ 19.870
Total Assets	100	100	2.591	5.035	7.223	10.494	12.502	18.889	21.456	22.377
Liabilities										
Accounts Payable	0	1	1	1	1	1	1	1	1	1
Other Short-term Debt	0	0	0	0	0	0	0	0	0	0
Short-Term Liabilities	0	1	1	1	1	1	1	1	1	1
Capitalized Interest	0	0	0	0	0	0	0	0	0	0
Longterm Debt	0	0	0	1.098	2.022	3.267	3.746	5.511	5.276	4.031
Longterm Liabilities	0	0	0	1.098	2.022	3.267	3.746	5.511	5.276	4.031
Shareholder Equity	103	110	2.382	3.481	4.404	5.649	6.128	8.991	9.680	9.680
Retained Earnings	-3	-10	209	455	797	1.577	2.626	4.386	6.499	8.665
Total Liabilities	100	100	2.591	5.035	7.223	10.494	12.502	18.889	21.456	22.377
Assumptions/Inputs										
ACCOUNTS RECEIVABLE										
Beginning Balance	$ -	$ -	$ -	$ 30	$ 61	$ 106	$ 212	$ 285	$ 463	$ 579
Sales	$ -	$ -	$ 366	$ 731	$ 1.276	$ 2.547	$ 3.416	$ 5.562	$ 6.952	$ 6.952
Collections	$ -	$ -	$ 335	$ 701	$ 1.231	$ 2.441	$ 3.344	$ 5.383	$ 6.837	$ 6.952
Ending Balance	$ -	$ -	$ 30	$ 61	$ 106	$ 212	$ 285	$ 463	$ 579	$ 579
Days in Receivables	30,0	30,0	30,0	30,0	30,0	30,0	30,0	30,0	30,0	30,0
ACCOUNTS PAYABLE										
Beginning Balance	0,0	0,3	0,6	0,6	0,8	0,8	0,8	0,9	0,9	1,0
Expenses	3,3	6,7	7,5	9,1	9,8	10,2	10,6	11,0	11,4	11,9
30 Day Payments	$ 3	$ 6	$ 7	$ 9	$ 10	$ 10	$ 11	$ 11	$ 11	$ 12
Ending balance	0,3	0,6	0,6	0,8	0,8	0,8	0,9	0,9	1,0	1,0
Days in Payables	30	30	30	30	30	30	30	30	30	30

A3.6.7 PRO-FORMAS: CASH FLOW

The Cash Flow statement characterizes the venture's cash flows, I.e. where the funds come from revenues, financing) and what they are used for (recurring and non-recurring expenses, financing costs). The statement incorporates assumptions on the firm's capital structure strategy, i.e. the proportion of debt and equity used for funding.

Figure A3.6.7.1 CSP Cash Flow Sheet

HOME | Financial Model HOME

(1) Lunar propellant for Earth	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	Cumulative
(1.2.4) No Devt, 0.7xProd, 2xWater, 2xDemand											
CASH FLOW											
SOURCES OF FUNDING											
Sources of Operating Cash											
Net Income	$ (3)	$ (7)	$ 219	$ 247	$ 341	$ 780	$ 1.049	$ 1.759	$ 2.113	$ 2.166	$ 8.665
Add: Depreciation & Amortization	$ -	$ 0	$ 0	$ 245	$ 511	$ 919	$ 1.236	$ 2.063	$ 2.772	$ 2.772	$ 10.519
Net Cash from Operations	$ (3)	$ (7)	$ 219	$ 492	$ 852	$ 1.699	$ 2.285	$ 3.823	$ 4.885	$ 4.938	$ 19.183
Working Capital											
Receivables	$ -	$ -	$ (30)	$ (30)	$ (45)	$ (106)	$ (72)	$ (179)	$ (116)	$ -	
Payables	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	
Net Change in Working Capital	$ 0	$ 0	$ (30)	$ (30)	$ (45)	$ (106)	$ (72)	$ (179)	$ (116)	$ 0	
Total Cash from Operations	$ (3)	$ (6)	$ 189	$ 461	$ 807	$ 1.593	$ 2.213	$ 3.644	$ 4.769	$ 4.938	$ 19.183
Financing											
Equity Investment	$ 103	$ 7	$ 2.273	$ 1.098	$ 923	$ 1.245	$ 479	$ 2.863	$ 689	$ -	$ 9.680
Other ST Debt	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	
Debt Financing	$ -	$ -	$ -	$ 1.098	$ 923	$ 1.245	$ 479	$ 2.863	$ 689	$ -	$ 7.298
Total Financing	$ 103	$ 7	$ 2.273	$ 2.197	$ 1.847	$ 2.490	$ 959	$ 5.726	$ 1.378	$ -	$ 16.979
USES OF FUNDING											
Investing											
CAPEX	$ -	$ 0	$ 2.461	$ 2.658	$ 2.653	$ 4.084	$ 3.172	$ 8.271	$ 5.224	$ 1.866	$ 30.389
Capitalized Development & IRAD	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Total Investing	$ -	$ 0	$ 2.461	$ 2.658	$ 2.653	$ 4.084	$ 3.172	$ 8.271	$ 5.224	$ 1.866	$ 30.389
Repayment of Debt											
Debt Principal Repayments	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 1.098	$ 923	$ 1.245	
Total Investing and Debt Repayment	$ -	$ 0	$ 2.461	$ 2.658	$ 2.653	$ 4.084	$ 3.172	$ 9.369	$ 6.147	$ 3.111	$ 30.389
Beginning Cash	$ -	$ 100	$ 100	$ 100	$ 100	$ 100	$ 100	$ 100	$ 100	$ 100	
Net Change in Cash	$ 100	$ (0)	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 1.827	
Ending Cash	$ 100	$ 100	$ 100	$ 100	$ 100	$ 100	$ 100	$ 100	$ 100	$ 1.927	
DEBT LOAD											
Beginning Balance	$ -	$ -	$ -	$ -	$ 1.098	$ 2.022	$ 3.267	$ 3.746	$ 5.511	$ 5.276	
Debt Pmts	$ -	$ -	$ -	$ -	$ (0)	$ (0)	$ (0)	$ (1.098)	$ (923)	$ (1.245)	
Incremental Financing	$ -	$ -	$ -	$ 1.098	$ 923	$ 1.245	$ 479	$ 2.863	$ 689	$ -	
Total Debt	$ -	$ -	$ -	$ 1.098	$ 2.022	$ 3.267	$ 3.746	$ 5.511	$ 5.276	$ 4.031	
Average Debt	$ -	$ -	$ -	$ 549	$ 1.560	$ 2.645	$ 3.507	$ 4.629	$ 5.394	$ 4.654	
Payback Period in Years	7										
Interest Rate	12%										
INTEREST EXPENSE											
Annual Interest Expense	$ -	$ -	$ -	$ 66	$ 187	$ 317	$ 421	$ 555	$ 647	$ 558	
Cumulative Interest	$ -	$ -	$ -	$ 66	$ 253	$ 570	$ 991	$ 1.547	$ 2.194	$ 2.752	
Other Short-term Debt											
Beginning Balance	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	
Debt Pmts	$ -	$ -	$ -	$ -	$ (0)	$ (0)	$ (0)	$ (0)	$ (0)	$ (0)	
Incremental Financing	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	
Total Debt	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	
Average Debt	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	
Payback Period in Years	7										
Interest Rate	12%										
INTEREST EXPENSE											

A3.6.8 SUMMARIES: FINANCIAL SUMMARY

The Financial Summary summarizes the key financial metrics from the Pro Formas: it provides brief versions of the income statement, the cash flow statement and the balance sheet on one page

Figure A3.6.8.1 CSP Financial Summary Sheet

HOME | Financial Model HOME

(1) Lunar propellant for Earth-orbit | PY | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016

(1.2.4) No Devt, 0.7xProd, 2xWater, 2xDemand

FINANCIAL SUMMARY

INCOME STATEMENT	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	Cumulative
Revenues	$ -	$ -	$ 366	$ 731	$ 1.276	$ 2.547	$ 3.416	$ 5.562	$ 6.952	$ 6.952	$ 27.804
Gross Profit	$ -	$ -	$ 366	$ 731	$ 1.276	$ 2.547	$ 3.416	$ 5.562	$ 6.952	$ 6.952	$ 27.804
EBITDA	$ (3)	$ (7)	$ 358	$ 722	$ 1.267	$ 2.537	$ 3.406	$ 5.551	$ 6.941	$ 6.941	$ 27.712
EBIT	$ (3)	$ (7)	$ 358	$ 477	$ 756	$ 1.618	$ 2.170	$ 3.488	$ 4.169	$ 4.168	$ 17.194
Net Income	$ (3)	$ (7)	$ 219	$ 247	$ 341	$ 780	$ 1.049	$ 1.759	$ 2.113	$ 2.166	$ 8.665

CASH FLOW	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	Cumulative
Net Cash From Operations	$ (3)	$ (7)	$ 219	$ 492	$ 852	$ 1.699	$ 2.285	$ 3.823	$ 4.885	$ 4.938	$ 19.183
Net Changes in Working Capital	$ 0	$ 0	$ (30)	$ (30)	$ (45)	$ (106)	$ (72)	$ (179)	$ (116)	$ 0	$ (578)
CAPEX/NRE	$ -	$ 0	$ 2.461	$ 2.658	$ 2.653	$ 4.084	$ 3.172	$ 8.271	$ 5.224	$ 1.866	$ 30.389
Taxes	$ -	$ -	$ 139	$ 164	$ 228	$ 520	$ 700	$ 1.173	$ 1.409	$ 1.444	$ 5.776
Annual Cash (Shortfall) Surplus	$ (3)	$ (7)	$ (2.273)	$ (2.197)	$ (1.847)	$ (2.490)	$ (959)	$ (5.726)	$ (1.378)	$ 1.827	$ (15.051)
Equity Financing	$ 103	$ 7	$ 2.273	$ 1.098	$ 923	$ 1.245	$ 479	$ 2.863	$ 689	$ -	$ 9.680
Debt Financing	$ -	$ -	$ -	$ 1.098	$ 923	$ 1.245	$ 479	$ 2.863	$ 689	$ -	$ 7.298
Principal and Interest Payments	$ -	$ -	$ -	$ 66	$ 187	$ 317	$ 421	$ 1.654	$ 1.571	$ 1.804	$ 6.020

BALANCE SHEET	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Total Assets	$ 100	$ 100	$ 2.591	$ 5.035	$ 7.223	$ 10.494	$ 12.502	$ 18.889	$ 21.456	$ 22.377
Short and Long Term Liabilities	$ 0	$ 1	$ 1	$ 1.099	$ 2.023	$ 3.268	$ 3.747	$ 5.512	$ 5.277	$ 4.032
Shareholder Equity	$ 103	$ 110	$ 2.382	$ 3.481	$ 4.404	$ 5.649	$ 6.128	$ 8.991	$ 9.680	$ 9.680
Retained Earnings	$ (3)	$ (10)	$ 209	$ 455	$ 797	$ 1.577	$ 2.626	$ 4.386	$ 6.499	$ 8.665

A3.6.9 SUMMARIES: VALUATION SUMMARY

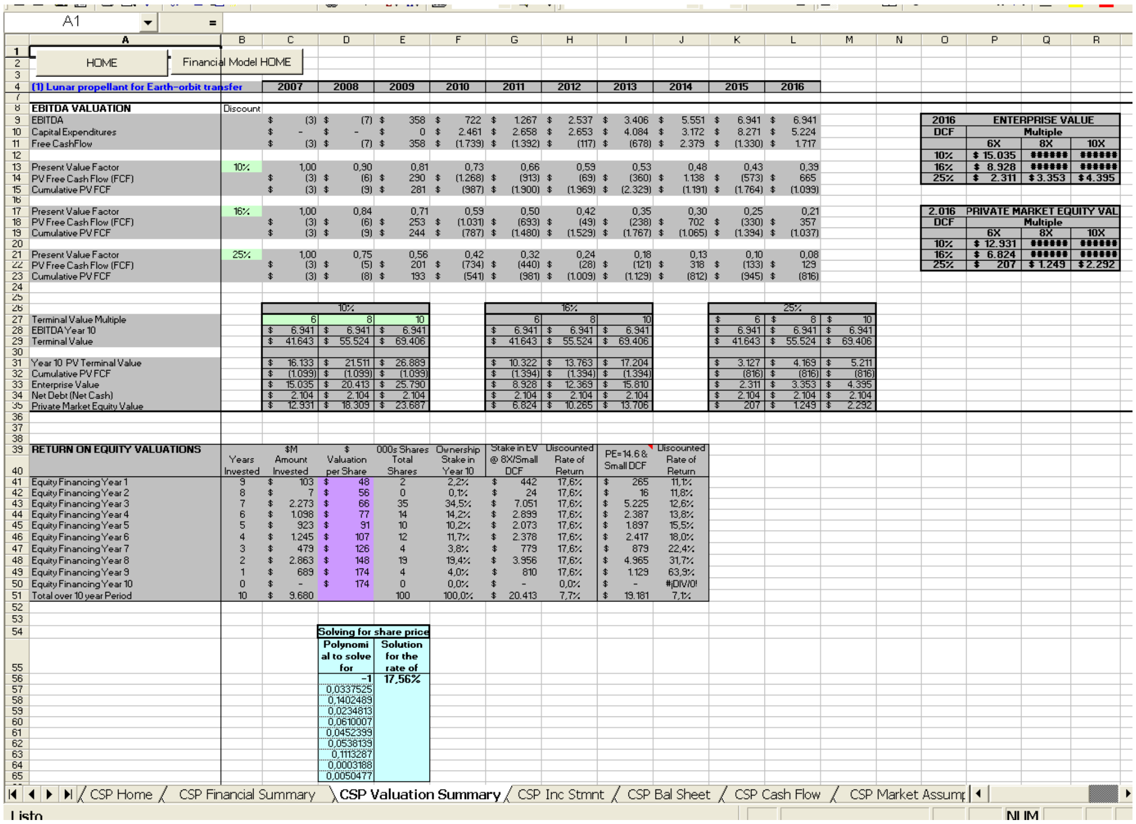
The financial model ultimately generates a Valuation Summary, which uses alternative methods for evaluating return on investment and value of the enterprise. These outputs are use to assess financial viability:

* The Enterprise Value (EV) is typically used when a company is privately held; EV in Year 10 is the cumulative net value of the cash that the investor would achieve if he sold his stake in Year 10.

* The discounted Price-Earnings (P:E) metric is used when the equity is publicly traded; P:E measures the value of the shares of stock as a multiple of the company's earnings per share.

* For each of EV and P:E, each year's investors are interested in the discounted rate of return on their equity. A decision to invest requires that the discounted future return on the investment not only be positive, but exceen an acceptable threshold, relative to the business' perceived level of risk and alternative uses of that capital (e.g., bonds).

Figure A3.6.9.1 CSP Valuation Summary Sheet



A3.7 STEP 7: SCENARIO OPTIMIZATION

The Outputs sheet summarizes a few key metrics of financial viability:

* The Net Present Value (NPV) and discounted project rate of return are the metrics traditionally used by engineers; they are cited here for reference even though they are not the best metrics for private investors.

* The Enterprise Value (EV) is typically used when a company is privately held; EV in Year 10 is the cumulative net value of the cash that the investor would achieve if he sold his stake in Year 10.

* The discounted Price-Earnings (P:E) metric is used when the equity is publicly traded; P:E measures the value of the shares of stock as a multiple of the company's earnings per share.

* For each of EV and P:E, each year's investors are interested in the discounted rate of return on their equity. A decision to invest requires that the discounted future return on the investment not only be positive, but exceed an acceptable threshold, relative to the business' perceived level of risk and alternative uses of that capital (e.g., bonds).

Step 7 consists in optimizing the architecture based on the mode results. This is best done by saving the file, then creating a new scenario for the case study.

Figure A3.7.1 Outputs Sheet

HOME

KEY MODEL OUTPUTS

Valuation	
Cumulative net income after 10 yr [$M]	$ 8.665
Enterprise Value in Year 10	$ 12.369
10	$ 10.265
Net Present Value [$M] in Year 10	$ 4.474
Investors Return on Equity (EV)	17,6%

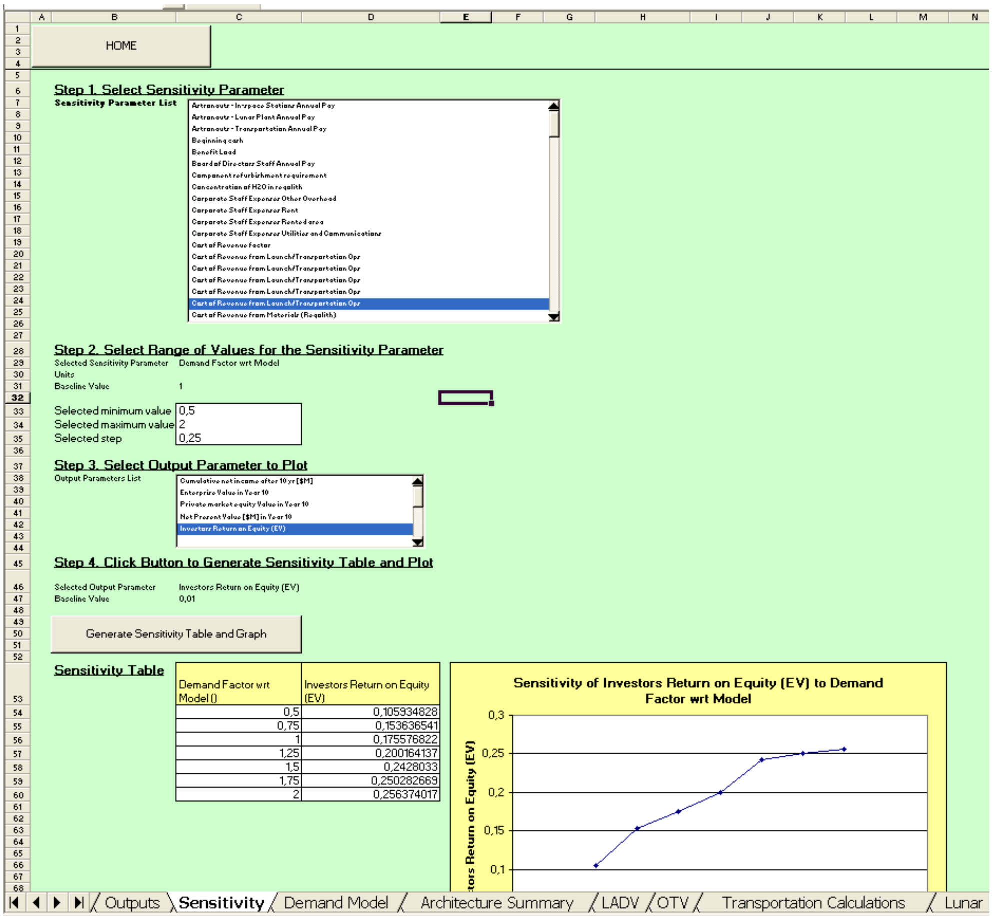
	Investors Return on Equity		**Project Rate of Return**	
	Public (EV)	Private (P:E)	EV	P:E
			8%	7%
Year 1	17,6%	11,1%		
Year 2	17,6%	11,8%		
Year 3	17,6%	12,6%		
Year 4	17,6%	13,8%		
Year 5	17,6%	15,5%		
Year 6	17,6%	18,0%		
Year 7	17,6%	22,4%		
Year 8	17,6%	31,7%		
Year 9	17,6%	63,9%		

A3.8 STEP 8: SENSITIVITY ANALYSIS

Once a good baseline scenario has been developed, sensitivity analysis is crucial a to identify the impact of various uncertain parameters and identify the conditions for and the drivers of financial viability. For example, what is the impact of various governement incentives, such as reduced tax rate, increased funding for development, or guaranteed price? What are the key technological drivers? etc.

In order to answer such questions, this "Sensitivity" sheet provides a tool to generate sensitivity tables and curves on any of the required or user-defined parameters. As an example, the current curve shows sensitivity of investors rate of return to demand for the example lunar propellant case study.

Figure A3.8.1 Sensitivity Sheet



A3.9 STEP 9: CONCLUSION

"What if?" studies and sensitivity analyses will help the user yield conclusions on the value of exploration missions and technology developments, optimal technical and business strategies, as well as the best public incentives to foster private sector involvement in space resource development.