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Research paper

The economics of moon mining

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ABSTRACT

The 50th anniversary of the first human landing on the Moon has revived the interest of space agencies and private companies on the Earth only natural satellite. Mining the Moon has become the topics of interest to the entire space community. This paper will address the following questions: (i) is space resource utilization by solely private markets sustainable, and (ii) if not, what type of public-private partnership are important/appropriate to enable the development of a private-sector market.

1. Introduction

Results from Moon's manned and unmanned missions indicate the presence of many resources on the Moon, such as Helium-3, rare earth elements, platinum and other precious metals, and ice. In the short-medium term, the most promising resources available are those (ice) needed for propellant production whose market is in space. The total mass of propellant for space missions launched from the Earth's surface places serious limitations on these types of operations. The low gravity of the Moon compared to the Earth creates new economic opportunities for Moon propellant (hydrogen and oxygen), and water and oxygen for life support systems in various orbits between Earth and the Moon, and even beyond.

A potential demand for propellant in space exists already. Counting the number of planned missions, both manned and unmanned allows the estimation of this potential demand. As NASA and international partners embark on the journey to Mars and beyond, fuelling and stocking vehicles at a cislunar refuelling point will be paramount in creating a feasible and sustainable exploration program. Low Earth orbit (LEO) can be also a destination for propellant to refuel the upper stage of rockets directed in geosynchronous orbit or to the Moon (see Chart 1).

Several exploratory mission have been undertaken to estimate the presence on ice on the Moon, among which the Clementine and the Lunar Prospector missions. On January 25, 1994, the Clementine probe started with the primary task of testing new infrared sensors, inertial gyrolaser and optical fibre systems, and large capacity solid-state memories, all technologies developed for military satellites and ballistic missiles. An altimeter in Lidar and four cameras operating in ultra-violet, visible, and infrared made more than one million images at the rate of 25,000 per day. Taken together, they form a complete atlas of the Moon with a resolution of between 100 and 200 m, which drops to 40 m for the Polar Regions. According to Clementine's data,[2] the regolith containing ice spanned 530 km to the North Pole and 6360 km to the South Pole.

The exploration of the Moon continued in 1998 with the launch of the Lunar Prospector probe. The Lunar Prospector probe has scaled down the estimates made by the Clementine probe. The frozen area is more restricted, but the water supply has been estimated at 300 million tons, about 100 times greater than was supposed. However, evidence of the existence of ice by both missions is indirect.[3] Hence, the need to validate the existence of ice, and to test the mining and recovering technologies, before investing in mining and propellant production facilities.

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[2] Scientists at the Lunar and Planetary Institute are using data acquired by Clementine to answer important questions about the Moon. These questions include the global three-dimensional composition of the lunar crust, the possibility of ice at the South Pole, the composition of mare basalts on the Moon's far side, and the chemical heterogeneity of the Apollo 16 landing site. See https://www.lpi.usra.edu/lunar/missions/clementine/data/; see also P.D. Spudis [1].

[3] The detector of the Lunar Prospector did not actually "see" the ice, but a neutron flux that the protons constituting the nucleus of hydrogen, hit by cosmic rays, bounce back into space. The strongest signals correspond to the Peary, Hermite, and Plaskett craters at the North Pole, and some areas of the Aitken basin at the South Pole. See A.B. Binder [2]; and http://lunar.arc.nasa.gov/results/neures.htm.

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2. Is space resource utilization by solely private markets sustainable?

In order to answer the question, the paper relies on estimation of the economic convenience of a Moon mining project, carried out applying the Net Present Value (NPV) methodology. NPV is used in capital budgeting and investment planning to analyse the profitability of a projected investment. It represents the difference between the present value of cash inflows and the present value of cash outflows generated by the investment over a period of time. An appropriate hurdle rate discounts the cash flows, which represents the required return by investors (time value of money[4]):

$$\sum_{n=1}^{N} \frac{F_n}{(1+r)^n} - C_0$$

where F_n are the net cash flows, C_o is the initial investment at time zero and r is the discount rate. An investor may determine the discount rate using the expected return of other projects with a similar level of risk.[5] The application of this idea to an environment that is unknown and, therefore, lacking in experience, requires an effort to adapt the concept to the new context. The cost of capital requested as the parameter to discount future and expected cash flows requires thus the identification of projects with similar riskiness so that their expected remuneration could constitute a proxy for the return expected by the Moon investor.

A positive Net Present Value indicates that the estimated earnings generated by a project exceeds the anticipated costs thus the investment should be accepted. In addition, to estimate the profitability of potential investments, the internal rate of return (IRR) is frequently used. The IRR is the rate that makes the NPV of all cash flows from a particular project equal to zero. The IRR is typically referred to as the "economic rate of return". The use of "internal" indicates the omission of external factors, such as the cost of capital or inflation, from the calculation. The higher a project's internal rate of return with respect to the discount rate or the expected returns of other projects with similar risk, the more desirable it is to undertake the project.

2.1. The project

The project adopted in the analysis of this paper is the Moon Mining model of the Colorado School of Mines.[6] As the mass constraints of a lunar polar water mine are highly restrictive because of delivery costs, an innovative concept was proposed. Instead of excavating, hauling, and processing, lightweight tents and/or heating augers extract the water resource directly out of the regolith in place by sublimation. A cold surface collects this water vapour for transport to a processing plant where electrolysis will decompose the water into its constituent parts (hydrogen and oxygen).

The equipment needed for lunar propellant operation will be built from existing technologies modified for the specific needs on the Moon. Little new science is required to build this plant. From a technological perspective, a lunar propellant production plant is highly feasible. Robotic services are crucial and need a correct implementation to ensure resilient, efficient operations. For ISRU to be feasible in the short-term, robots will have to perform most tasks autonomously, to communicate with each other, and to work together toward a common objective, while being watched over by tele operators in case intervention is needed.[7] There is a multitude of companies working on these technologies, with large organizations and smaller start-ups making significant progress in their development.[8]

An *exploration project* by a private company consists of two steps: reserve definition (prospecting), and mining and recovering technologies rendering. The first step consists thus in characterizing the resources as a proven reserve.[9] The second step entails the identification of economical extraction and processing methods. The exploration mission thus consists in the following two steps (Table 1):

The downside risk of an exploration investment is that the overall cost would be lost if, for whatever reason, the necessary follow up investments to capitalize on the results of exploration are not made. Hence, one has to define the uncertainties associated with the assessment of ice deposits and of adequate mining and recovering technologies. The exploration decision relies on probabilities p_1 and p_2 of finding adequate ice reserves and adequate mining and recovering technologies[10]. *The first phase* of the exploration project (prospecting) consists in the identification of the location of ice reservoirs on the Moon, and in assessing the quality and quantity of the ice with success probability p_1. With probability $1\text{-}p_1$, all initial investments and other operating expenses are lost. During *the second phase* (extraction and processing methods), further investments are required to test the extraction technologies and to perform a demo extraction procedure. If the ice reservoir and the extraction technique are adequate, the project continues with probability p_2 into the mining operations, with probability $1\text{-}p_2$ that all investments and other operating expenses up to T_2 are lost.

Once concentration, quantity and disposition, depth, and geotechnical properties of water ice has been discovered, the development phase requires the definition of the technologies to carry out the project and the estimation of their costs, together with contractual and legal aspects of the project, and its financing. The road map indicated by the Colorado School of Mines for the development phase is two years as the extraction and processing technologies have already been developed during the exploration phase. This paper assumes that the duration of the production phase is 20 years.

The demand for propellant and all costs of the project are derived from the study of the Colorado School of Mines. The demand scenario represents a state where all customers (Moon, Moon orbit, and low earth orbit) come to market. In this case, there is the largest demand on the system and a wide variety of geosynchronous, cislunar, and deep space activities are underway. These assumptions are reported in Tables 2 and 3.

3. The business model

In order to implement the project, the paper assumes two business

[4] There are three reasons why a dollar tomorrow is worth less than a dollar today: i) preference for current consumption; ii) expected inflation; iii) uncertainty in the future cash flows. The mechanism for factoring in these elements is the discount rate: a higher discount rate will lead to a lower value of cash flows in the future.

[5] The discount rate is also an opportunity cost, since it captures the returns that an individual would have made on the next best opportunity.

[6] See G. Sowers et al. [3].

[7] The first experiments of teleoperations on the Moon were conducted by the Soviets in the 19070s with the missions "Lunochod", which in Russian means "lunar walker". These were semi-moving robots that carried out wide explorations between eleven and thirty-seven kilometers. A team of five took care of the remote guide: the commander, the pilot, the engine driver, and the radio operator. Since then robotics and artificial intelligence have made several steps forward (see F. Ingrand et al. [4]. This makes the design of an automated system with tele operator possible with existing technologies but with adaptations of these technologies to the conditions of the project.

[8] See https://www.nasa.gov/mission_pages/tdm/archinaut/index.html. https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20120008777.pdf, and R.P. Muller et al. [5].

[9] Reserve definition requires exploration within the Permanently Shadowed Regions (PSR) with all the technical challenges that it would bring. It is critical to survey and prospect "appropriate ground", as extensive wide area surveys on the ground are not feasible on the Moon.

[10] The probabilities are independent, i.e. the probability of mining is not dependent on the previous phase but only subsequent.

Table 1
Exploration phases.

Mission description	Timeframe	Objectives
Prospecting	3 years	Anchor geologic models, calibrate remote sensing data; Richness of ice deposits, characterization of ice deposits, characterization of site.
Extraction and processing methods	2 years	Verification of economic viability, mapping of the deposit, extraction demo

Table 2
Demand.

Customers	Demand (MT/year)	$/Kg
Moon surface	100	7500
Moon orbit	280	3750
Low Erath orbit	1260	500

Table 3
Costs.

Investment costs (millions of dollars)	
Exploring hardware development[a] and launch costs	520
Mining hardware development[b] and launch costs	4044
Operating costs (millions of dollars)	
Exploration operating costs	280
Mining operating and replacement costs	2580

[a] It represents four mission categories: ground truth lander, Cubesat swarm/impactor swarm, tethered sensor landers, rover/sampler. According to Sowers, the total cost of the exploration campaign should be kept under one billion US dollars.

[b] It represents the cost of lunar plant based on the Colorado School of Mines Thermal Mining method.

strategies with different risk-return profiles: a venture fully financed by private investors, and a private-public partnership strategy. The first one implies that private companies solely conduct the various stages of exploration and mining operations embracing the risk of failure on the entire mission. The second strategy is a technique that involves public investments on a prospecting mission aimed at establishing proven reserves of ice at lunar poles. Once public activities have established proven reserves, private companies will undertake an exploration mission to identify extraction technologies and an extraction demo, followed by investments in mining activities and the production of propellant.

3.1. Private model and private-public partnership

Equation (1) describes the *private model* taking into consideration the probability of success during the exploration phases[11]:

$$NPV_{private\ model} = E\left[p_1 * p_2\left(\sum_{i=k}^{n}\frac{FCF_i^*}{(1+r)^{i-1}}\right)\right] - \left[(p_1) * \sum_{j=q}^{s}\frac{C_j}{(1+r)^{j-1}} + \sum_{j=1}^{m}\frac{C_j}{(1+r)^{j-1}}\right] \quad (1)$$

where C are investment and operating costs during the exploration phase, FCF* includes all revenues and capital and operating costs during the mining phase, and p_1 and p_2 represent the probabilities of success during the exploration phases. *n, k, q, s* and *m* define the length in years of mining and exploration operations including each of the exploration phases respectively.

A *private-public partnership* would entail initial public investments on a prospecting mission, followed by investments of private companies in extraction assessment, mining activities, and production of the propellant.[12] Equation (2) describe the NPV of the private companies taking into consideration the probability tree of the exploration phase:

$$NPV_{private-public} = E\left[p_2\left(\sum_{i=k}^{n}\frac{FCF_i^*}{(1+r)^{i-1}}\right)\right] - \left[\sum_{j=1}^{z}\frac{C_j}{(1+r)^{j-1}}\right] \quad (2)$$

In this case, the investment and the operating costs referred to the exploration activities only include those of the second phase.[13]

3.2. Main assumptions of the NPV model

Lack of data makes it difficult to quantity *exploration risks* (p_1 and p_2). On Earth, the average exploration failure in the oil industry between 1999 and 2017 was around 60%. There is a high variability in the failure rates ranging from 80% (wildcat) to 25% (established reservoirs). Failure rates in wildcat operations may better approximate mining operations on the Moon. However, there are indications that about 40% of exploration failures[14] were due to equipment failure and other related causes, resulting in a delay of development and operations. These risks are transferable, so that the average risk of losing exploration investments should be in the range of 50%.

This paper assumes these risks for a Moon prospecting mission equal to 50% for p_1. There are no historical data for the Moon extraction assessment risks. This paper assumes that these risks (p_2) equal to 60%. However, probabilities of failure and success in Moon prospecting and extraction assessment are subjective probabilities. Subjective probability is a type of probability derived from an individual's personal judgment or own experience about whether a specific outcome is likely to occur. Subjective probabilities differ from person to person and contain a high degree of personal bias. One often thinks of probability in terms of the classical probability definition, which is the number of favourable events divided by the total number of events. However, this is one narrow case of probability and it is not suitable for all areas of research. A broader definition indicates that a subjective probability does not refer to the system itself but to the knowledge or lack thereof that one has of the system.

Cost of capital refers to the opportunity cost of making a specific investment. It is the rate of return that earned by putting the same money into a different investment with equal risk. Thus, the cost of capital is the rate of return required to persuade the investor to make a given investment. It requires the identification of projects with similar riskiness so that their expected remuneration could constitute a proxy for the return expected by the Moon investor. In the first case, the activity taken as reference is the venture capital investment in high-tech, very innovative companies. The analysis of a wide sample of venture capital deals show an annualized return, over more than thirty years of

[11] To find the probability of two independent events that occur in sequence, one finds the probability of each event occurring separately, and then one multiplies the probabilities.

[12] NASA is planning a mission at the Moon South Pole in 2022. The mission consists in sending a mobile robot to the South Pole of the Moon to get a close-up view of the location and concentration of water ice in the region, and for the first time ever, actually sample the water ice at the same pole. See https://www.nasa.gov/feature/new-viper-lunar-rover-to-map-water-ice-on-the-moon.

[13] According to the Colorado School of Mines, the investment costs could be estimated at about 365 million dollars.

[14] See Ref. [6].

observation, around 20%, on average.[15]

In the second case, the oil industry, and the often-related exploration and mining activities are the starting point to identify a panel of possibly comparable companies, listed on the Stock Exchanges, whose riskiness parameter, the beta, is a proxy in this context. The beta parameter resulting from the analysis of a portfolio of listed companies in the mining industry[16] is around 1.3. The application of the Capital Asset Pricing Model (CAPM) to the average levered beta could be a solution, but, even without the un-levering procedure to keep the risk parameter at a higher and more cautious level, the equilibrium return is in the range of 8/9%. In addition, a premium to estimate the risk/return for the mining activity on the Moon is necessary, bringing the discount rate to 13.6%. However, in order to consider the overall riskiness of the assessment activities, this paper assumes the simple average between the two above identified discount factors (around 17%) avoiding additional and arbitrary valuations about the weight of the two rates in the interrelated operating phases.

In order to compute the NPV, the paper assumes a standard corporate depreciation rate period of ten years and a corporate tax rate of 21% equal to the tax regime in Luxembourg and in the United States, the only countries that have adopted a legal framework for mining of celestial bodies.

4. The results of the deterministic NPV model

Table 4 below reports the results of the deterministic NPV for both the private model and private-public partnership case.

They indicate that the net present value of the private model is negative (thus not acceptable as project), while the NPV of the private-public partnership case is positive. As the internal rate of return of the private model is below the discount rate, it is a further indication of the non-profitability of the strategy.[17] On the contrary, the internal rate of return of the private-public partnership model is much higher that the discount rate, confirming a high profitability of these investments.

However, the estimates of investment and operational costs and revenues of the Colorado School of Mines model are highly uncertain. One way to deal with these problems is to use a Montecarlo simulation.[18] Today this technique is widely used when there is a need to analyse phenomena with several uncertain starting data, such as in physics, engineering, meteorology, and finance.

Table 4
Results of the deterministic NPV calculations.

	Private model	Private-public partnership model
NPV (billions of dollars)	-0.04	1.84
IRR	19.3%	30%

5. Montecarlo simulation

This section applies the Montecarlo simulation to the *private-public business model* to analyse the robustness of NPV and the profitability results obtained with the deterministic model. Monte Carlo simulation performs risk analysis by building models of possible results by substituting a range of values -a probability distribution - for any factor that has inherent uncertainty.

It provides a number of advantages over deterministic, or “single-point estimate” analysis. Results show not only what could happen, but how likely each outcome is. Using Monte Carlo simulation, analysts can see exactly which inputs had which values together when certain outcomes occurred. It thus furnishes the decision-maker with a range of possible outcomes and the probabilities they will occur for any choice of action.[19]

5.1. Distribution assumptions

5.1.1. Capital expenditures (Capex)

During a Monte Carlo simulation, values are sampled at random from the input probability distributions. In the present simulation, all investment costs are distributed as lognormal random variables with median equal to the corresponding deterministic values and standard deviation equal to 20%. The percentages of the costs spent in each year are kept the same as in the deterministic case. The assumed distribution for costs of investment is asymmetric, with a long right tail, which gives positive probabilities to costs much higher that the median, while the probability of having very low costs is null[20].

5.1.2. Revenues

Yearly Revenues are also distributed as lognormal random variables with median values equal to the yearly revenues in the deterministic model and standard deviation equal to 20%. This assumption ensures that revenues are always positive, but that they may range widely around the deterministic value. Such variations may be caused by changes in either the price or the quantity demanded of the propellant.

[15] The reference to highly risky investments is considered cautious and in line with the principle of prudence in the estimation of values. Our data source is Preqin database (www.preqin.com). The venture capital deals are among the riskiest investments, which require the proportionally highest expected return. We are not able yet to identify the appropriate comparable initiatives for on the moon projects, therefore, the decision to adopt the historical returns, offered by a sample of very uncertain deals, can be considered suitable, in terms of risk and return appreciation.

[16] A group of huge mining companies, including giants as Glencore PLC and Rio Tinto, among the others, was analyzed in terms of historical betas. The choice of an equilibrium model (specifically the Capital Asset Pricing Model, CAPM) could seem premature, but the valuation of investments' sustainability could require the inclusion, in the selected methodology, of the long term results for the investors.

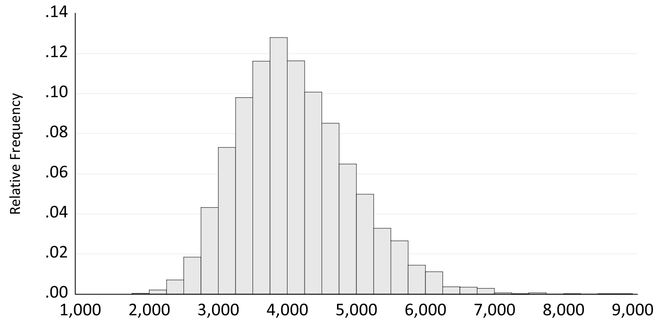
[17] A previous version presented at the IAA annual conference in Turin, analyzed a quasi-integration business model, which sees the presence of two companies, an Explorer and a Miner. A possible interpretation of the agency theory is to consider the Miner as the principal, who engages the Explorer as the agent to perform the activity of survey, recognition, and assessment, on a sort of its behalf. Montecarlo simulations indicate that probabilities of negative net present values are negligible for the mining company, but non-negligible for the exploring company. These results indicate that the quasi-vertical integration business model is extremely risky. It is doubtful that a private exploring company would invest under these conditions.

[18] The first application of the Montecarlo method dates back to the eighteenth century, when George-Louis Le Clerc, Count of Buffon, showed that a random and probabilistic approach could be used to estimate the value of pi. According to Nicholas Metropolis, Fermi was the first to use a modern version of this technique in 1930 applying it to the neutron diffusion study, but never published the results. It was the later work of Ulam and von Neumann that spread the use of this method.

(*footnote continued*)

[19] Monte Carlo simulation is commonly used to evaluate the risk and uncertainty that would affect the outcome of different decision options. It allows the business risk analyst to incorporate the total effects of uncertainty in input variables, such as costs of investments and revenues of the project. The main idea behind this method is that the results are computed based on repeated random sampling and statistical analysis. The Monte Carlo simulation is, in fact, random experimentations, in the case that, the results of these experiments are not well known. Monte Carlo simulations are typically characterized by many unknown parameters, many of which are difficult to obtain experimentally.

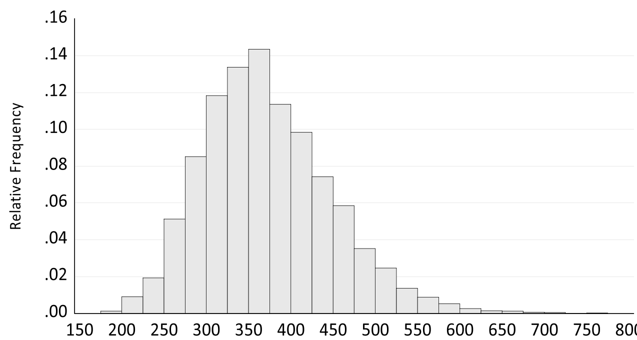
[20] According to Pierre La Roque (2012), on Earth out of 76 mining projects, 61 went over budget, or 80% of the mining industry's project overrun their budget. The distribution curve resemble a lognormal distribution with a long right tail, with the majority of the overrun budgets around the median and the 50% of the original estimates.



Descriptive statistics

Mean	4,115
Median	4,028
Maximum	8,960
Minimum	1,887
Std. Dev.	836

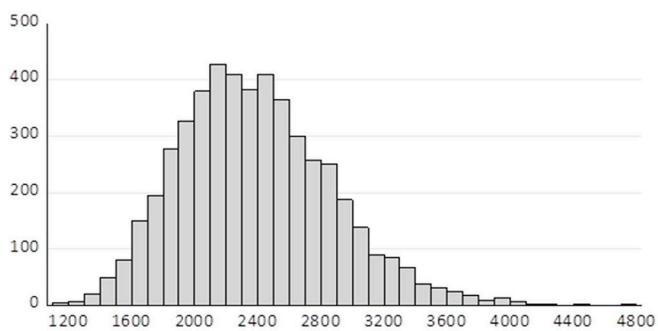
Fig. 1. Mining phase Capex Lognormal distribution.



Descriptive statistics

Mean	372
Median	363
Maximum	764
Minimum	181
Std. Dev.	76

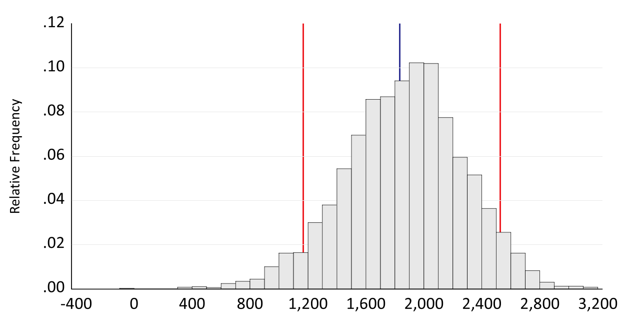
Fig. 2. Exploration phase Capex Lognormal distribution.



Descriptive statistics

Mean	2,385
Median	2,340
Maximum	4,778
Minimum	1,120
Std. Dev.	484

Fig. 3. Revenues lognormal distribution.



Descriptive statistics

Mean	1,867
Median	1,889
Maximum	3,171
Minimum	-91
Std. Dev.	409
5% quantile	1,166
Deterministic	1,843
95% quantile	2,526

Fig. 4. Private-public partnership NPV distribution.

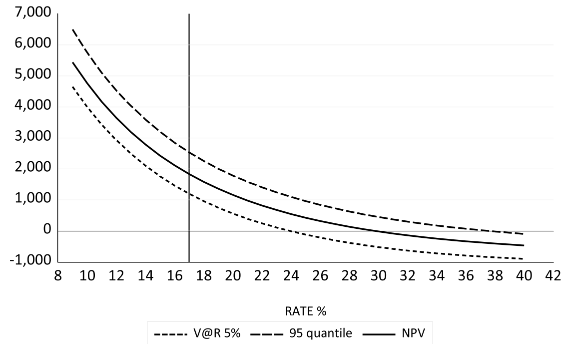
5.2. Montecarlo experiment

5.2.1. Simulation methodology

The present Monte Carlo simulation consists in replicating 5000 times the following steps.[21] At each iteration:

- a new value of the total costs of investments are extracted from the above lognormal distribution (Figs. 1 and 2);
- yearly operative costs, and depreciation are computed using the same percentages of the total expenditures as in the deterministic model;
- revenues are extracted year by year from the above lognormal distribution (Fig. 3);
- discounted free cash flow to firm (FCFF) for each year of the project

[21] The software used to perform the Montecarlo simulation is E-views version 10.



Descriptive statistics		
	NPV	IRR
	Rate 17%	(NPV=0)
5% quantile	1,166	23%
Deterministic	1,835	29%
95% quantile	2,526	37%

Fig. 5. Private-public partnership NPVs for different discount rates.

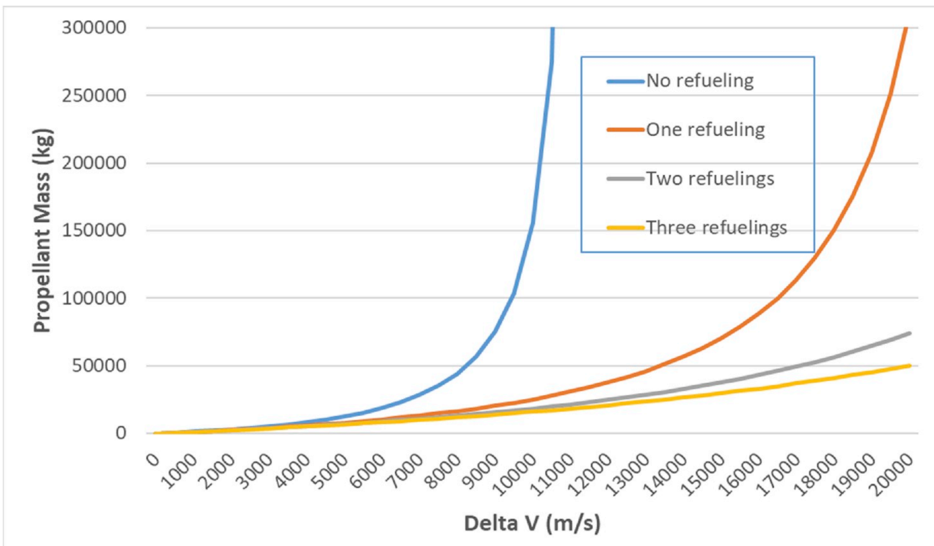


Chart 1. Propellant mass and Delta-v[1].
Source: George Sowers [3].

are computed using discount rates from 10% to 50% with 1% increment;

- NPV of the business model is then calculated.

5.2.2. Results

The combination of all uncertainty and risk components introduced in this Montecarlo exercise yields a NPV that range from very high values, relative to the deterministic outcome, to negative values, the latter with very negligible probability. The NPV computed at the start of the exploration activity, at a 17% annual discount rate, ranges from a minimum of −91 million dollars to a maximum of 3171 million dollars. The probability of negative NPVs is much less than 0.5% (Fig. 4).

Fig. 5 presents the 5% and 95% percentiles of the simulated NPVs, computed for different discount rates together with the IRR of the operation. If the prospecting mission by space agencies produces positive results, the simulated NPV in Fig. 4 suggests that the company faces more than 99% probability of obtaining a positive NPV and an IRR above the 17% discount rate.

[1] In astrodynamics and aerospace, a delta-v budget is an estimate of the total delta-v required for a space mission. Delta-v is a scalar quantity dependent only on the desired trajectory and not on the mass of the space vehicle. As input to the Tsiolkovsky rocket equation, it determines the required propellant for a vehicle of given mass and propulsion system.

6. Conclusions

Given the potential for commercial uses of Moon produced propellant, this paper proposed two business models to test the conditions that would allow private firms to profitably mine the ice to produce oxygen and hydrogen. It rejects the *private model* as it produces a negative NPV. From a financial standpoint, the reasons behind the negative value generated by the *private business model* are twofold. First, the company as a whole takes on the uncertainties derived from the entire exploration phase, which negatively affect the value of the expected cash flows. Second, the longer exploration period also extends the span of time without revenues that are in turn reduced due to the value time of money. Instead, both the deterministic and the Montecarlo simulations indicate that the *private-public partnership model* produces positive a NPV, provided a successful completion of a prospecting mission by government. The Montecarlo simulation shows that the private company faces almost 100% probability of positive NPVs and of IRR much above the 17% discount rate indicating a high profitability of the model.

A final question is why governments should undertake prospecting missions at the lunar poles. This paper demonstrated that long duration of prospecting, and extraction and processing mission means that the time cost of exploration greatly exceeds the nominal cost; and the high-risk means that companies must spend several times the average discovery cost to have a reasonable probability of success making such model economically and financially unfeasible. Government prospective missions mitigates those challenges. First, they attracts exploration investment by allowing industry to identify areas of favourable mineral potential. Second, they increase exploration efficiency by making it unnecessary for individual companies to duplicate common information. Third, they increase exploration effectiveness by providing key information inputs to risk-based decision-making.

Prospecting missions on the Moon by governments should occur if and only if their return exceeds the opportunity costs. Returns are based on expectations of higher revenues such as taxes, higher employment and growth, all events that would happen here on Earth. Based on the discounted tax revenues generated by the private-public partnership model, the return is about 6% per year.[22] The opportunity costs consist of reduced consumption and displaced private capital. However, lunar poles prospecting mission not only crowed in private investments by improving their returns through reduction of prospecting costs and risks, but also increase consumption in the medium term through higher private investments and increase in employment. Moreover, they make government solar system exploration missions much cheaper, thus contributing to the advance in science that is in itself a major government goal. In summary, the social rate of return of government prospecting mission including all benefits and costs to members of society, not just financial returns to government itself, would be much higher than 6% per year.

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