SDA Bocconi School of Management | SEE Lab Space Economy Evolution

FOURTH SESSION

BUSINESS AND TECHNICAL RISKS:

A PROBABILISTIC INTERPRETATION OF THE GENERAL BUSINESS MODEL

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GENERAL MODEL

Moon mining is a very complicated endeavor. Many **high risk factors**, such as uncertainties about presence and concentration of space resources, technology readiness, relatively **high initial investment** requirements, and negative cash flow during the first few years, affect these projects.

It is thus important to develop a robust economic model and a definition of the associated risks.

The economic model involve four steps:

1. Identification of commercial uses
2. Prospecting and Exploration
3. Development
4. Production

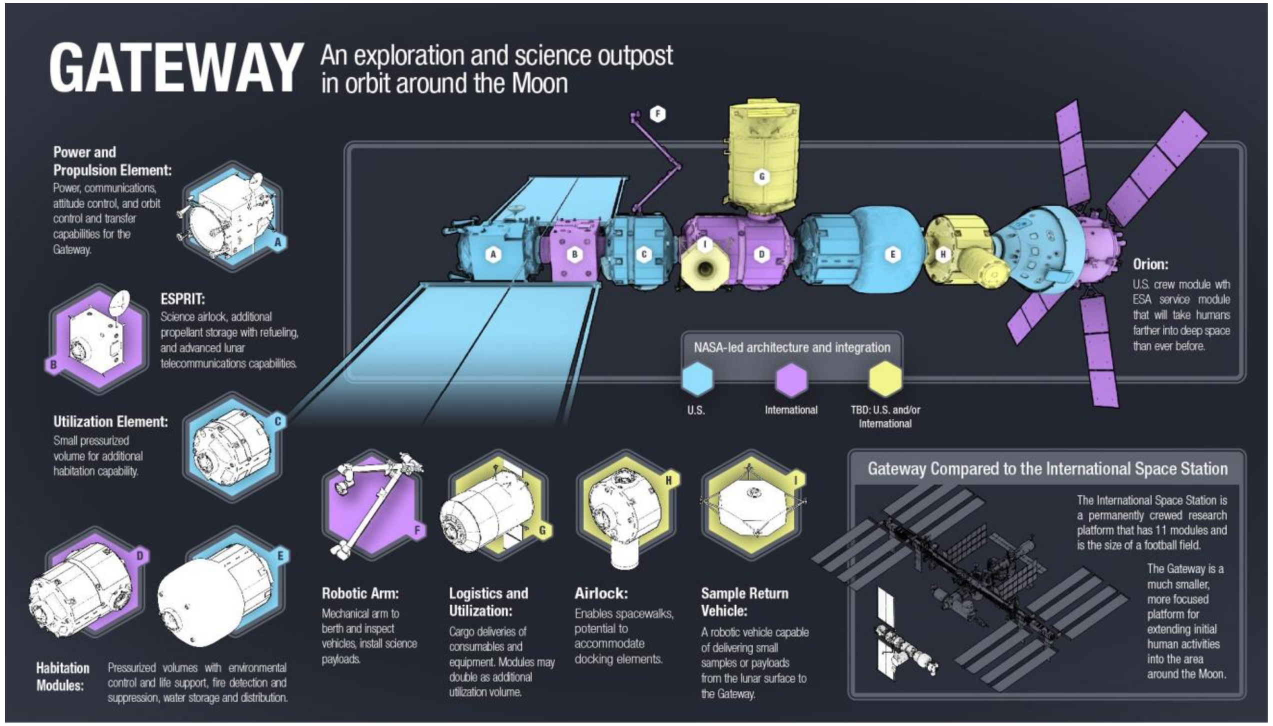
GENERAL MODEL

1. IDENTIFICATION OF COMMERCIAL USE

Many resources are estimated to exist on the Moon, such as Helium-3, platinum, and other precious metals. However, the most promising resources available are those needed for **propellant production**.

The total mass of propellant needed for space missions launched from the Earth's surface places serious limitations on these types of missions.

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 orbit between Earth and the Moon, and even beyond.



GENERAL MODEL

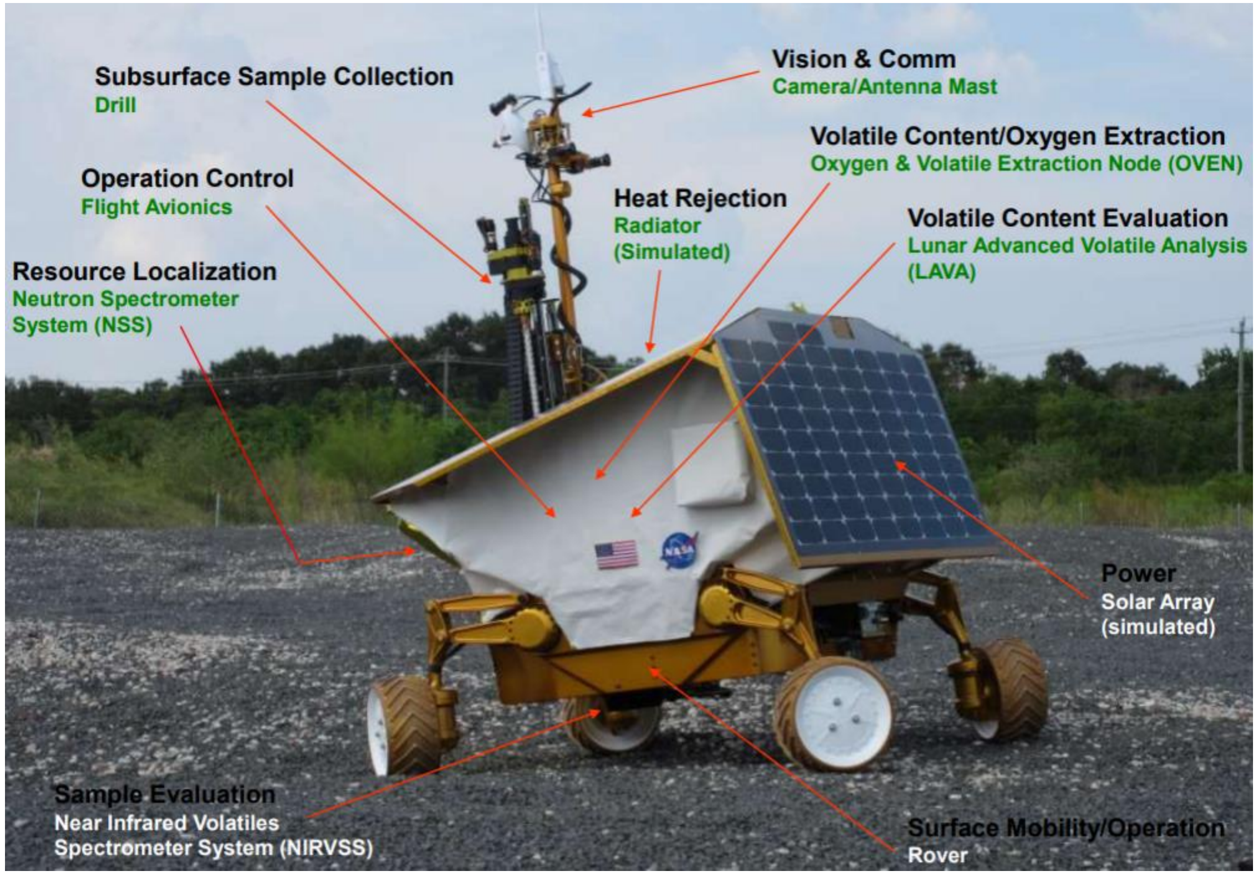
2. PROSPECTING AND EXPLORATION

On **Earth**, **prospecting** is the first stage of a geological analysis of a territory. It is the physical search for minerals, fossils fuels, precious metals or mineral specimens.

Once the different geophysical surveys are collected, **exploration** missions are carried out to reduce the search area, and to identify concentration, quantity and disposition, depth, and geotechnical properties.

Governments typically conduct prospecting, while private companies carry out exploration.

We assume the **same logic in Moon mining**.



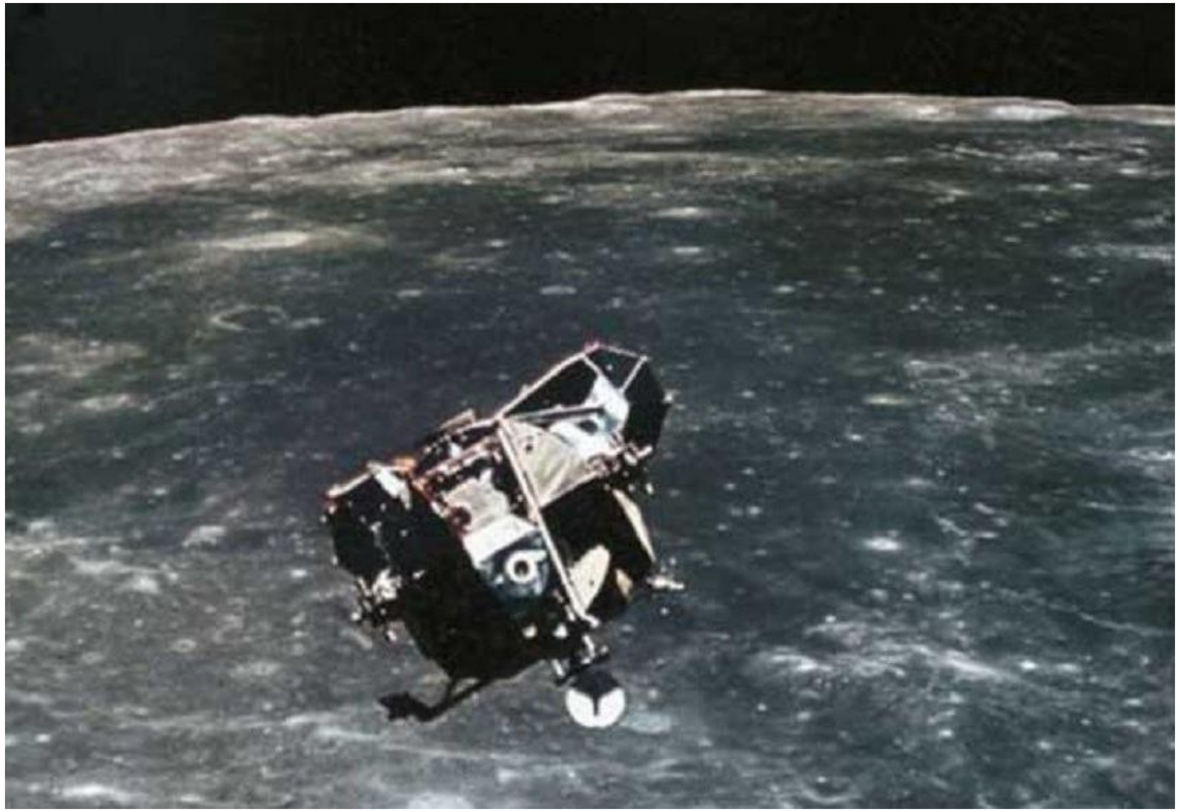
GENERAL MODEL

2. PROSPECTING AND EXPLORATION

At present, there are numerous **prospecting Moon missions** in the pipeline, trying to figure out where the ice is, in what concentrations and with what kind of variability across the lunar surface.

The European Space Agency (ESA) and Russia are working together to investigate the moon's resources - specifically, water ice and other volatiles at the lunar poles. ESA is developing a drilling and sample-analysis payload (Prospect), which will fly to the moon aboard Russia's Luna 27 mission in the 2022-23 period.

Private companies in the United States, such as Moon Express, indicate their willingness to launch exploratory missions to the Moon in view of future mining operations.



GENERAL MODEL

2. PROSPECTING AND EXPLORATION

Estimating the **costs of exploration** in space presents a challenge. Historically, government space projects have experienced between 50 and 100 per cent excess in actual cost over initial cost estimates. In many cases, this was the result of political ploys to get R&D money and then spend more. Private companies, operating independently of government procurement for R&D, should be able to do a better job. However, **the risk of a longer than expected R&D period** remains.

GENERAL MODEL

2. PROSPECTING AND EXPLORATION

Exploration investments present the highest risk. 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.

Lack of data makes it difficult to quantity this risk. For the purpose of this analysis, we rely on the experience of the **oil and gas industry**, although a note of caution is warranted, as oil and gas risks are more predictable than space exploration risks.

GENERAL MODEL

2. PROSPECTING AND EXPLORATION

The average commercial failure rate in the oil industry between 1999 and 2017 was around 53% (Wood Mackenzie). There is a high variability in the failure rates ranging from 80% (wildcat) to 25% (established reservoirs). However, there are indications that about 40% of exploration failures (Hai Wen, 2014) 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 **30%**.

Is it possible to **mitigate this risk**? The answer is yes. Following the theory of portfolio diversification reducing the risk of investment, adding the extraction of precious metals, such as platinum, and platinum group metals, to the project reduces the risks associated with the production of one single resource (ice). Moreover, economies of scope indicate the advantage of producing both propellant and precious metals is more cost effective.

GENERAL MODEL

3. DEVELOPMENT

The development phase requires a feasibility study covering the definition of the technologies required to carry out the project and the estimation of their costs, together with contractual and legal aspects of the project, and the fainancing.

The next session will examine the contractual and legal aspects of space mining. We concentrate here on the costs of the investment. In the development phase, there is risk that these costs may have value change. However, good planning and appropriate contractual system make this risk moderate.

GENERAL MODEL

4. PRODUCTION

Once the production plant is completed and the facilities are commissioned, the production phase starts. The production phase itself passes through three sub-phases:

I. **Build-up phase**: During this phase, production is progressively brought on stream, which means that the production rises at a relatively constant rate until it reaches an anticipated level of production.
II. **Plateau phase**: During this phase, the production rate remains steady. The duration of the plateau phase may be difficult to estimate, and it depends on the amount of ice present in the chosen location.
III. **Decline phase**: During this phase, the production rate declines. This phase lasts longer than other phases of production.

Risks in the production phase are the business risks related to prices, quantity, and costs. Major risks of a Moon project concern prices of the final product. The major competitor of propellant from the Moon is propellant supplied from Earth. Possible reductions of launching costs of propellant from Earth in various orbits would certainly affect prices of the final product supplied from the Moon.

GENERAL MODEL

An economic assessment of mining operations on the Moon is then based on:

1. Calculation of the **net present value** of the project. This is a deterministic model that has to be **integrated with probabilistic approaches** to evaluate the project under risk;

2. A **Monte Carlo** simulation accomplishes this task by modeling the probability of different outcomes and assessing the risks.

The numerical model (pre-feasibility study) based on the Colorado School of Mines project concentrates on propellant production only. It is important to underline that this model should be integrated with extraction of precious metals. In this case, we have to go back to the blackboard to design a new technical and economic architecture satisfying both the in-space and the Earth markets. However, the results of the present numerical simulation will give some important insights.

MOON MINING: Deterministic Net Present Value

CISLUNAR SPACE

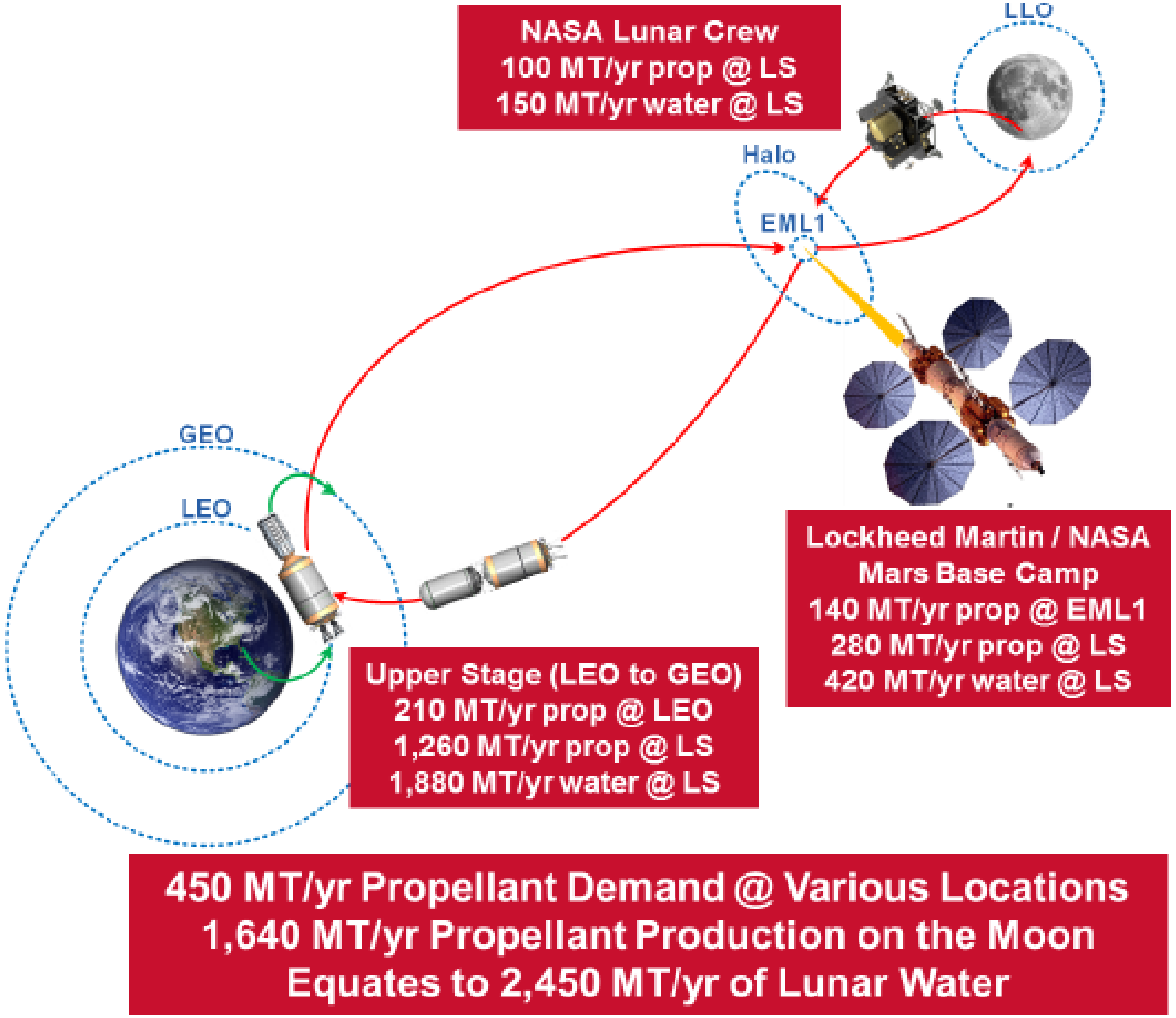
LEO – Low Earth Orbit

GEO – Geosynchronous Earth Orbit

Mars Base Camp – Gateway

EML1 – Earth-Moon Lagrangian point

LS – Lunar Surface



MOON MINING: Deterministic Net Present Value

COST OF EXPLORATION AND DEVELOPMENT

	LUNAR PLANT COSTS	EXPLORATION COSTS**
Mass (kg)*	30,000	3,000
Cost ($/kg)	100,000	100,000
Cost of development ($)	3,000,000,000	300,000,000
Cost of transport to the Moon ($)	1,080,000,000	108,000,000
Total cost ($)	**4,080,000,000**	**408,000,000**

* The mass necessary was taken from the report of the Colorado School of Mines, and is calculated so it is possible to extract 2,450MT/yr of water on the Moon.
** The exploration costs are in line with the NASA cancelled mission concept Resource Prospector.

MOON MINING: Deterministic Net Present Value

PRICING FUEL ON THE MOON

- Assumption of complete knowledge of the missions;
- Average price moon surface = $\sum \frac{\text{demand orbit}}{\text{total demand}}$ x price orbit
  - The orbits are LEO, EML1, lunar surface

COSTS OF PROPELLANTS ($/kg)				
	Delivered from Earth	**Delivered from lunar surface**	**Multiplier***	**At lunar surface**
To LEO	4,000	3,000	6	500
To EML1	12,000	7,500	2	3,750
To lunar surface	36,000	n/m	n/m	7,500
Average price	n/m	n/m	n/m	1,482

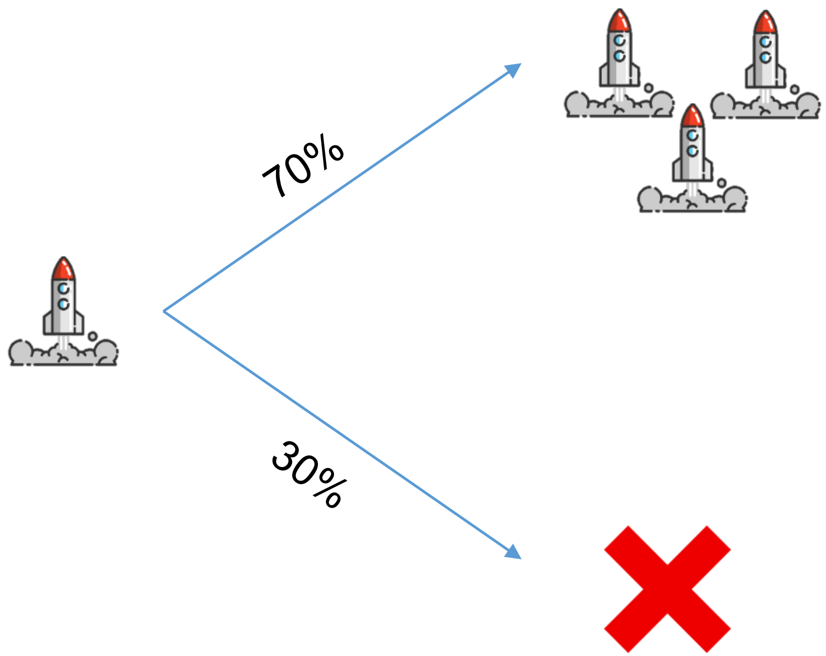
* To have x kgs of propellant on LEO, 6x kgs need to be produced on the moon, and 2x for EML1.

MOON MINING: Deterministic Net Present Value

GO / NO_GO

We assumed on the basis of Oil and Gas Industry experience a 30% probability of **non-transferable risk failure**;

We assumed 70% probability of success under the condition of considering an exploration phase of 1 extra-year with respect to Colorado School of Mines work.



MOON MINING: Deterministic Net Present Value

FREE CASH FLOW PROJECTIONS

- Exploration capex
- Development capex
- Operating Costs
- Revenues = total demand * fuel price
- Taxes = Luxemburg 21% corporate tax
- Cost of capital (discount rate) = 16%

- Exploration mission development
- Exploration mission launch
- Main mission development
- Main mission launch
- Operations and maintenance
- 1,640Mt x 1,482($/kg) = 2,430,000 $/Mt

$$NPV = \sum \frac{FCF_t}{(1+d)^t}$$

$$NPV_{weighted} = Pr_{Go} NPV_{Go} + Pr_{NoGo} NPV_{NoGo}$$

$$Pr_{Go} = 1 - Pr_{NoGo}$$

MOON MINING: Deterministic Net Present Value

SUMMARY RESULTS OF DETERMINISTIC MODEL

PV GO (10 years) ($)	4,328,585,388
Probability GO	70%
PV NO GO ($)	- 435,778,835
Probability NO GO (%)	30%
Weighted PV ($)	2,899,276,121

NPV GO (16 years) ($)	1,481,563,579
Probability GO	70%
NPV NO GO ($)	- 435,778,835
Probability NO GO (%)	30%
Weighted NPV ($)	906,360,855

Profitability Index	1.10

MOON MINING: Deterministic Net Present Value

COST OF CAPITAL

Assumptions:

- the cost of capital is a discount rate expression of the opportunity cost of a project of similar riskiness;
- in the analyzed case there is neither a financial nor a real market for analogous investments, so, continuing with the reference to the oil and gas industry (and adding the mining metal sector), we attempt to estimate a minimum hurdle rate for the investment;
- it is a first step, because the embedded volatility in the “Mining the Moon” project is definitely higher. We decided to compare this lowest discount rate with the annualized returns offered by alternative private equity investments in “high technology” industries.

MOON MINING: Deterministic Net Present Value

COST OF CAPITAL

BETAS IN MINING AND METAL INDUSTRY		
Comparable companies	**Unlevered Betas**	**Levered Betas**
Glencore PlC	1.05	1.52
Rio Tinto PlC	1.20	1.24
BHP Group	N.A.	1.31

BETAS IN OIL AND GAS INDUSTRY		
Comparable companies	**Unlevered Betas**	**Levered Betas**
Exxon Mobile Corporation	0.82	0.94
Royal Dutch Shell	0.96	1.15

MOON MINING: Deterministic Net Present Value

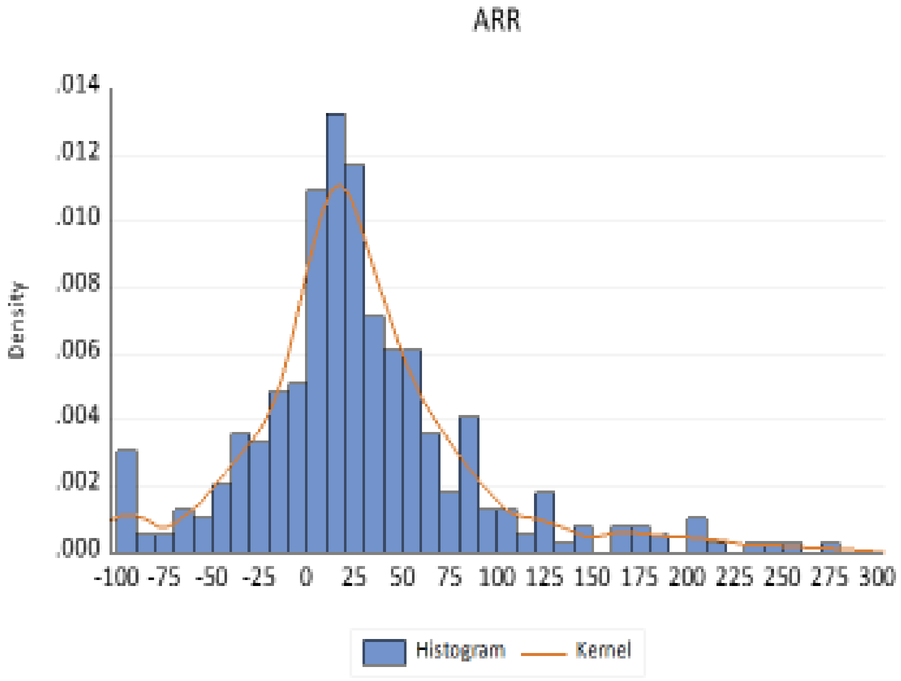
COST OF CAPITAL

Average unlevered betas mining and metal industry	0.89
Average unlevered betas oil and gas industry	1.0075
Risk free rate	2.4%
Market risk premium	5.45%
Unlevered cost of equity	7.89%
Average levered betas of the two industries	1.232
Cost of capital with levered betas	9.1%

MOON MINING: Deterministic Net Present Value

COST OF CAPITAL

A comparison with the annualized rates of return (ARR) of private equity investments in high-tech industries.



	ARR
Mean	30.1
Median	20.85
Maximum	372.4
Minimum	-100
Std. Dev.	65.57

MONTE CARLO SIMULATION

ASSUMPTIONS

The reference setup is the deterministic model:

- CAPEX is a normally distributed random variable, centered around $ 4,044 millions, the CAPEX in the deterministic model;
- the percentages of CAPEX spent each year are kept the same as in the deterministic case – this includes the expenditures in the exploration phase of the project;
- Yearly Revenues are lognormal random variables with median values equal to the yearly Revenues in the deterministic model.

MONTE CARLO SIMULATION

PROCEDURE

Perform a Monte Carlo Exercise with 1000 iterations.

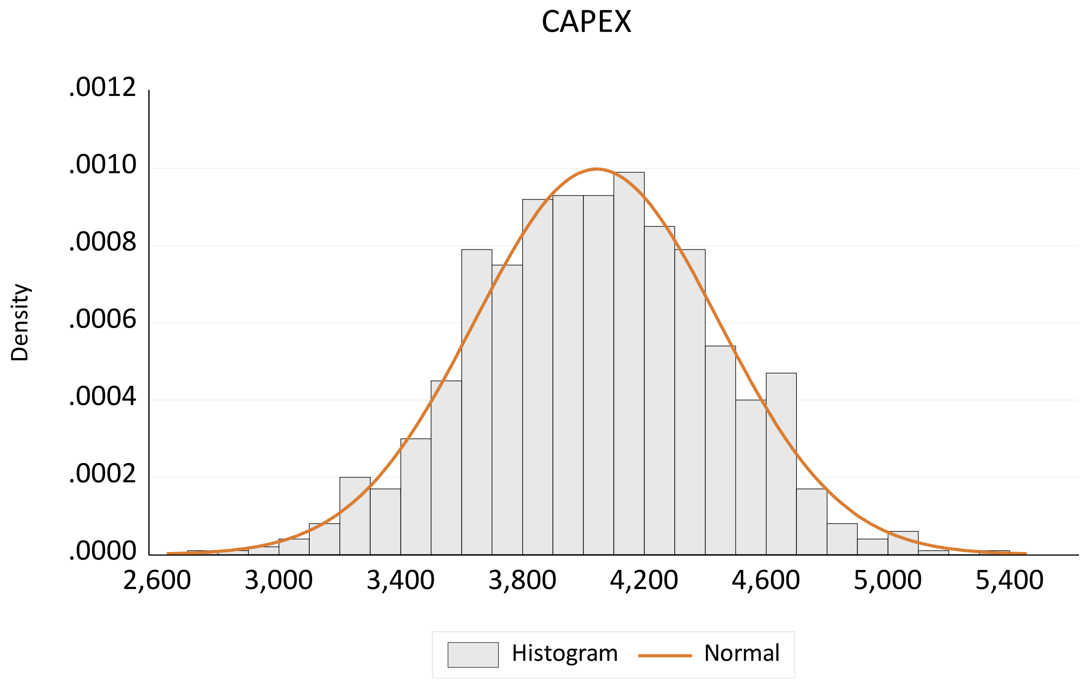
At each iteration:

- a new value of Capex is extracted from the appropriate distribution;
- yearly capital expenditures and Depreciation are computed using the deterministic model percentages;
- revenues are extracted year by year from the appropriate distribution;
- Discounted Free Cash Flow to Firm (FCFF) for each of the 16 years of the project are computed using discount rates from 10% to 50% with 1% increment;
- NPV_GO, NPV_NOGO, NPV_Weighted at 30% risk of NOGO, and profitability indexes are computed.

MONTE CARLO SIMULATION

DISTRIBUTION ASSUMPTIONS: CAPEX

Normal distribution with mean 4,044 and Std. Dev. 400

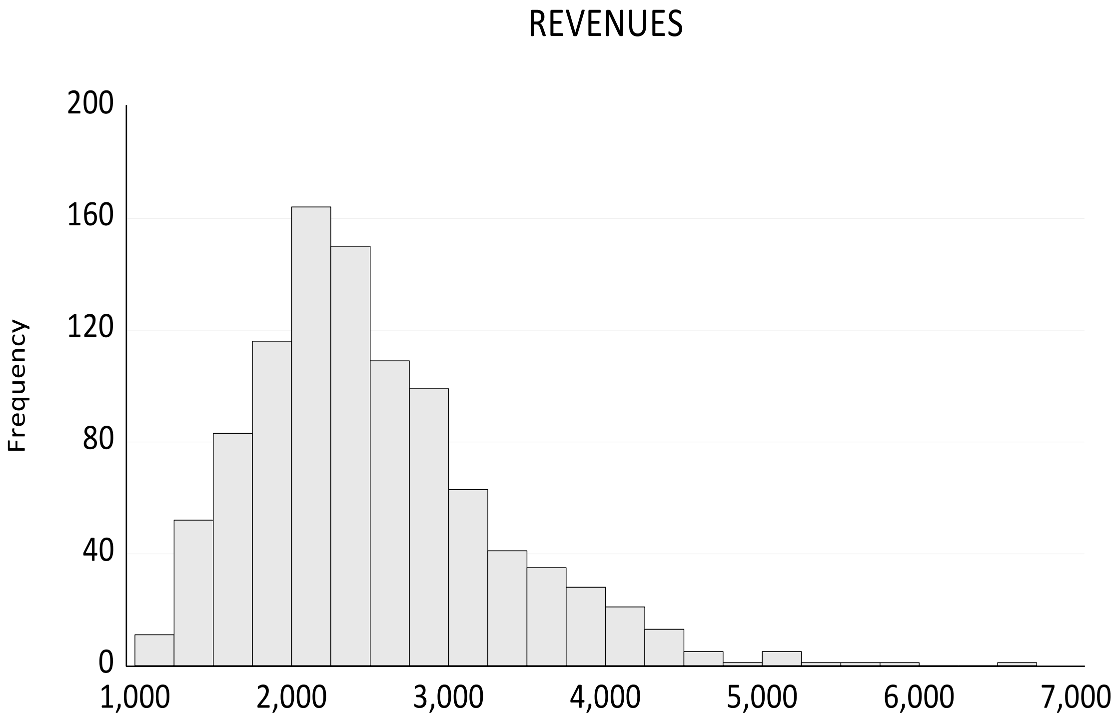


CAPEX (mln $)	
Mean	4,044
Median	4,044
Maximum	5,400
Minimum	2,700
Std. Dev.	400

MONTE CARLO SIMULATION

DISTRIBUTION ASSUMPTIONS: REVENUES

Lognormal with median = 2,430 and σ =30%

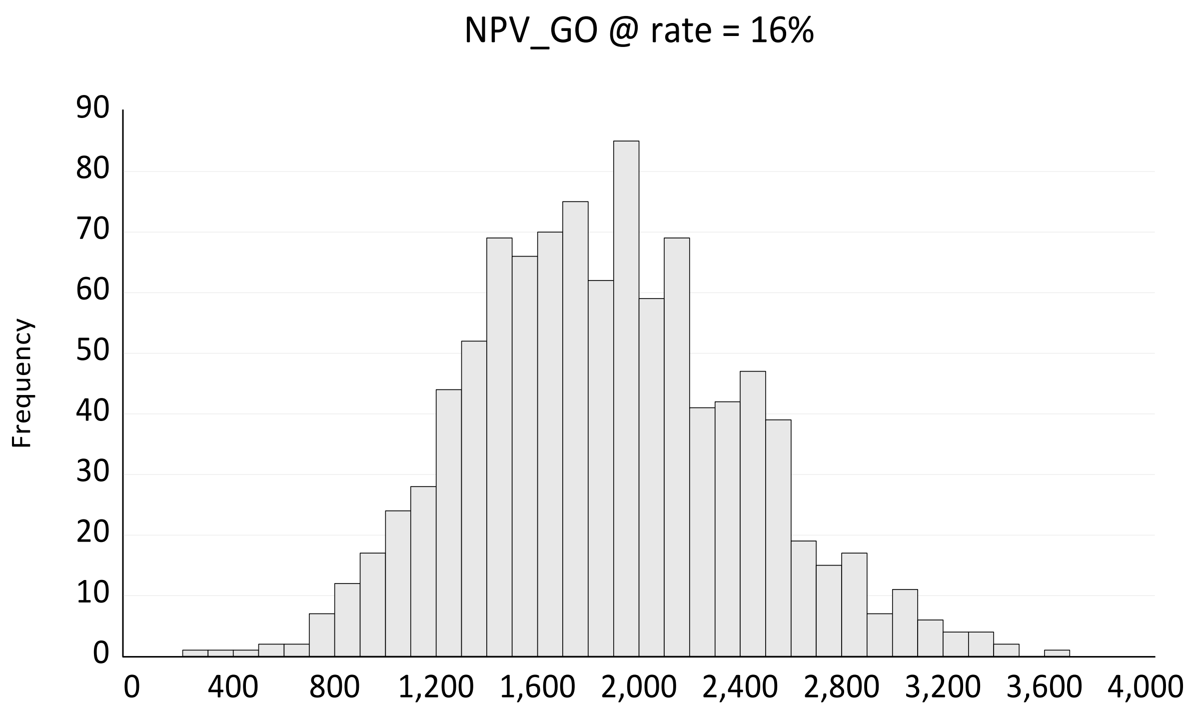


REVENUES (mln $)	
Mean	2,540
Median	2,430
Maximum	6,033
Minimum	833
Std. Dev.	761

MONTE CARLO SIMULATION

RESULTS OF SIMULATIONS

NPV_GO and its distribution



NPV_GO @ 16% (mln $)	
Mean	1,871
Median	1,850
Maximum	3,645
Minimum	290
Std. Dev.	537

Jarque-Bera	9.52
Probability	0.01

MONTE CARLO SIMULATION

RESULTS OF SIMULATIONS

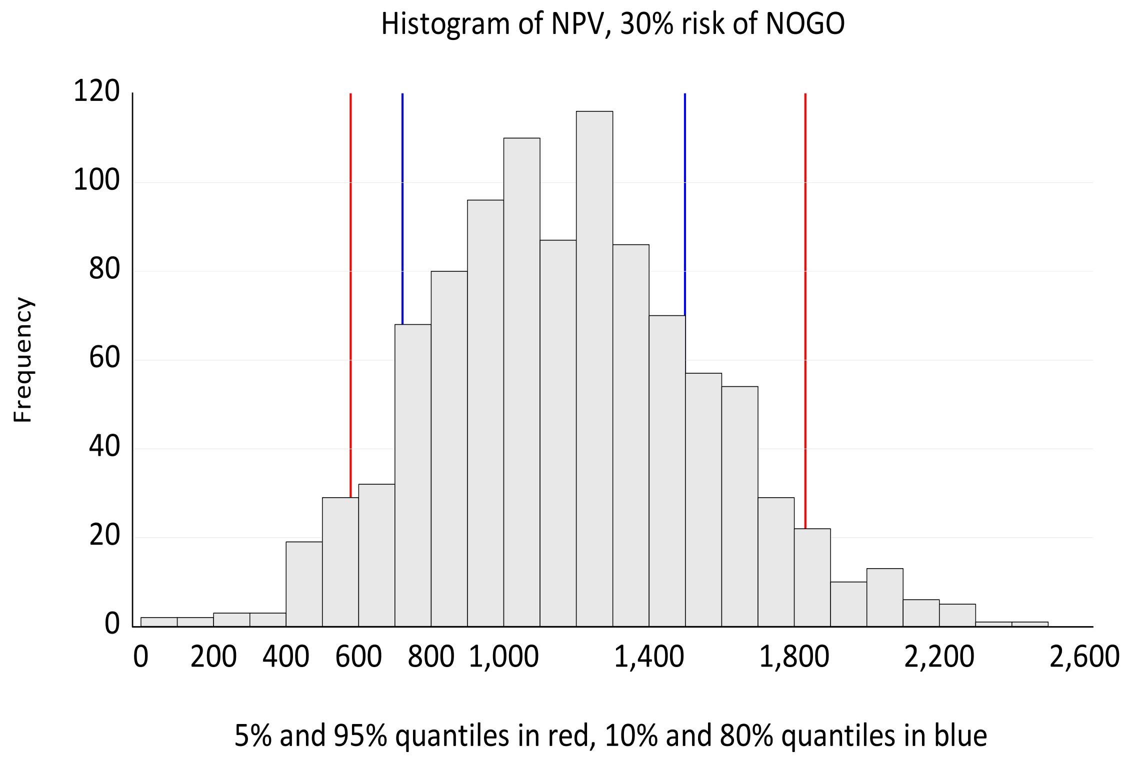
Profitability index for NPV_GO

	PI	Rate @ PI = 1
5% percentile	1.35	22%
Deterministic	1.64	26%
95% percentile	2.17	34%

MONTE CARLO SIMULATION

RESULTS OF SIMULATIONS

NPV_weighted @ 30% risk of NOGO Distribution at discount rate = 16%

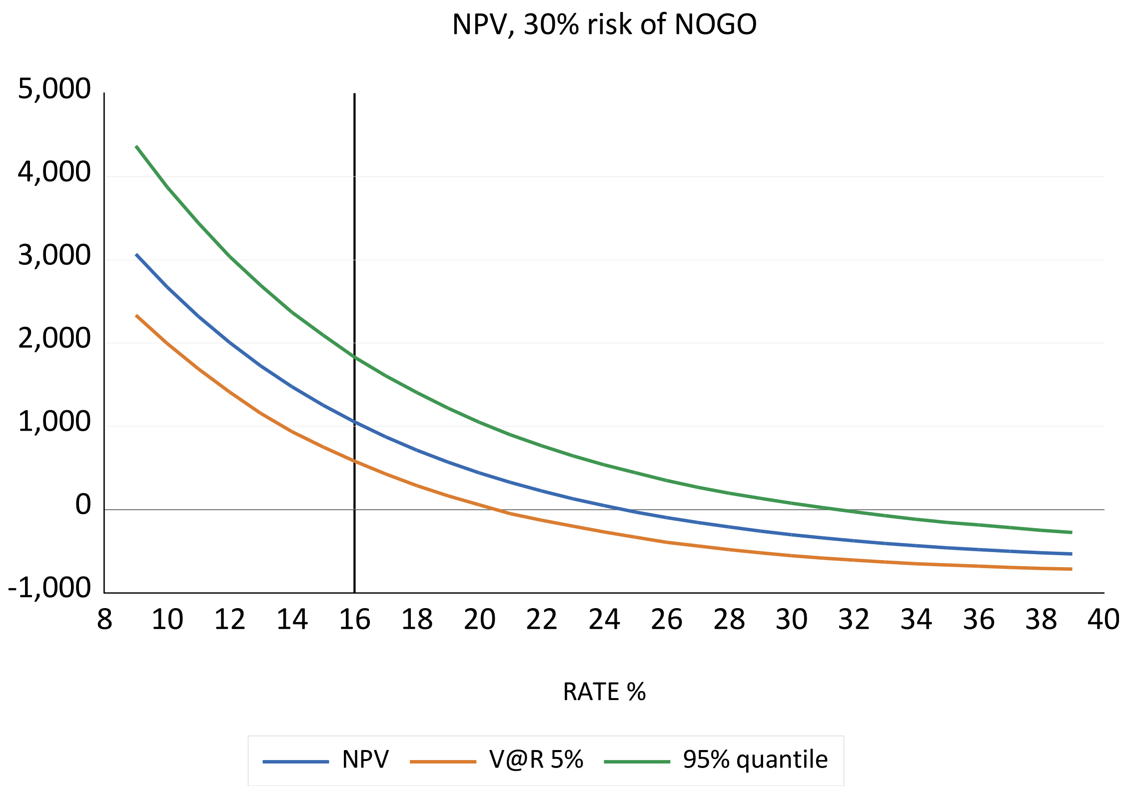


NPV 30% Risk NO GO @ 16% (mln $)	
Mean	1,179
Median	1,160
Maximum	2,450
Minimum	50
Std. Dev.	381
Jarque-Bera	8.76
Probability	0.01

MONTE CARLO SIMULATION

RESULTS OF SIMULATIONS

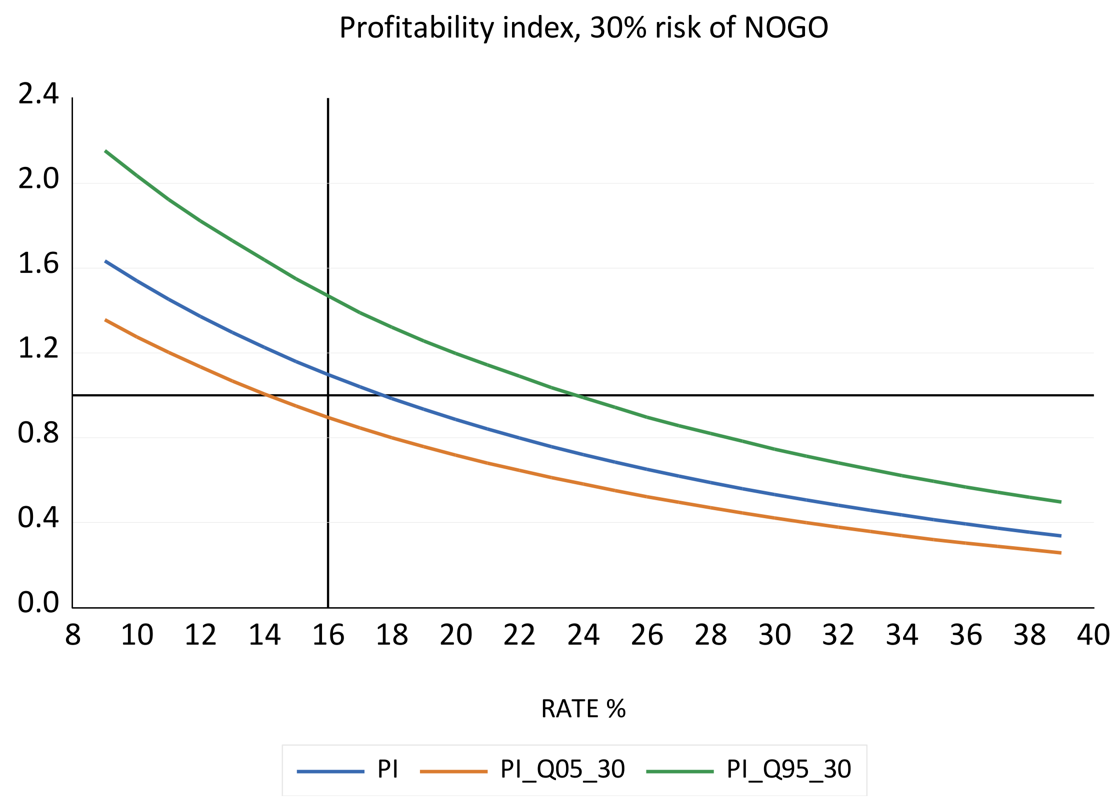
NPV_weighted @ 30% risk of NOGO



	NPV @ rate = 16% (mln $)	IRR	
5% percentile	578	20%	Lower Bound (5%) IRR
Deterministic	1,000	24%	IRR
95% percentile	1,831	31%	Upper Bound (95%) IRR

MONTE CARLO SIMULATION

RESULTS OF SIMULATIONS



	PI at rate = 16%	Rate @ PI = 1
5% percentile	0.90	14%
Deterministic	1.10	17%
95% percentile	1.47	24%

MONTE CARLO SIMULATION

REMARKS ON THE OUTCOMES

- Even in the worst scenario, the IRR equals 20% (acceptable on the Earth for alternative investments with high risk).
- The deterministic NPV is close to the median of the distribution, implying that 50% of cases have Profitability Index larger than 1.
- If there were no NO_GO risk, the project would yield a Profitability Index higher than 1 in more than 95% of cases.
- With the NO_GO risk, the project requires a diversification analysis to mitigate the risk.

CONCLUDING REMARKS

- The analysis indicates that without the presence of the three markets for propellants, the project is not economically sustainable. This implies that an appropriate PPP is based on governments investing in space infrastructures to pursue scientific and exploration goals, while the private sector invests in the development of the resources which are decisive for the success of government space missions.

- The most important problem facing an investor is an evaluation of the NO_GO risk. Adding the extraction of precious metals, such as platinum, platinum group metals, and gold to the project is a way to mitigate this risk.

- The model considers the economic perspective of the project. However, the use of appropriate financial instruments could provide liquidity and favor risk management and sharing. This is a very important aspect that should be included in the full feasibility study once the legal and contractual aspect are clarified.