Evaluation of Private Sector Roles in Space Resource Development

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Abstract. An integrated engineering and financial modeling approach 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 paper presents the modeling approach and its results for a transportation service using propellant extracted from lunar regolith. The analysis starts with careful case study definition, including an analysis of the customer base and market requirements, which are the basis for design of a modular, scalable space architecture. The derived non-recurring, recurring and operations costs become inputs for a 'standard' financial model, as used in any commercial business plan. This model generates *pro forma* financial statements, calculates the amount of capitalization required, and generates return on equity calculations using two valuation metrics of direct interest to private investors: market enterprise value and multiples of key financial measures. Use of this model on an architecture to sell transportation services in Earth orbit based on lunar propellants shows 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 can be used to evaluate any other possible private ventures in space, and conclude on the respective roles of NASA and the private sector in space resource development and solar system exploration.

INTRODUCTION

NASA is studying options for expanded solar system exploration, and the NASA Exploration Team (NExT) is exploring alternative mission architectures. 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. What is 'the business case' for private sector investment in the specific products and services associated with space exploration? What actions can (or should) NASA take to catalyze the expansion of the private sector in space, which the agency in turn can draw upon to further its objectives?

The NASA Exploration Team (NExT) chartered the Jet Propulsion Laboratory (JPL) to develop a new modeling tool that complements engineering studies by adding the private sector investor's point of view. Although qualitative arguments can be made for the benefits of on-orbit servicing, space manufacturing, space bodies mining, etc., no realistic conclusion can be reached without quantitative analysis of the financial viability of a private venture. To reach general conclusions, a flexible, integrated financial and engineering model is needed that can be applied to any possible space resource development venture. A multi-disciplinary science, engineering and financial team was gathered to accurately model all aspects of such a tool and bridge the gap between NASA and the private sector. To JPL's experience in solar system exploration, the Colorado School of Mines (CSM) added its extensive expertise in mining and lunar resources utilization studies, and CSP Associates, Inc. added their long experience counseling NASA and the private sector on space business finances.

This paper summarizes the general framework and modeling tool development efforts. The first part makes the case for a new approach to space resource development case studies, based on the private investor perspective. The second part describes the modeling approach and its core financial model. The third part illustrates the tool results on a lunar propellant case study that is described in more details in companion papers (Duke, 2003 and Blair, 2003).

THE CASE FOR A PRIVATE INVESTOR PERSPECTIVE

A number of studies have shown the great potential space resource utilization holds for space exploration. For example, Duke (1998) analyzed possible lunar ice extraction techniques. A study by NIAC (Rice, 2000) showed how using this ice to produce H_2/O_2 propellants would reduce the Earth launch mass (ELM) for a reference lunar outpost mission by up to 68%. Based on similar outpost assumptions, Nelson (2001) calculated how much a private venture must charge to transfer cargo and astronauts to the Moon. Borowski (1997) studied the lunar transportation improvements that nuclear thermal propulsion could provide. Considering low Earth launch costs, Stancati (1999) showed that using lunar-based LOX and LH_2, and nuclear thermal propulsion, ELM for space exploration could be improved by up to 51%, but cost improvements would be negligible. These are only a few examples of the wealth of interesting engineering studies that characterize what we might call the "potential for space resources supply".

A few studies also characterized the "potential for space resources demand". Outstanding examples include the commercial space transportation study (CSTS, 1994), which systematically quantified potential markets for future launch services; but also propellant demand studies such as Smitherman (2001), who quantified the demand for H_2/O_2 propellants in low Earth orbit (LEO) for LEO-to-GEO (geostationary) Earth orbit transfer.

Between these two bodies of research and analysis, there is a clear gap: among all the architectures proposed for space resources development, do any suggest (financially) viable private ventures? An integrated financial and engineering model based on a private investor perspective is the only way to bridge this gap, for three main reasons:

First, an engineering-optimized architecture is not necessarily the most interesting to a private investor. For example, economies of scale could lead the engineer to build upfront the capacity to meet optimistic demand growth; while the private investor might prefer a scalable architecture, building capacity only as demand increases.

Second, the metrics that interest private sector investors differ are not always the same ones that public sector engineers 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 an outcome that depends on specific 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 needed.

INTEGRATED ENGINEERING & FINANCIAL MODELING APPROACH

This part describes the nine general analysis and modeling steps in carrying out any space resource case study:

(1) Identification of the space resource and definition as a specific product or service,
(2) Case study selection and definition through a high-level engineering / financial trade,
(3) Customer benefits analysis and modeling of relevant demand factors (market size, anticipated price, etc.),
(4) Architecture design to meet customer requirements and development of a minimal engineering model structured around scaling laws,
(5) Engineering cost analysis and modeling,

(6) Financial model run and results analysis,
(7) Scenario optimization to improve the venture's financial viability (if necessary),
(8) Sensitivity studies to identify critical technology investments, incentives, bottlenecks, and uncertainties,
(9) Conclusions on the respective roles of NASA and the private sector.

In detailing these modeling steps, the following definitions will prove useful:

- **Space Resource:** any product or service that can be made available for a certain price in space, including products from raw materials, such as asteroids metals, as well as services, such as transfer from LEO to GEO.
- **Case study, Scenario, Version** A *Case Study* is defined by the determination of a specific space resource to be sold to specific customers. A *Scenario* is a particular architecture to meet the case study requirements; it involves a space architecture design and operational concept, and cost estimates. *Versions* of a Scenario incorporate different numerical input assumptions that might affect financial viability. Table 1 gives examples.

TABLE 1. Case Study, Scenario and Version Examples.

Case Study	Extraction of H_2/O_2 cryogenic propellant from ice mined out of lunar regolith; propellant transported and 'sold' in LEO for satellite refueling and orbital transfer.
Scenario	Design of one lunar plant, one L1 electrolysis and storage station, and two transport vehicles; alternative designs would define alternative scenarios (for example, add a storage station in LEO)
Versions	Varying parameters such as: launch cost, lunar plant efficiency, concentration of water in lunar regolith, participation of the government in development cost, etc.

The model implies a constant interaction between the engineering and financial analyses. At each step, engineering factors (costs, schedule, performance, risk) have a direct impact on such issues as total investment requirements, type and cost of financing, time to achieve positive cash flow, and venture operating margins and profitability.

Metrics of Interest to Private Investors

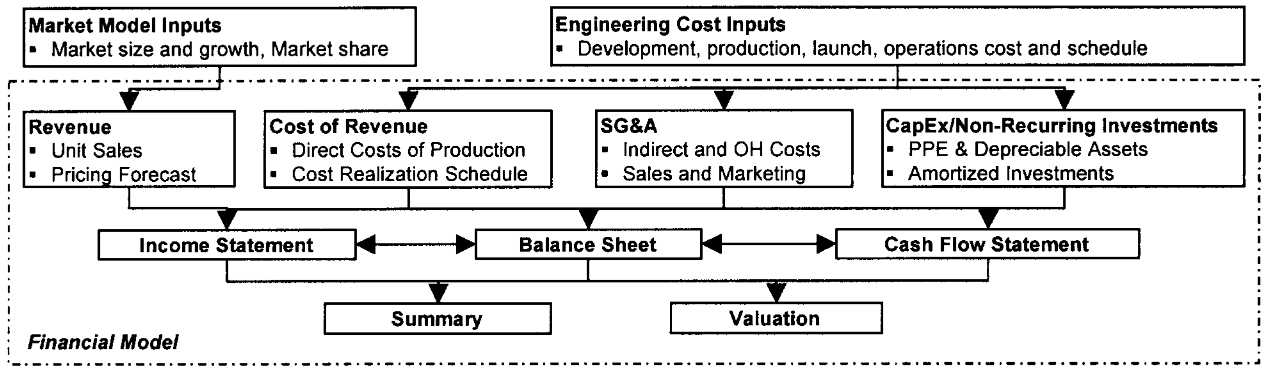
As a team of public-sector engineers designs a space architecture, the only economic information they can compute with traditional tools are the architecture cost elements (development, production, launch, operations). Applying a government discount rate and adding up yearly costs yields the Net Present Value (NPV) metric that is widely used to compare designs. For example, to assess the potential of using Orbital Transfer Vehicles (OTVs) for LEO-to-GEO transfer, one would compare the life cycle NPV of a GEO mission with, and without, OTV. If the latter is 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 not. Capital markets view commercial space as unpredictable, illiquid and high risk: high capital intensity, extensive R&D and regulatory costs translate into long, expensive development cycles. Markets are often unpredictable or have small perceived growth potential. Governments often subsidize competition. Market exit is "sticky". Shareholdings are illiquid and long term. Accordingly, any venture starts against significant financial impedance, and a simple NPV calculation is insufficient for a private company to make its investment decision.

The first question asked by an investor is "What are the *discounted* NPV 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-Earnings (P:E) multiple value in "Year X" (with "Year X" defined in terms that an investor might be willing to endure – at most seven to ten years).

- 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 investor would achieve if he sold his stake in Year X.
- The discounted **Price-Earnings** 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 value predicts what the shares will be worth in Year X, which is 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 may then consider a "breakeven" analysis.

FIGURE 1. Financial Model Structure.

Typically, this moves from the top to the bottom of an Income Statement: how soon can we achieve breakeven in gross margin (revenues greater than direct costs of production), EBITDA (revenues greater than on-going cost of running the business), EBIT (make net revenues after accounting for the depreciation of capital) and Net (make money after paying the interest on loans and taxes)? The financial attractiveness of a venture improves as these breakeven periods contract; conversely, as the breakeven periods lengthen, investors become less tolerant of risk and will impose a higher discount rate to account for uncertainties.

The Financial Model (Step 6)

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 used to calculate the performance of a private sector enterprise and yield the desired valuation metrics:

- 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 sales, general and administrative costs (SG&A), estimated depreciation and amortization, debt interest payments, and calculates taxes, to finally yield a net income.
- 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 any physical plant) versus its liabilities (sum of current payments owed by the company, long term debt, investor's equity and retained earning/losses).
- A **Cash Flow Statement** characterizes the venture's cash flows, i.e where 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.

As illustrated on Fig. 1, these *Pro-Forma* statements require four types of financial inputs that in turn rely on outputs from the demand and engineering analyses (Steps 1 through 5):

- **Revenue** inputs require a demand estimate as a function of time, in terms of quantity of demand (total market in terms of number of units each year), market share of the venture, and unit price forecast.
- **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.
- **SG&A** inputs describe the indirect business operations cost, including management, executive and marketing staff, staff training, overhead, rent, etc.
- **CAPEX** (Capital Expenditures) inputs are an estimate of non-recurring investments and their amortization schedule; this comprises costs for development, facilities and equipment, including all space elements.

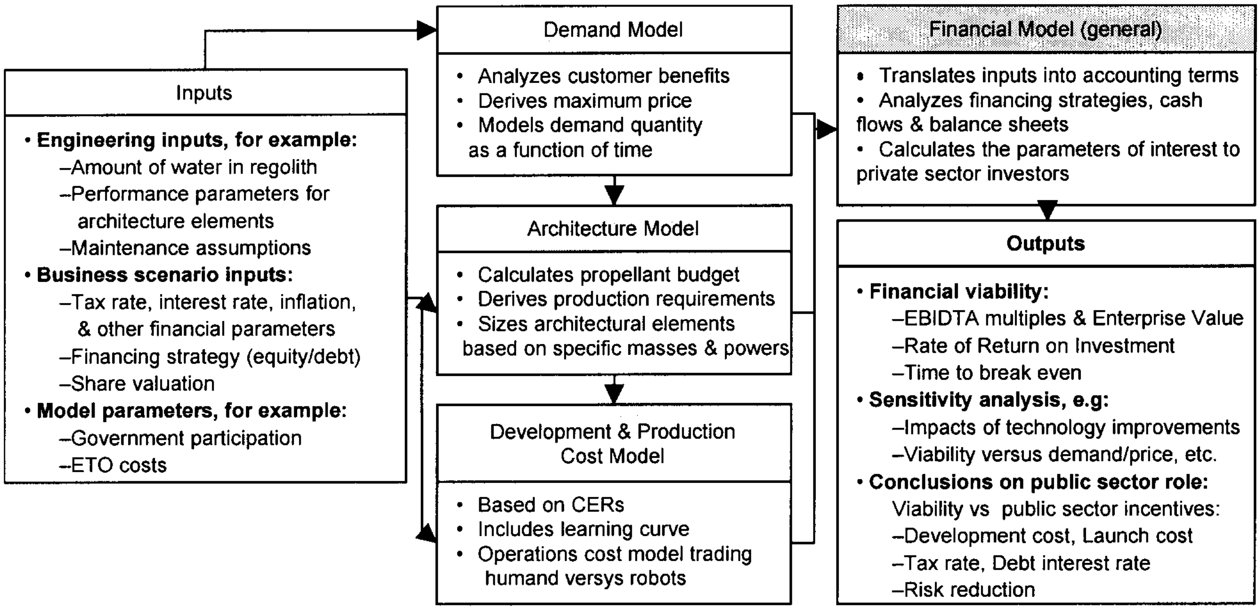


FIGURE 2. General Structure of the Integrated Engineering and Financial Model.

Selecting and Characterizing Case Studies (Steps 1 and 2)

Selection of a 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 propellant 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 exist that guide initial pricing assumptions: (1) direct launch into GEO, and (2) use of Earth-based propellants transported to LEO.

Demand Modeling (Step 3)

Once a product or service has cleared an initial "sanity check", a more detailed business case must be developed. This includes a market or demand model that yields three main outputs:

- **Total Market Demand** is the number of space resource units (product or service) expected to be bought each year. Several studies (CSTS, 1994; Smitherman, 2001) have been forecasting the number of satellites to be launched as a function of year in the future, orbital regime, satellite type, and satellite size. They can be used as starting points, together with an emerging markets assessment. An example of demand modeling is provided by Blair (2003).
- **Price** forecast modeling involves analyzing the maximum price each type of customer mission might 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 provides an upper bound on the price charged. For example, the price for "LEO-to-GEO transfer using lunar propellant" must, be less than the cost of a traditional staged launch to GEO, and less than the cost of an OTV using Earth-based propellant). A more involved analysis is required to estimate the maximum price that will allow potential new markets to emerge; nested "private ventures in space" analyses might be required if the new market is itself a space venture.
- Finally, **Market Share Growth** accounts for the rate at which potential customers swtich to the venture. This depends on factors such as number of competitors, market differentiation, and perceptions of risk.

Engineering and Cost Models Development Approach (Steps 4 and 5)

Although architecture design is scenario-specific, there are a number of engineering modeling rules to follow for any space venture scenario. The objective is a realistic approximation of the engineering requirements and costs necessary to populate the financial model and capture the trades that influence the financial viability metrics.

The model must capture anticipated technology and design development, production, launch, operations and maintenance costs; as well as engineering and technological risk. Depending on the level of detail and accuracy desired, this might comprise as little as a technology list and mass breakdown, or as much as a full technical description. The initial set of inputs defines a "baseline scenario". They are fed into the financial model to develop an initial financial viability assessment. The financial results will likely point to the cost drivers – this in turn can be used to explore either alternative scenarios, or different versions of the baseline scenario.

Rather than a point design, what is required is therefore an engineering model that can accommodate a range of starting assumptions or cost factors. Database-linked or analytical engineering scaling laws provide the required flexibility to market demand, as well as model flexibility to address uncertainty in demand and technological performance. An example of such a model is provided by Duke (2003). Similarly, cost models based on analytical Cost Estimating Relationships (CERs) provide the required flexibility to quickly adapt to changing designs.

Once the various analysis steps 1 through 5 are completed, the demand, engineering and financial models can be linked together to tailor the global financial and engineering tool. The schematic depiction in Fig. 2 illustrates that the model structure is the same for any possible space venture.

ILLUSTRATION ON A LUNAR PROPELLANT CASE STUDY

An architecture to sell in-space transport based on lunar propellant passed the initial sanity-checks. Smitherman (2001) showed that there is 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 closer than the Earth's surface to LEO in terms of delta-V requirements. In addition, the Lunar Prospector mission data indicated sufficient concentration of presumed water ice to form the basis for lunar *in-situ* mining as a source of H_2/O_2 propellants. Such propellant could also be very useful to NASA solar system exploration missions if provided at the Earth-Moon L1 Lagrange point, public as well as private interest. Finally, preliminary engineering analysis by CSM 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 LEO. Based on these preliminary checks, the team set out to analyze a case study for "LEO-to-GEO transport using lunar-based propellants".

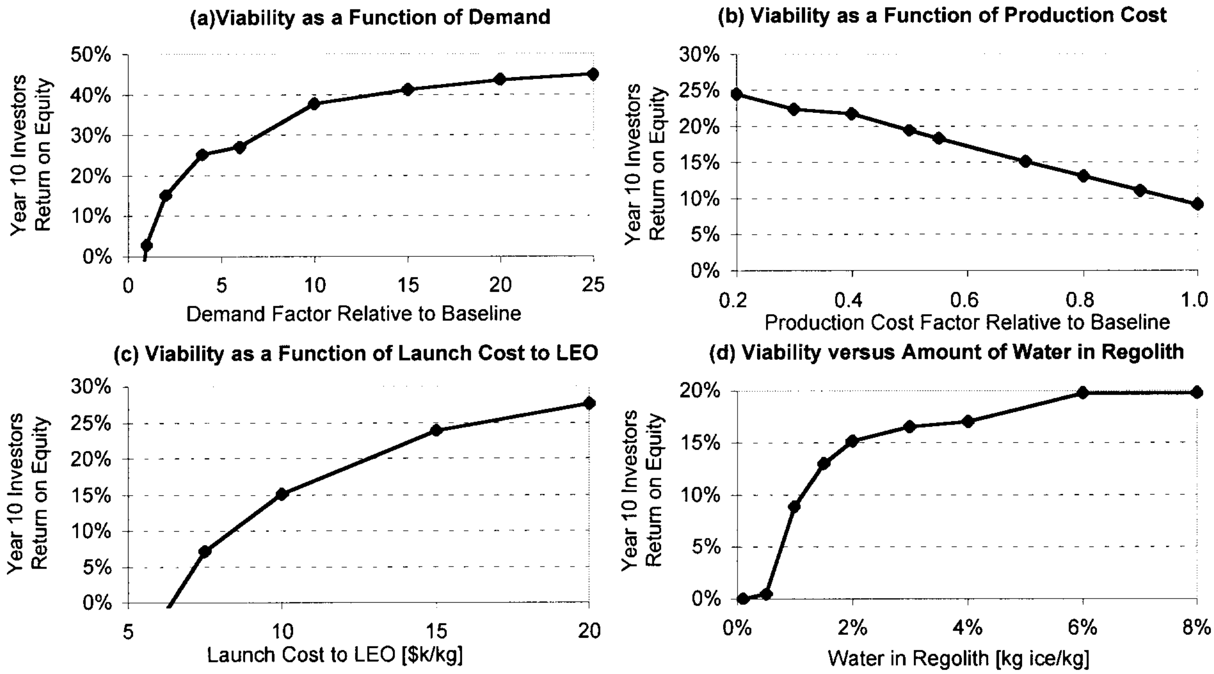
An Architecture to Sell In-Space Transport Using Lunar Propellants

The space resource is a service: transport from LEO to GEO, priced as a function of satellite mass (dollars per kilogram transported). CSM developed a demand model based on the Smitherman (2001) demand model for in-space water-based propellants (Blair, 2003). For the purpose of this paper, a conservative bottom line is a constant demand of 150 mt/year (average of 30 satellites per year, with a 5000 kg average mass). The pricing model is here straightforward. The main advantage for customers is Earth launch cost savings. The maximum price that can be charged is the difference between the cost to launch to GEO and the cost to launch to LEO. It was assumed that an interesting price to capture the market would be 80% of that difference. The capture model starts off with 10% market share in the first operational year, and increases linearly to 100% after 7 years of successful operations.

CSM considered design options for the lunar plant, space processing and storage segment, and transportation. A first model run helped select the best architecture design: the resulting architecture is detailed in Duke, 2003. This scenario comprises modular "architecture units" launched incrementally as demand increases. Each unit features a nuclear-powered lunar plant to extract lunar ice from regolith, melt it into water, and electrolyze part of it to fuel a lunar ascent and descent vehicle (LADV). The LADV transports water to an L1 processing and storage station (LPSS) where the water is electrolyzed into H_2/O_2 to fuel the LADV for lunar return as well as an orbital transfer vehicle (OTV). The OTV aerobrakes into LEO, where it performs rendezvous and capture with a customer satellite to transfer it to GEO before returning "empty" to the LPSS.

Model Results

Although some of the assumptions were simplistic and some important factors omitted, the results are a good illustration of the quick analytic capabilities offered by the proposed modeling tool. 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 NPV was quite negative, as shown in Tab. 1. But the integrated model makes it possible to explore in real time the conditions for financial viability. As an example, Tab. 1 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). These results show how the model allows quick "what if" studies:

- What if the government pays for the upfront development and first unit costs?
- What if, in addition, the efficiency of commercial production reduces costs by 30% compared to the traditional NASA development and procurement approach?
- What if, in addition, the concentration of H_2O in lunar regolith (uncertain) is twice our conservative baseline?
- What if, in addition, the demand for LEO-to-GEO transport is twice as high as our conservative forecast?

TABLE 2. Example of Results for a "LEO-to-GEO Transfer Using Lunar Propellant" Scenario.

Version	Year 10 Investors Return on Equity	Net Time to Breakeven [years]	Overall Project Return on Investment	Net Present Value [$M]
Baseline Assumptions	-	> 10	-	-5,006
Version 1: the public sectors pays for development and first unit cost	-30.57%	> 10	-12%	-567
Version 2: same as 1, plus 30% production cost reduction	-10.1%	7	-5%	+240
Version 3: same as 2, plus twice the ice concentration in lunar regolith	-1.6%	3	0%	+726
Version 4: same as 3, plus twice the demand quantity	+15.2%	3	+6%	+2,461

The above calculations incorporated a discount rate of 16%, which is consistent with a venture that would have a high level of perceived risk and a long investment horizon. The most liberal assumptions (version 4) yield 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).

Sensitivity analysis provides other insights into the conditions under which the venture might be viewed as a good private sector investment. For example, the sensitivity to demand (Fig. 4.a) shows that the venture would become viable with an increase in demand of about five 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 like orbital debris removal and/or avoidance, should be evaluated in future versions.

The sensitivity to production cost (Fig. 4.b) can help identify target performance for technology development as well as production chain efficiency. In this case, technological improvements alone cannot ensure financial viability.

The sensitivity to launch cost (Fig. 4.c) shows how non-intuitive results can also be reached. "What if launch costs were reduced?", is a typical question asked when trying to improve space business prospects. But the launch segment is here also a competitor. The net result is that viability decreases with reduced launch cost to LEO.

Finally, Fig. 4.d shows venture viability increases with water concentration in lunar regolith. This shows how the modeling approach can be used to estimate the value of exploration missions, and more generally the value of potential NASA's actions to mitigate sources of uncertainty.

CONCLUSIONS

We have developed an integrated engineering and financial modeling approach to quickly analyze 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

FIGURE 4. Sensitivity Analyses for the Example Case Study Scenario.

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 developments, 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.

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