Investigating Economic Potential of Asteroid Mineral Resources: A Case Study on Platinum and Water

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March 2018

A thesis submitted to McGill University in partial fulfilment of the requirements for the degree of M.Eng.

Abstract

The mining industry steps into a new age through resource extraction from asteroids. Countries and corporations have a growing interest in asteroid mining. Direct examination of meteorites and remote study of asteroids reveals mineral richness far beyond currently mined terrestrial deposits. Hence, asteroid mining firms need to account for markets where resource scarcity, stunts demand growth. Doing so avoids potential market shocks and secures the end supply chain, in turn, bringing in investors and stable prices. The thesis shows that the viability of asteroid mining in Established and Unestablished Markets is directly affected by long-term demand. Without a continued need for asteroid resources, prices drop, and the prospect is rendered unfeasible. The first exchange of goods in Unestablished Markets sets the price level, allowing the first asteroid mining firm to adjust to fast material growth without competition. As the market matures, prices drop with increasing supplies. Resolving resource constraints in markets where traditional resource extraction is not viable, is the first market barrier to the success of asteroid mining and eventually utilizing asteroid resources in Established Markets.

Résumé

L'industrie minière entre dans une nouvelle ère grâce à l'extraction des ressources des astéroïdes. Les pays et les entreprises s'intéressent de plus en plus à l'exploitation des astéroïdes. L'examen direct des météorites et l'étude à distance des astéroïdes révèlent une richesse minérale bien au-delà des dépôts terrestres actuellement exploités. Par conséquent, les entreprises minières d'astéroïde doivent tenir compte des marchés où la rareté des ressources nuit à la croissance de la demande.. Cela évite les chocs potentiels sur le marché et sécurise la chaîne d'approvisionnement finale, ce qui, à son tour, amène des investisseurs et des prix stables. Le mémoire montre que la viabilité de l'exploitation des astéroïdes dans les marchés établis et non établis est directement affectée par la demande à long terme. Sans un besoin continu de ressources d'astéroïdes, les prix baissent et la project devient irréalisable. Le premier échange de biens dans les marchés non établis fixe le niveau des prix, permettant à la première entreprise minière d'astéroïdes de s'adapter à une croissance matérielle rapide sans concurrence. À mesure que le marché arrive à maturité, les prix chutent avec l'augmentation de l'offre. La résolution des contraintes sur les

ressources dans les marchés où l'extraction traditionnelle des ressources n'est pas viable est le premier obstacle au succès de l'exploitation minière des astéroïdes et et éventuellement à l'exploitation des ressources dans dans les marchés établis.

Acknowledgements

I would like to express my gratitude and admiration for Prof. Mustafa Kumral for allowing me to partake in this research; his guidance and patience were vital in writing this work. I would also extend my thanks to Alp Bora, Tom Boushel and Amit Virmani.

Contributions of Authors

The author of this thesis is the primary author. Professor Mustafa Kumral was the supervisor of the author's Masters of Engineering degree.

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Abbreviations

AU Astronomical Unit

e Eccentricity

EPMA Electron Probe Microanalysis

CRM Critical Raw Material

FCEV Fuel Cell Electric Vehicle

GEO Geostationary Orbit

GTO Geosynchronous Transfer Orbit

ICEV Internal Combustion Engine Vehicle

ISRU In-Situ Resource Utilization

JPL Jet Propulsion Lab

LEO Lower Earth Orbit

MIT Massachusetts Institute of Technology

NEA Near Earth Asteroid

PGM Platinum Group Metal(s)

1 Introduction

1.1 Problem Statement

Nascent companies seeking to generate profits by extracting resources from asteroids are facing challenges and opportunities unbeknownst to terrestrial mining operations. Terrestrial ore bodies are finite, and the economic driver is mainly commodity price, defining the duration and feasibility of extraction. In contrast, the resource potential some asteroids infer is orders of magnitude greater than currently extracted deposits. Assuming the extraction of the entire resource at current prices will not be sufficient as resource potential of one asteroid in critical metals such as Platinum Group Metals, Cobalt and Zinc exceed total worldwide production. Therefore, the abundance of asteroid resources formulates a unique mineral macroeconomics problem in pursuing markets for asteroid mined resources.

Firms will need to seek markets limited in growth because of restricted supplies. Whereas, by obtaining a resource from an asteroid, demand will increase in response to the new supply. These markets can be already established or unestablished until the resource is mined from asteroids.

1.2 Research Objectives

- Establish asteroid population and mineralogy profile
- Assess utilisation of asteroid resources technologies
- Analyse water extraction from asteroids for use in the space industry
- Study of platinum extraction from asteroids for use in the automotive industry

The goal of this research is to determine when asteroid-mined resources are economically sustainable from a supply and demand standpoint. Doing so requires assessing resource potential of asteroids, quantifying possible market dynamic shifts as a result of added supplies, and eventually determine which end markets are most suited for asteroid mined resources.

1.3 Originality and Success

Maximizing the economic impact of asteroid resources requires looking beyond short-term price volatility “boom-bust cycles”. Firms should not anchor feasibility on price volatility. Unlike existing extraction efforts, asteroid mining cannot match the current pace of ramp-ups in production and exploration. Consequently, firms should assess the longterm feasibility of asteroid resource extraction.

Commodity prices over long periods of time are primarily demand driven; whereas, material intensive economic growth corresponds with growth in global productivity, large-scale industrialisation and infrastructure expenditure (Farooki, 2009).

The originality of this thesis rests in setting forward initial price paths for asteroid resources. The first, towards Established Markets on Earth, the second targeting resource gaps in Unestablished Markets in outer space. Resource gaps refer to the difference between a market’s current resources and the resources it will need to satisfy future needs.

If the resource path is Established Markets on the Earth, then asteroid mining firms must position themselves where they are at an advantage. In Established Markets, goods are exchanged at a prevailing price between buyers and sellers whom are free to bargain. Moreover, goods can be obtained from sources independent of the manufacturer or supplier.

Represented by a case on Platinum Group Metals (PGMs), the thesis shows how restricted supplies can impede innovation and models how asteroid resources can solve resource constraints in PGM dependent industries. More than half of extracted PGMs end up in catalytic converters for automobiles. As the automotive industry evolves, new technologies and policies put more strain on current supplies of PGMs, which can lead to an increase in price, rendering the new technologies and policies impossible to implement. Asteroid resource extraction for PGMs can potentially solve the supply constraint, maintaining the supply/demand equilibrium and nullifying potential price increases.

If the resource path is Unestablished Markets in Space, then the first firm to successfully extract essential goods will not face market competition. Unlike in Established Markets, there has yet to be the initial exchange of goods between buyers and sellers.

Moreover, independent manufacturers or suppliers have yet to emerge. Water is a crucial resource for the Space industry and will be our case study in Unestablished Markets. It has numerous uses, and the technology required in mining water from asteroids is significantly less challenging than mining base or precious metals. We show that water harvesting from asteroids is economically feasible in the short term. The success of the first few operations will lead to significant cost reductions for consumers and diminishing returns for producers.

1.4 Social Impacts and Economic Benefits

Near Earth Asteroids (NEA)s present an opportunity and a threat. The threat lies in the potential of planetary impact which can lead to global disaster. Deflecting potentially hazardous asteroids will utilise the same technologies needed for tugging asteroids to stable orbits and facilitate extraction.

Evidence from meteorites and remote spectroscopy of NEAs shows resource potential orders of magnitude higher than historically and currently extracted terrestrial deposits. Significant resource potential highlights the opportunity of asteroid mining arises from supporting long-term material sustainment on the Earth to expanding towards the Solar System.

The European Commission (2018) defines Critical Raw Materials (CRMs) as metals and minerals that "are particularly important for high tech products and emerging innovations". The commission highlights how the transition to a low carbon economy in the EU will increase demand for CRMs by a factor of 20, come the year 2030.

If asteroid mining resources are successfully retrieved and returned to Earth, there will be no concern regarding the limitation in the availability of such materials in accelerating technological innovation cycles. For example, the constricted supply of PGMs is one of the leading causes for the diminishing adoption of fuel cells in the automotive industry.

Additionally, every object placed in outer space is entirely sourced from Earth. Asteroid mining will completely transform current supply dynamics, eventually catalyzing the development and operations of in-orbit infrastructure. The significant mass requirement for construction, shielding and ballast can all be obtained from the products obtained by mining Near Earth Asteroids (NEAs). Successfully extracting and delivering water to in-orbit infrastructure, will allow a significant reduction in the cost of exploration and exploitation.

Asteroid mining removes the boundaries of resource restrictions on innovations and opens new markets that were previously deemed unattainable.

1.5 Thesis organization

This thesis encompasses five chapters:

Chapter 1 portrays the problem, its original contributions, and its socioeconomic relevance.

Chapter 2 describes the criteria for asteroid resource extraction criteria.

Chapter 3 presents the case where Platinum Group Metals extracted from an asteroid are subject to Established Market conditions.

Chapter 4 demonstrates the case where water harvested from asteroids becomes a traded commodity in an Unestablished Market.

Chapter 5 concludes by discussing which market pathway is best suited for asteroid resources and how to improve model reliability through future work.

2 Near Earth Asteroids

In the spirit of the new "Space Age," on November 10, 2015, former President Barack Obama signed the Commercial Space Competitiveness Act (Tronchetti, 2016), thereby giving private American firms the right to harvest any resource in space. With the development of a regulatory framework and incentives in place, private companies such as Planetary Resources and Deep Space Industries are now able to take the next steps towards the realization of their goals.

Socio-political implications are not the main implications facing this novel industry. Economic cost and technological advancement are the main considerations in allowing such endeavours to be feasible, sustainable and worthwhile for investors and the public. In the life of a terrestrial mine, prospecting and exploration are the first stages; it determines preliminary information on accessibility and concertation of a deposit. In the first stages, the economic viability of a terrestrial deposit is underlined by the balance between accessibility and concentration (Robertson & Blackwell, 2014). Similarly, in the case of asteroids, accessibility is derived from orbital parameters (distance, size,), that eventually determine the mining approach. Mineralogical profile (content, concentration) of the targeted asteroid population determines the processing requirement for delivering end products to their prospective markets.

2.1 Orbital Parameters

Many asteroids are found between the orbits of Jupiter and Mars within 2.0 to 3.3 Astronomical Units (AU) from the Sun. This constitutes the Main Asteroid Belt. A well-established hypothesis for the presence of asteroids in this region is the strong gravitational influence of Jupiter which prevents planetesimals (a body that could or did come together with many others under gravitation to form a planet) from amalgamating to form a planetary core (William F Bottke et al., 2002; Wisdom, 1983).

The gaps in the distribution of asteroid semi-major axis in Figure 2.1 at 2.5, 2.8, 3 and 3.3 AU, the so-called "Kirkwood Gaps", are due to orbital resonances with Jupiter. The planet's dominant gravitational influence disperses the area of asteroids. Kirkwood Gaps are thought to be one of the causes of asteroids found in regions outside the main belt. Relative to the millions of asteroids in the main belt, few are lying outside the region at 4 AU, and few others found closer, some of which are termed Near Earth Asteroids "NEAs" at less than or equal to 1.3 AU.

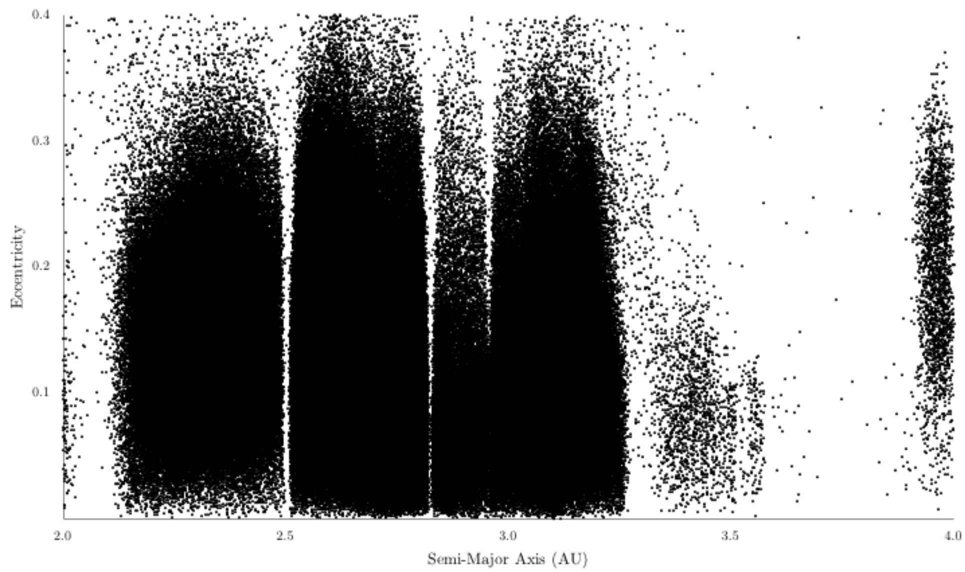

Figure 2.1 Main Belt Asteroid Semi Major Axis against Eccentricity

NEAs are further classified per their orbit and apparent composition. NEAs whose orbits cross the Earth's orbit fall into Apollo or Aten NEA categories. Those that cross the orbit of Mars and approach Earth's orbit are called Amors (see Figure 2.2)

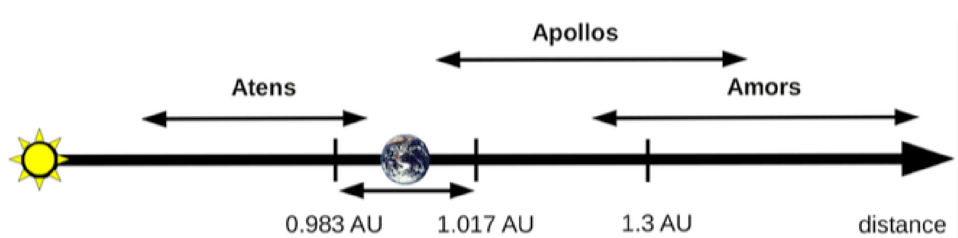

Figure 2.2 Classes of Near Earth Asteroids (Mainzer et al., 2011)

In addition to distance distributions, asteroid frequency increases with decreasing diameters. The trend in Figure 2.3 follows a size distribution comparable to a power curve (Gladman et al., 2009). For example, the largest asteroid, Ceres is four times larger than the next asteroid, Vesta, and Vesta measures half of the total mass of the smaller Main Belt Asteroids.

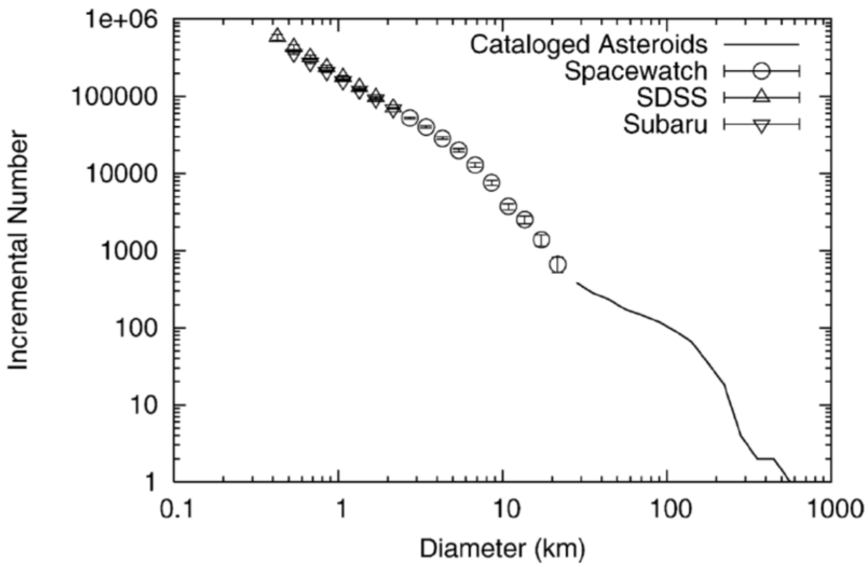

Figure 2.3 Main Belt Asteroids size distribution (William F. Bottke et al., 2005)

2.2 Accessibility and Delta V

Choosing an NEA as a target for resource extraction becomes apparent when demonstrating the relationship between accessibility and energy expense. The Jet Propulsion Lab "JPL" continuously updates a database of the necessary energy requirement for a NEA rendezvous from a Low-Earth Orbit "LEO" (Benner, 2016). LEO is the first step into Space with an altitude range between 200 and 1,200 km above the Earth's surface. The ideal rocket equation showcases the accessibility to the NEA Population. Equation (1) determines the delta v (Δv), the speed necessary to reach the chosen destination. As Δv increases the propellant mass increases exponentially (Prussing & Conway, 1993):

$$\Delta v = v_e \ln \frac{m_i}{m_f} \tag{1}$$

$$m_f = m_i e^{-\Delta v / v_e} \qquad m_i = m_f e^{\Delta v / v_e} \tag{2}$$

$$M_f = 1 - \frac{m_f}{m_i} = 1 - e^{-\Delta v / v_e} \tag{3}$$

Δv is the speed necessary to reach a target location (km/s)

M_f is the fraction of weight that is spent on fuel

v_e is the energy present in rocket propellant

m_i is the initial mass with propellant and m_f the final mass without propellant

Per equation (3), two choices ultimately govern the propellant to payload ratio. First is the choice of destination, it sets the energy investment against gravity. Δv. is a good measure of the energy investment as it represents the speed required to reach a destination. For example from LEO to the surface of the Moon and Mars, Δv is 6.0 and 8.0 km/s respectively.

Figure 2.4 is a percentile rank of NEAs as a function of Δv., The lower the Δv, the higher the rank. Δv for NEAs at $P_{99.99}$, P_{99} and P_{95} is greater than or equal to 3.8, 4.4 and 5.0 km/s respectively.

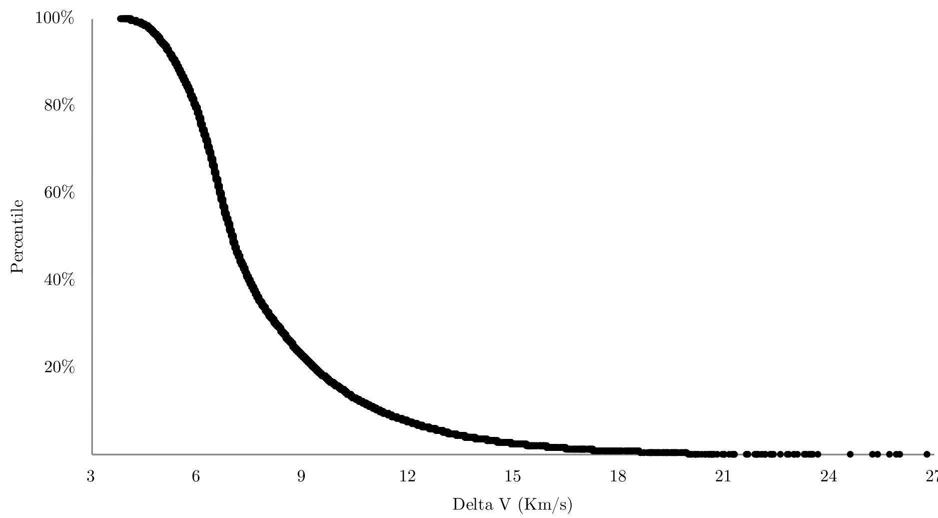

Figure 2.4 Percentile Plot of 17,000 NEAs in order of increasing ΔV

The second is energy present in the rocket propellant "v_e". Propellant refers to both fuel and the oxidizer in the engine. v_e falls in the range between 3.0 and 4.5 km/s in typical chemical rocket propellants such as kerosene-oxygen, methane-oxygen and hydro-oxygen(Sutton & Biblarz, 2017). Figure 2.5 illustrates the propellant to payload ratio from LEO to select a destination with v_e at 4.0 km/s.

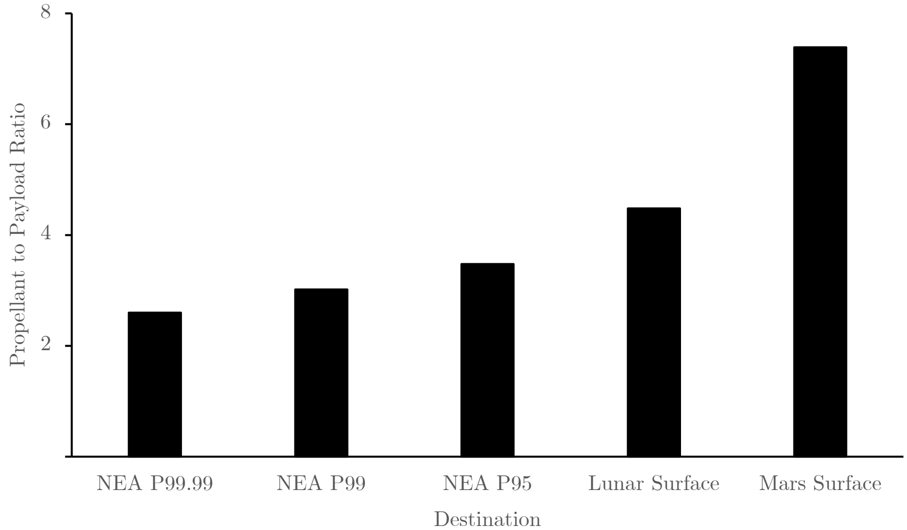

Figure 2.5 Propellant to Payload ratio from Lower Earth Orbit

Rendezvous with any of the 2,000 NEAs located at P_{95} will require half the propellant as landing on Mars, and that is without including departure from the surface of the Moon or Mars which adds $1/6^{th}$ and $3/8^{ths}$ of the energy required to leave Earth's surface respectively. With the destination in mind, the focus shifts towards NEA’s mineralogical composition.

2.3 Mineralogical Composition

The mineralogy of asteroids is not as of the surfaces of the Moon or Mars. To date, there has not been a direct sampling of asteroid regolith (loose soil) (Elvis, 2013). To infer the mineralogy of an asteroid, one can inspect meteorites (direct sampling) or analyze reflectance spectra of some asteroids (remote sensing).

Direct sampling entails identifying the mineralogy and bulk chemistry by applying traditional analytical techniques to meteorites. X-ray diffraction, electron microscope phase and oxygen isotopic analysis deliver an accurate mineralogical profile of the sample. To some extent, this permits the grouping of meteorite samples (Boynton, 1983).

The remote sampling of asteroids involves observing light from an asteroid's surface and comparing it to laboratory spectra of known minerals on Earth; it eventually allows one to infer the average surface composition of an asteroid (Gaffey, Burbine, & Binzel, 1993).

The following subsections breakdown the classifications of each method and briefly exhibit how they are used to refer to asteroid mineralogy along with their advantages and disadvantages.

2.3.1 Direct Sampling

Meteorites are small fragments of asteroids that survived entry through Earth's atmosphere and land as rocks on the Earth's surface. The introduction of electron probe microanalysis (EPMA) to the study of meteorites allowed qualitative and quantitative analysis of individual mineral grains without destroying the samples.

In 1962, there were only 38 minerals identified in meteorites, and by the late 90s, the utilization of EPMA on an increased number of retrieved meteorites raised the number to 295 identified minerals. EPMA and the related ion microbe establish accurate mineralogical profiles from meteorites (34 subtypes) (McGee & Keil, 2001). The remaining challenge is linking the samples to the parent asteroid.

Chondrites are derived from asteroids or comets that did not experience planetary differentiation. Achondrites are remains of igneous rock from differentiated asteroids and planetary bodies (Mars, Moon). Figure 2.6 displays the different meteorite classifications, whereas there are 34 subtypes of chondrites, achondrites and iron meteorites (Binzel & Xu, 1993; Gaffey, Bell, et al., 1993; Nakamura et al., 2011).

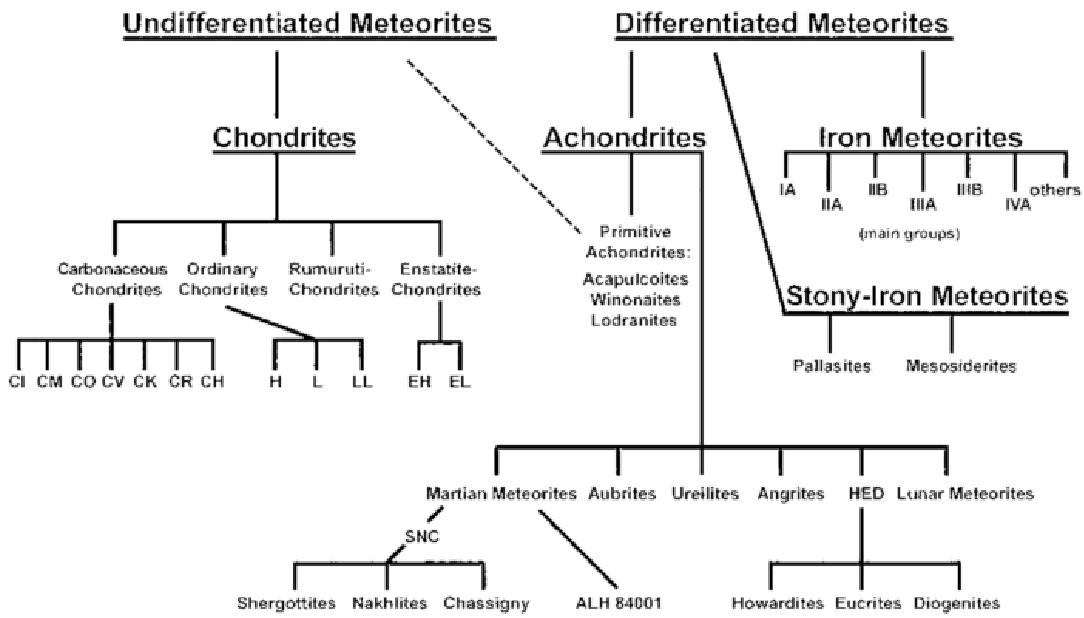

Figure 2.6 Meteorite classification chart (NASA, 2017)

Since asteroids failed to coalesce during planetary formation, the variation in class type resembles different layers of the protoplanet. It does not explain the presence of undifferentiated samples. Moreover, undifferentiated chondrites are usually porous and have low coherent strength, meteorites of this kind tend not to survive entry through Earth's atmosphere, even if a sample survives entry, volatiles evaporate. (William F Bottke et al., 2002).

Metal (% by wt. else g/tonne)	*Abundance in Metal of H-Chondrite*[a]	*Abundance in Metal of LL-Chondrite* [b]	*"Best" Iron Asteroid (90th percentile Iron Meteorite)* [c]	*Earth Crust*	*Merensky ore* [d]
Industrial Elements					
Cobalt	0.4-0.6 %	0.80 - 1.4 %	0.43-0.75 %	25	-
Nickel	8.0 – 12.0%	20.0 - 30.0%	5.4-16.5 %	120	0.13%
Iron	80%	64%	82.0-94.0 %	55,000	-
Critical Elements					
Ruthenium	5.8	17.8	21.5	0.001	0.44
Rhodium	1.1	3.3	4.0	0.001	0.17
Palladium	4.5	14.0	16.5	0.015	1.38
Osmium	3.9	12.1	14.5	0.0015	0.04
Iridium	3.9	12.0	14.0	0.001	0.06
Platinum	8.0	24.7	29.0	0.0005	3.25
Gold	1.1	3.5	0.6	0.004	0.18
Sum	28.3	87.4	100.1	0.024	5.52

Table 2-1 Mineral Richness from meteorites, Earth Crust and an orebody

[an] H-Group: High Iron Content (approx. 36% of Chondrites, 75% of meteorites are Chondrites)
[b] LL-Group: Low Free Iron, Low Free Metal (approx. 2% of Chondrites), LL are more oxidized, making free metal less abundant but PGMs and Gold are harder to oxidize, making them more concentrated.
[c] Abundance of PGMs in Iron Meteorites correlate linearly with Nickel and inversely with Gold, average iron meteoritic contains 2 ppm IR and richest contains 55 ppm which correlates to PGM richness, at 90th percentile is about ¼ as rich. g/tonne = ppm (Kargel, 1994)
[d] 80% of World PGMs comes from three orebodies in South Africa. One of the mined strata is known as the Merensky Reef, PGM + Au content ranges between 4 and 10 g/tone (R. Jones, 1999)

Table 2-1 shows the concentration of industrial and critical elements for chondrites and iron meteorites. Whereas critical metal concentration is an order of magnitude higher than currently mined deposits. Moreover, the mineralogical profiles in Table 2-1 are more diverse in industrial metals than any terrestrial deposit.

Meteorites differ significantly in density and mineralogy, it dates to the origin of asteroids, whereas geochemical analysis of differentiated meteorites shows the particular grouping of elements following the path of protoplanets where high heat and pressure separated heavy and lighter elements (Britt, Yeomans, Housen, & Consolmagno, 1987; Carry, 2012).

Direct sampling of meteorites delivers accurate mineralogical profiles. The population of directly sampled meteorites is orders of magnitude lower than the total asteroid population. Remote sensing plays an essential part in understanding the distribution of different asteroids classes.

2.3.2 Remote Sampling

Asteroid spectroscopy offers insight into a much larger population. Meteorites are merely a fraction of asteroids found in the solar system. However, the chemical bonds in minerals of asteroids absorb light at different wavelengths resulting in a reflectance spectrum.

Almost all asteroid spectroscopy is done in the visible and near-infrared (VNIR) region of the electromagnetic spectrum (0.4 µm to 2.5 µm). Larger telescopes and spacecraft can access another area of the electromagnetic spectrum, such as thermal infrared and radar. Conversely, spectral and photometric measurements at different wavelengths (Ultraviolet (UV) to Infrared (IR)) allow inferring of surface properties of an asteroid, such as mineralogy, the extent of space weathering, grain size (Burbine, 2015; DeMeo, Binzel, Slivan, & Bus, 2009; Tholen, 1989).

Larger datasets and improvements in measurement accuracy helped expand asteroid spectroscopy classification from Tholen's (1989) to Bus and Binzel (2002). Currently, the planetary spectroscopy group at MIT classify objects with DeMeo et al. (2009), the taxonomy in Figure 2.7 identifies three complexes and nine end members. The lines shown represent the different absorption bands that resemble a specific grouping of studied asteroids.

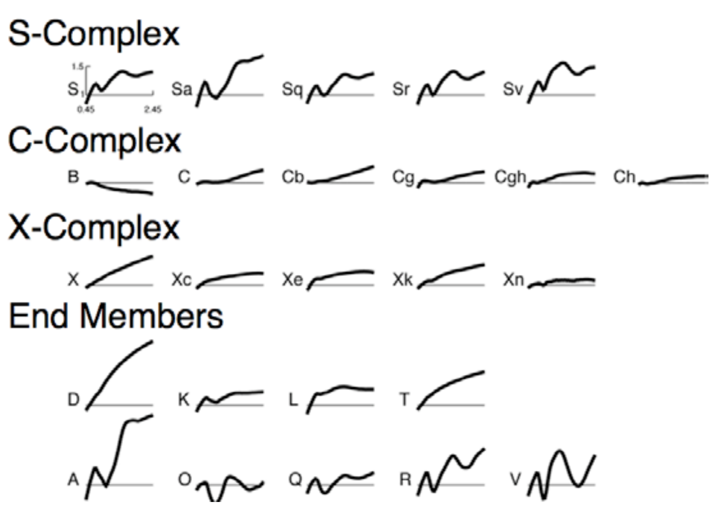

Figure 2.7 Bus-Demeo Taxonomy Key (DeMeo et al., 2009)

The three main complexes (C, S and X) of DeMeo et al. (2009) are the same as the main groups in the previous taxonomy iterations. C-Complex asteroids get their name from their connection with carbonaceous chondrites. C-Complex asteroids are the most common type of asteroids (75%). They are rich in volatiles and are frequently mentioned in literature as a possible source of fuel for Space bound craft (Farquhar et al., 2002). C-Complex asteroids are less dense and more porous than S and X Complexes (Britt et al., 1987). This entails low cohesive strength, a property that eases breaking, handling and processing of regolith.

Establishing a detailed mineralogical description of C-Complexes is difficult due to scarce and low absorption in the reflectance spectra. Low absorption in the reflectance spectra is linked to hydration features which relates to the hydration effect of aqueous alteration present in CI and CM chondrites.

S Complexes (S, Sa, Sq, Sr, and Sv) initially stand for siliceous composition, along with Q class, which have been successfully linked to meteorites. The absorptions in the spectra were familiar, and the Hayabusa spacecraft confirmed the association (Badescu, 2013).

X-Complexes do not have prominent absorption bands with some weaker ones identified. The connection to meteorites has been widespread. The variation in X Complexes is more profound than in S and C Complexes. X-Complexes of asteroids have somewhat of an undefined spectrum (Elvis, 2014a). This variation is also prominent in density estimates, where X-Complex asteroids cover a wide range of densities with Xc having the highest density of 4.9 g/cm^3(Carry, 2012).

A subset of X-class is M type asteroids. Mazanek et al. (2015) suggest that it contains PGMs, elemental metals (Ni-Fe) and metal oxides. Elvis (2014) shows a study of PGMs in meteorites linked to this subclass, where 10% of the M-type asteroids have >100 ppm PGM. In contrast, to terrestrial mines having concentrations of 2-6 ppm. Rough estimates show PGM rich asteroids can constitute $1/2000^{th}$ of the NEA population.

Asteroid spectroscopy can provide an essential link between meteorites and their corresponding asteroid population. Burbine (2015) lists setbacks in using spectroscopy for asteroid classification. One is that the absorption bands do not represent abundance as bands overlap and are influenced by multiple time-sensitive factors such as temperature. Also, space weathering (solar flare, cosmic rays) play a role in altering the band absorption. Furthermore, the accuracy of spectral classification depends on the number of observations of a single object.

The quality of data increases with more readings, yet there can be intrinsic differences as most asteroids are not uniform in their mineralogical composition at different areas of their surface.

2.4 Extraction and Processing Technology

The following subsections detail the limitations in different extraction approaches and technologies required to separate and process asteroid resources. Asteroid physical parameters, targeted commodity and end users, all influence the choice of approach, extraction and processing.

2.4.1 Extraction Approach

J. R. Brophy and Oleson (2012) listed three approaches for mining asteroids:

I) On asteroid mining, processing and the return of only processed material.

II) Only mining at asteroid with the return of unprocessed ore.

III) Return an entire small asteroid for processing.

Asteroids can be placed possibly at Earth/Moon L1 and L2 Lagrange points with the preferred position being by the Moon's orbit (Figure 2.8).

Another approach would be to IV) Mine and Store for upcoming Life-Support resupply rendezvous (Taylor, Kistler, & Citron, 2009).

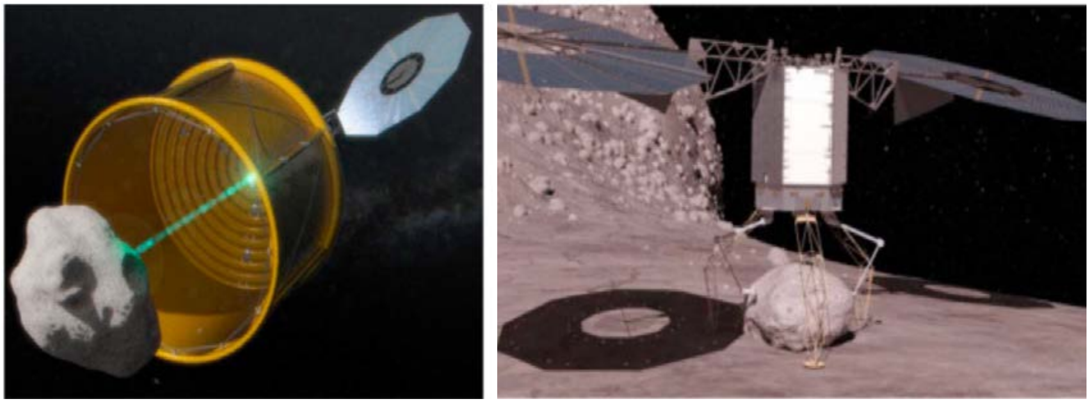

Figure 2.8 Asteroid recapture approaches (Mazanek et al., 2015)

Figure 2.9 illustrates furthermore how the diameter of the targeted NEA determines the mining approach. NASA's Asteroid Redirect Mission (ARM), showed the technological capability of tugging a 7-meter asteroid to cis-lunar orbit (J. Brophy et al., 2012). Others followed suit by expanding the capacity of the mission, from 7-meters in diameter to 12-meters (Benner, 2016; J. R. Brophy & Oleson, 2012; Mueller, Sibille, Sanders, & Jones, 2014).

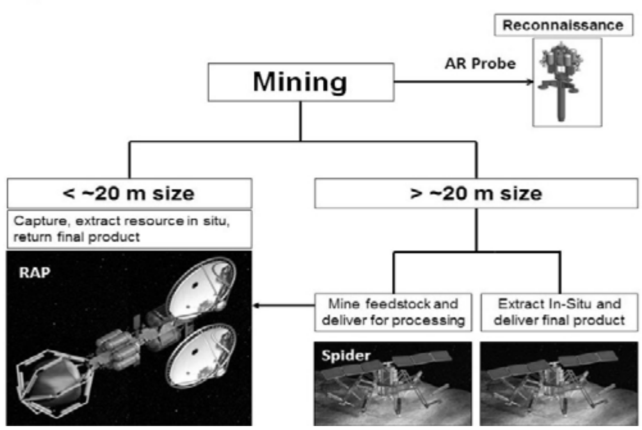

Figure 2.9 Asteroid diameter and extraction approach (AIAA: 2013)

2.4.2 Acquisition and Beneficiation

Resource acquisition requires that the extraction machinery be able to withstand extreme conditions. One condition is low gravity: to solve it, either the mining equipment scales up to overcome it or excavation forces are reduced dramatically (Mueller & Van Susante, 2012). However, launched mass is a crucial component in determining the feasibility and the viability of all space-bound missions, hence, literature is abundant with work on reducing excavation forces (Table 2-2).

Concept/Method	*Workings*	*Comments*
Pneumatic mining device	Lightweight and effective excavation	Requires consumable gas
Percussive excavation	90% reduction in excavation forces	Allows scalable operation
Small Scoops	Bucket ladder Bucket wheel devices	NASA CSA tested LHD designs
Bucket Drum Excavator	Stacked bucket wheels with carrier for container	Efficient but requires traction
Auger Based Drilling	Multi-Purpose volatile	Tested on frozen arctic soils
Counter Rotating Bucket Drums	Counter-rotating buckets drums on a bi-stability platform	Zero net reaction force (fixed traction and exaction problem)

Table 2-2 Concepts to reduce extra-terrestrial mining excavation forces (Mueller & Van Susante, 2012)

Severe temperature fluctuations add another layer of difficulty to extraction efforts. Zacny et al. (2012) proposed a drilling approach similar to ones applied in the Arctic and Antarctic, where iced - soils under extremely low temperatures can be stronger than concrete (Figure 2.10).

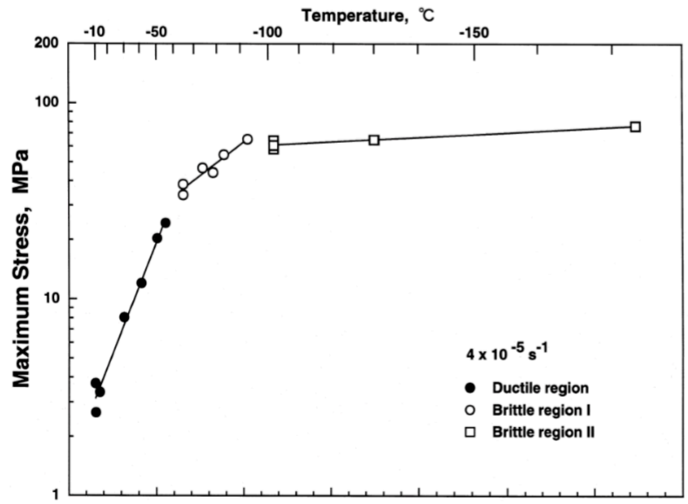

Figure 2.10 Strength of frozen soil (Arakawa & Maeno, 1997)

From arctic drilling observations, Zacny et al. (2012) introduced an auger based excavation approach which is directly linked to the extraction plant. Ice sublime can be fed directly into the system and not be stuck in transportation enroute to the processing facility. Figure 2.12 shows how auger based drilling was further conceptualized for asteroid use by T. Jones et al. (2011).

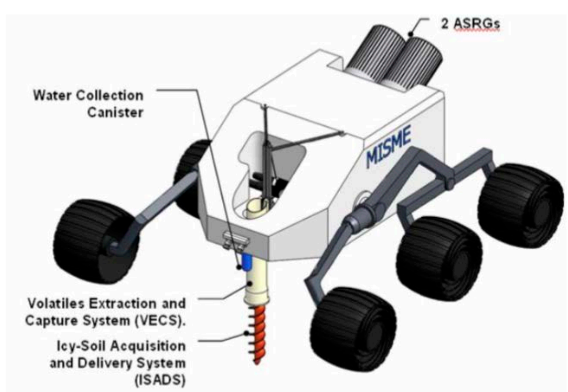

Figure 2.11 Conceptual in-situ water extractor (Zacny et al., 2012)

Figure 2.12: Auger drilling for the mission to Amore NEA.

Drilling and excavating machinery need to anchor to the asteroid's surface safely. NASA's Microspines in Figure 2.13 show proof of the concept of possessing the capability to grasp irregularly shaped boulders in micro-gravity.

Figure 2.13 Testing of Microspine prototype (Merriam et al., 2016)

Dust from excavation efforts is another condition extraction machinery need to overcome. The backbone of drilling and extraction efforts is advanced autonomous robotics and machine intelligence. Table 2-3, (Mueller and Van Susante (2012), Hyatt and Straka (2010)) list the major challenges and potential resolutions in mining resources from asteroids.

Challenge	Technology Development Area/ Possible Solution
Low Gravity	New mining techniques and devices (Microwave assisted counter rotating drum)
Operating in regolith dust	Electro Dynamic Dust Shield Lotus Coating SPARCLED[1] CO_2 Shower
Fully autonomous operations	Advances in fields of self-driving vehicles and new propulsion technologies
Unknown water ice/regolith composition and deep digging	Asteroids specific space-bound missions Linking meteorites to asteroids
Grappling /De-spinning	Microspines

Table 2-3 Potential solutions to challenges facing an asteroid mining operation. (Mueller and Van Susante (2012), Hyatt and Straka (2010))

2.4.3 Going beyond conventional

Innovation will play an essential role in tackling operational constraints. For example, one way to reduce extraction force is by a combination of microwave and mechanical energy. However, additional power is required for microwaves to assist in drilling. Further work is required to assess the power needed versus the amount of excavation (Satish, Ouellet, Raghavan, & Radziszewski, 2006)

[1] Space Plasma Alleviation of Regolith Concentrations in Lunar Environments by Discharge

Other concepts do not consider disturbing the regolith; Figure 2.14 shows how Planetary Resources (2016) is devising the extraction of volatiles. If target resource is in ice form, then extracting and crushing the regolith to liberate the resource might not be the only way to retrieve it. If the parent body is porous enough then encapsulating, and heating it with sufficient radiation will liberate the liquefied ice seeping out of the parent body.

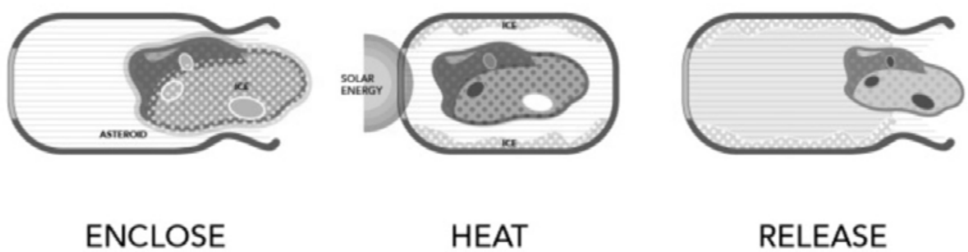

Figure 2.14 Asteroid Microwave Heating (Planetary Resources, 2016)

Klas et al. (2015) proposed the incorporation of *extremophiles* (microbes that can survive extreme chemical and physical conditions). The authors' preliminary analysis points to the possibility of generating methane gas on C-Complex asteroids. However, the harsh climate of Space and need of water for the survival of microbes puts the incorporation of biotechnology behind other researched avenues.

2.4.4 Processing Regolith

After acquisition and beneficiation, a feed supply moves to a processing application. Processing will utilize reduction, followed by the refining of the desired raw materials and purification to the required level, all of which requires on-site power.

Three primary asteroid resources are applicable for commercial and in-situ resource utilization "ISRU" use:

1. Regolith
    a. Oxygen from mineral oxides
    b. Iron, Nickel, and PGMs.
2. Water and other volatiles in the regolith
3. Bulk material for radiation shielding and construction

Resources of main interest according to NASA (2016) are Oxygen, Water, Hydrogen, Carbon/CO_2, Nitrogen, Metals and Silicon.

The reduction will encompass the removal of O_2 from any oxides. Each asteroid will differ in composition with different elements breaking their bond(s) with O_2. For example, an S-complex asteroid will have Si-O_2 bonds, which with proper separation and purification, the metal by-product remains beneficial. Multiple authors (Hepp et al., 2014; Moses & Bushnell, 2016; Zacny et al., 2012) list ways to reduce extra-terrestrial regolith.

i) Magma Electrolysis: theoretically the most straightforward method to reduce broken material into reduced metals and liberated oxygen. The process institutes heating the regolith up to its melting point (1300 °C) and then running a current of electricity through the melt, electrolyzing the anions at one electrode and cations (Si and Metals) at another.

ii) Calcium Process: two-step process that requires substantially lower temperatures than magma electrolysis and is more efficient in reducing oxides than H_2 or carbon thermal reduction processes.

The process involves heating of regolith with metallic calcium, converting silicate into metals along with Calcium Oxide.

$$MgFeSiO_4 + 4Ca \rightarrow 4CaO + MgFeSi \qquad (4)$$

The Calcium oxide is heated to 825 to 900 °C to produce metallic Calcium and oxide.

$$CaO \rightarrow Ca\ (metal) + \frac{1}{2}O_2(gas) \qquad (5)$$

More separation and purification steps will be required to produce a refined ready to use the product.

ii) Fluorine Process: in the presence of fluorine, regolith is heated displacing O_2 from the rock and producing Fluorides. The Fluorides can be displaced with Potassium. This will produce reduced metals and Potassium Fluoride (KF) which is later electrolyzed.

$$FeF_3 + 3K \rightarrow 3KF + Fe \qquad (6)$$

$$AlF_3 + 3K \rightarrow 3KF + Al \qquad (7)$$

In conclusion, the exact chemistry and mineralogy of a targeted asteroid are required to lay out the process architecture of handling the regolith fully. Moreover, simple processes that take place on Earth will be impossible to replicate with the given conditions on asteroids.

Extraction	Method/s
Oxygen from Minerals	Hydrogen Reduction of Iron Oxides Methane Reduction of Silicates Molten Oxide Reduction
Metals from Minerals	Molten Oxide Reduction Ionic Liquid Acid Biological Extraction

Table 2-4 Processing Routes for Asteroid Regolith (Moses & Bushnell, 2016)

2.5 Resource Extraction Criteria

Terrestrial mining considers accessibility before feasibility. With that in mind, potentially viable asteroids for mining are narrowed down by suggesting that the energy required to reach one should be lower than the energy required to reach and/or the Moon and Mars. In contrast, delta-v for transferring from Low-Earth Orbit to rendezvous with the Moon and Mars is 6.0 km/s and 6.3 km/s respectively (J. R. Brophy & Oleson, 2012). There are over 2,000 NEAs with $\Delta v < 5$ km/s.

If asteroid mining is to take place in the short term, X-Complex and L-Class asteroids are likely the most economical (Elvis, 2014b), as L-type is considered to contain considerable amounts of aluminum and X-Complex's different density is a strong indication of PGMs. Since there is no exact measurement of asteroid mineralogy, Burbine (2015), estimates of materials tend to be exaggerated. The key in commercial asteroid mining will be minimizing the cost per unit mass of material return to the point of use. This is not the only type of asteroids that have economic potential; there is a significant demand for volatiles (water) in Space. For mining approach, NEA retrieval reduces the time between payload delivery, but onsite mining can make use of economies of scale in justifying delays between payloads.

Table 2-5 lists asteroid resource extraction criteria. The list shows how to narrow down the selection process initially. It requires knowing the targeted commodity and then finding the best suitable characteristics. The objective is to provide enough information on potential NEA candidates to warrant prospecting. Reliable physical and mineralogical profile can only be accomplished by directly prospecting asteroids.

Category	*Resource Extraction Criteria*
Distance & Distribution	Near Earth Asteroids (Apollo, Aten or Armor) ≤1.3 AU
Propulsion System	Non-Continuous Thrusting Ion Rock Propulsion Solar Electric
Classification	For Critical Metals: Remote: X-Complex (X, Xe, Xk, Xc) S-Group Direct: LL Chondrite For Volatile Extraction: Remote: C-Complex Direct: CI or CM Chondrites
Delta-v	P95: Less than or equal to 5.0 km/s
Diameter	Asteroid Retrieval ≲ 20 m Asteroid Mining ≳ 300 m
Upcoming Close Approaches	Less than 30 years

Table 2-5 NEA resource extraction criteria

3 Established Market: Platinum Group Metals

In this chapter, a long-term demand and supply forecast demonstrate the impact of a new supply of PGMs in an Established Market. In such markets, goods are exchanged at a prevailing price between buyers and sellers whom are free to bargain. Moreover, goods can be substantiated from sources independent of the manufacturer or supplier. If PGMs are successfully mined from an NEA and delivered to an Established Market, the added supply will interact with pre-existing market conditions. The prevailing market price will adjust accordingly, and the adjustment in price will determine if the new supply can compete with established sources, which showcases whether obtaining PGMs from asteroids is feasible or not.

The chapter concludes by showing how limited PGM supply makes the mass adaptation of novel technologies implausible. Nonetheless, if there is a new independent stock of PGMs such as from an asteroid mining operation, adaption at current and eventually lower prices becomes feasible for producers and consumers. Such circumstances are where asteroid resources demonstrate their significant potential in an Established Market.

Long-term demand and supply forecasting of metals require full knowledge of the forces behind total market demand. Most notable of Platinum Group Metals are platinum, palladium and rhodium. They share similar characteristics and are used interchangeably depending on market conditions.

Over 95% of PGM primary production is platinum and palladium. Palladium has been substituted for platinum in most gasoline-engine catalytic converters because of the historically lower price for palladium relative to that of platinum. Approximately 25% of platinum can routinely be substituted for palladium in diesel catalytic converters; the proportion can be as much as 50% in some applications.

For some industrial end uses, one PGM can substitute for another, but with losses in efficiency. PGMs are a vital component that can unlock innovation and drive future demand drawn from new industries. However, significant resource restrictions along and a fragile supply chain, cast away innovative technologies that depend on PGMs.

PGM supply is an oligopoly and decades of records to which multiple industries contribute to, provide valuable insight into the supply chain of PGMs. Table 3-1 highlights the steps in assembling information regarding the PGMs and analyzing its forecast drivers for long term predictions.

Steps required for the total-market forecast	**Details**
1st Define the market	Primary Production: Oligopoly Mining (90% from two regions) Secondary Production: Recycling
2nd Divide total demand into main sections	Two Major components (Automobile, Jewelry and others)
3rd Forecast drivers of demand in each section	Jewelry/other: demand is linear with around 110 tonnes continually increasing Automobile: demand depends on specific scenarios draw from current regulation and taxation on emissions
4th Sensitivity Analysis	Assume that the automobile industry is the primary driver of change in Pt demand and that from historical data other sectors remained relatively constant in their increasing demand

Table 3-1 Four Steps to Forecast Total Market Demand (Barnett, 1988)

3.1 Define the Market

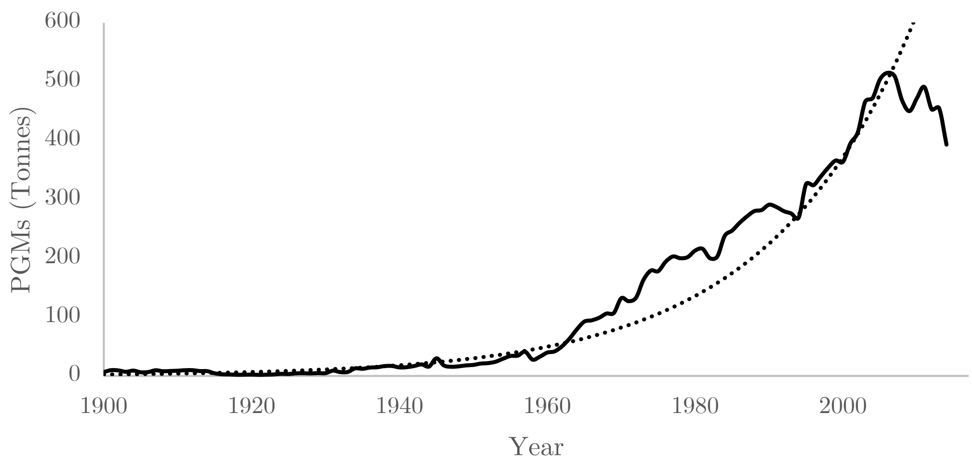

Figure 3.1 Annual PGM primary production from 1900 to 2015 (USGS, 2016)

The development of new analytical techniques in the 1960's allowed the identification of PGM deposits at low concentrations. New regulations implemented in the US and Japan required the placement of catalytic converters in each combustion engine vehicle sold.

The combined effect of enhanced discovery and increased demand lead to a substantial increase in infrastructure development and exponential growth until the financial crisis of 2007-2008. Nowadays, around 90% of the world's PGM originate from South Africa (80%) and Russia (10%). Other countries such as Canada, the United States and Zimbabwe contribute to the latter (Hilliard, 2000).

In the case of PGMs notably platinum, (1) geological restriction (2) non-primary actors and (3) fragility of the supply chain, have a direct impact on price (Sommariva, 2015).

A recent example was in 2008, where an electrical outage in South Africa's primary platinum operation, ceased all operations for two weeks and lead to a price increase of 4%.

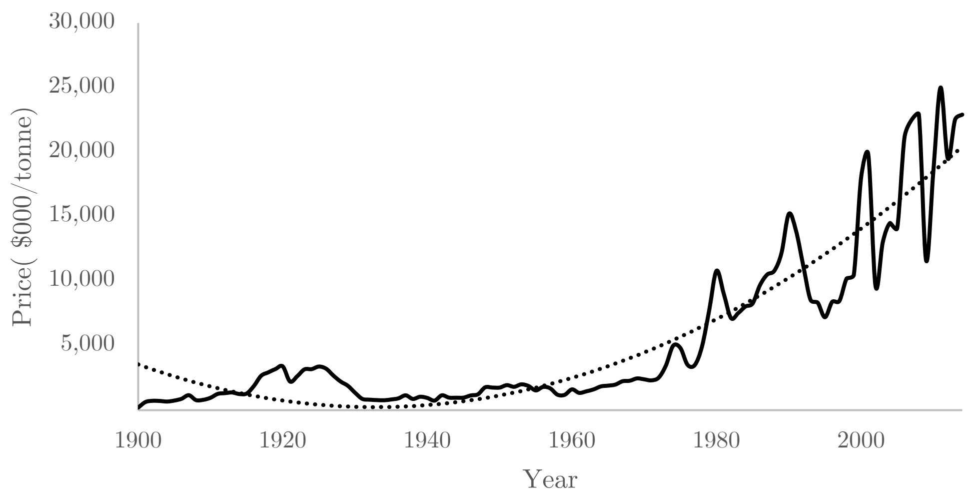

Figure 3.2: Inflation adjusted platinum price per kilogram of platinum (USGS, 2016)

The principal use of platinum is in the catalytic converters of automobiles and light trucks, where it reduces the carbon monoxide, unburned hydrocarbons, and nitrogen oxides in exhaust gases to levels acceptable by national standards (Figure 3.3).

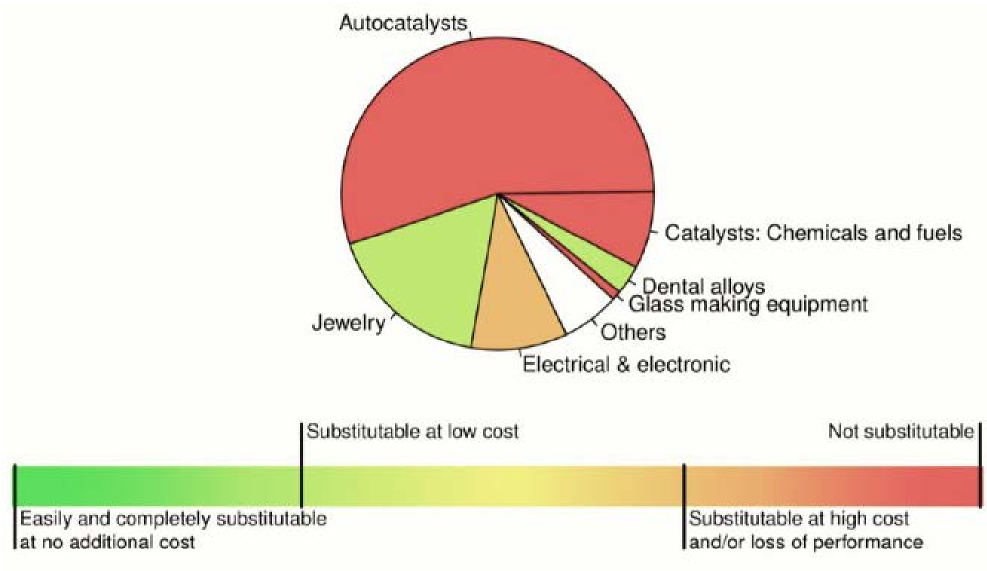

Figure 3.3 Uses of platinum and substitution potential (Association, 2013)

Figure 3.4 shows the division in platinum demand between automotive and non-automotive (jewelry, chemicals, electronics and other). A fair assumption to make is that recycled content solely originates from the automotive industry.

Recycling takes place in areas where platinum cannot be easily substituted, i.e. autocatalysts and industrial catalysts. In industrial settings, Platinum is recycled for use back in the same operation. However, Recycling of autocatalysts is independent of the manufactures, and the transaction occurs in a defined market which in turn reduces Platinum demand from primary sources in the automotive sector.

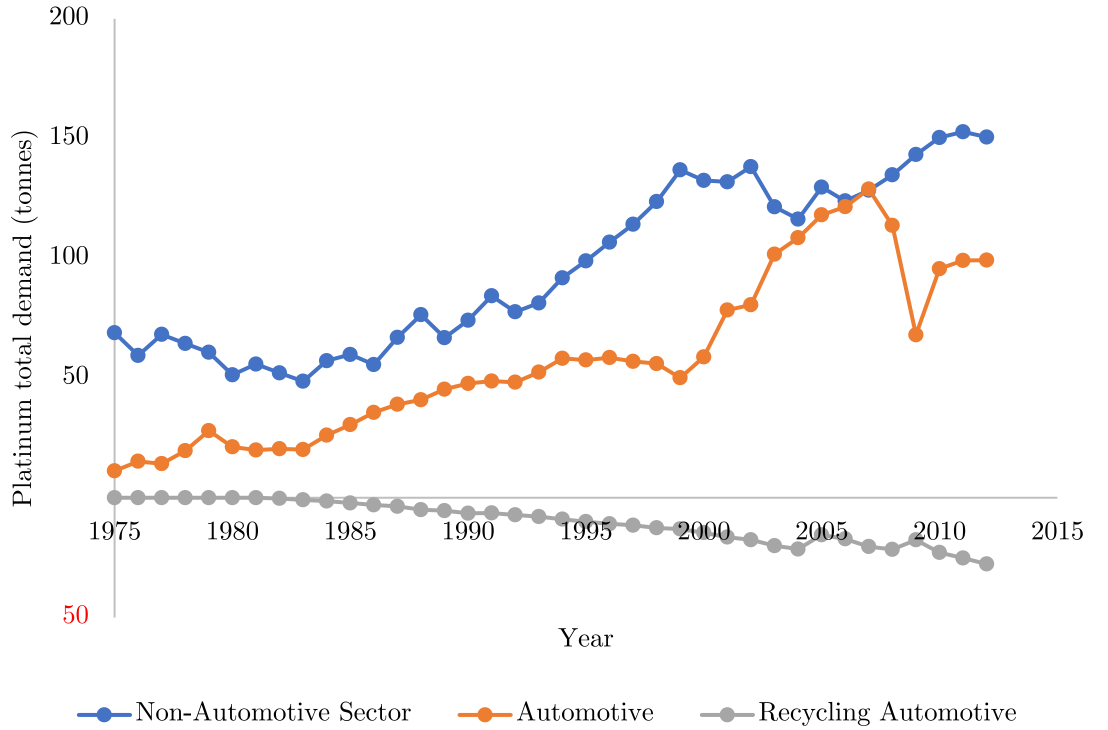

Figure 3.4: Platinum demand and recycling from 1975 to 2012 (USGS, 2016)

To estimate long-term platinum demand, consumption equal to total demand is split into three sectors: Non-automotive, automotive and recycling from automotive.

3.2 Divide and Forecast scenarios

3.2.1 Non-Automotive demand

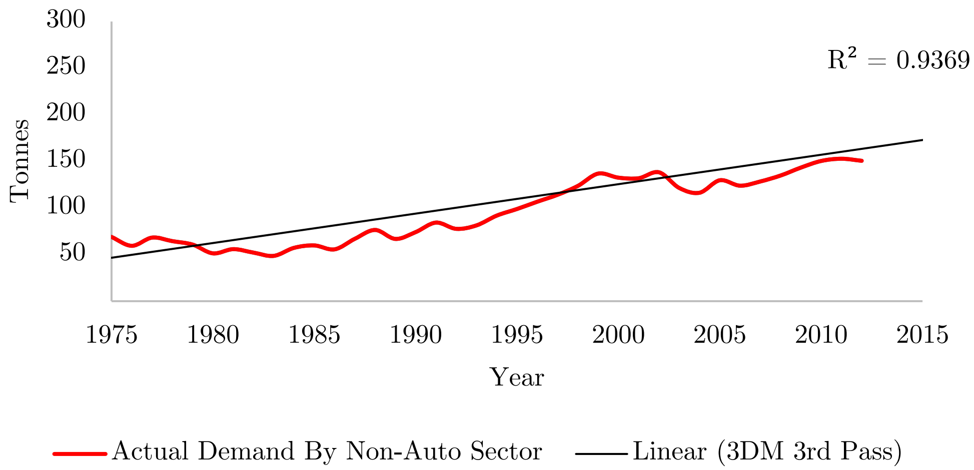

Figure 3.5 Platinum Demand by Non-Automotive Sectors from 1975 to 2012

Figure 3.5 indicates that demand for Platinum from 1975 till 2012 is linear, the indication is adequate to warrant the use of the trend line to draw the long term non-automotive sector demand. The estimation assumes non-automotive demand maintains similar linear growth as that of 1975 until 2014 (Figure 3.6).

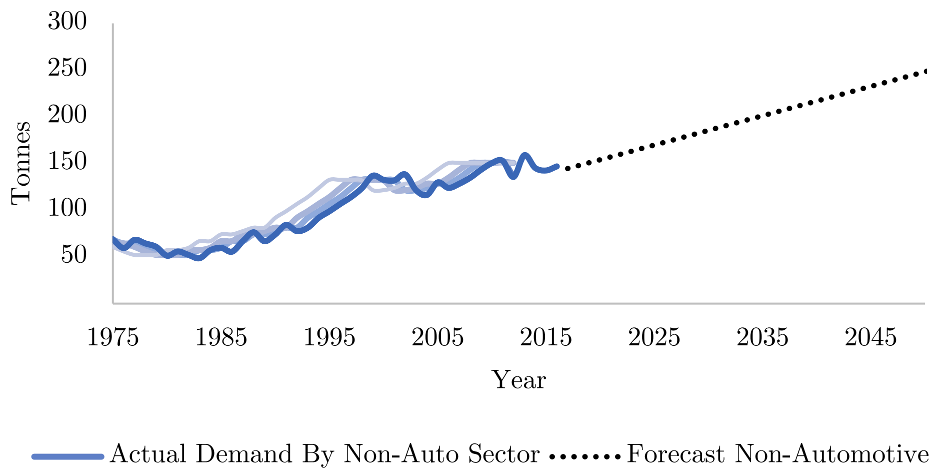

Figure 3.6 Actual & Presumed Platinum demand from non-automotive sector

3.2.2 Automotive Sector

The automotive sector is competitive and innovative with numerous worldwide influencing socio-economic factors (Holmes, 2015). However, transportation is second to power generation in Green House Gas "GHG" emissions. For example, transportation accounts for 30% of the U.S emissions of which 60% is from light-duty vehicles.

The automotive sector is bound by impeding technological changes. The International Energy Agency annually publishes its Energy Technology Perspectives "ETP" model (IEA, 2017). The ETP model uses applied hypothesis on gross domestic product, population growth, technology, deeds and socio-economic parameters in at least 29 regions. In the transportation portion, ETP lays out the share of different technologies in Light Driving Vehicles "LDVs" stock (Figure 3.7).

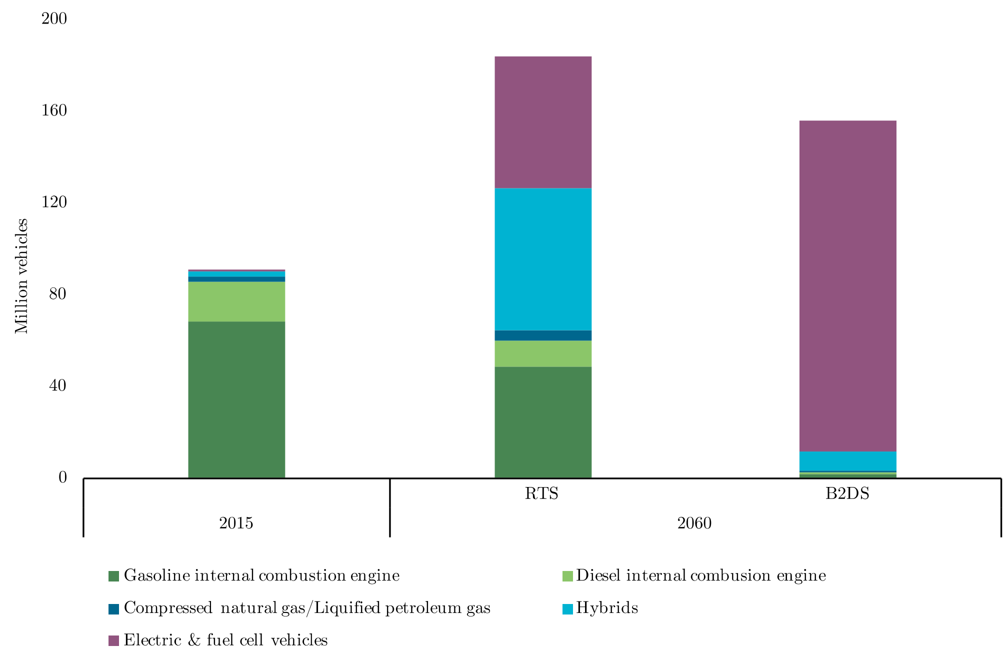

Figure 3.7 LDV Share in 2015 and 2060 in the Reference Technology Scenario and Beyond 2°C Scenario (*Energy Technology Perspectives 2017*)

IEA's (2017) Reference Technology Scenario (RTS) accounts for countries commitment in limiting emissions and improving energy efficiency, incorporating the National Determined Contributions (NDCs) under the Paris Agreement. Under RTS, average temperatures increase to 2.7°C by 2100, at which point temperatures are not stable and are expected to increase further.

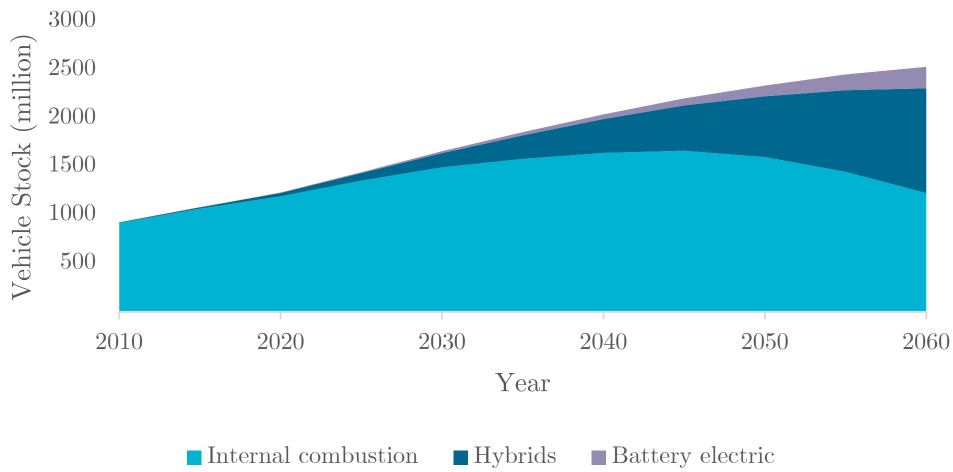

Figure 3.8 RTS LDV global stock

In RTS, LDV stock doubles to over 2 billion by 2060, with conventional of Internal Combustion Engine (ICE) Vehicles (ICEV) maintaining their market penetration until 2040. The decline in the stock of Internal Combustion Engine Vehicles (ICE, ICEV) combines with an increase in hybrid's market share (Figure 3.8).

In the Beyond 2°C Scenario (B2DS) there is a 50% likelihood of limiting global temperature increase to 1.7°C by 2100. B2DS pushes technological adaption and innovations to the maximum to achieve net-zero emissions by 2060, all without unforeseen breakthroughs or restrictions in economic growth (Figure 3.9).

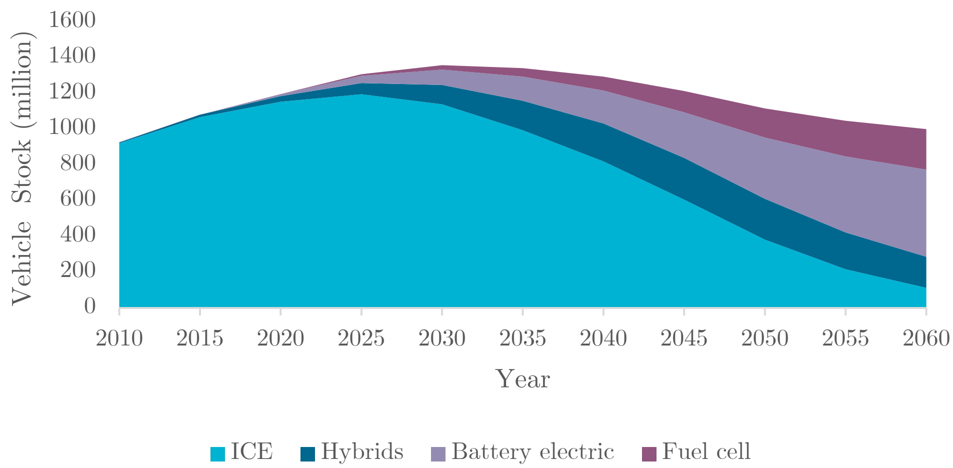

Figure 3.9 B2DS global vehicle stock

3.2.3 Recycling & Technological Change

Recycled platinum from vehicles at the end of life reduces the extraction efforts by reintroducing the supply to the market. Current historical recycling rates from the automotive industry are low at around 20% and have an inverse relationship with primary production. Conversely, recycling efforts increase when the price of platinum is high, which increases the supply stock and drives the price down until recycling efforts are no longer feasible.

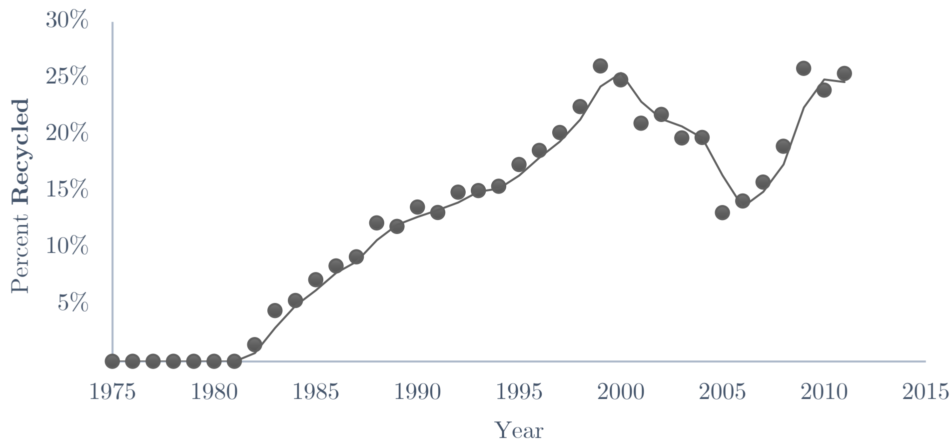

Figure 3.10 Historical platinum recycling rates from automotive sector

Authors (Holmes, 2015; Yang, 2009) and reports (Busby, 2005; l'énergie, 2008) put the recycling of platinum by the automotive sector at approximately 50 to 60% in their long-term outlooks. In estimating supply from secondary production for Internal Combustion Engine Vehicles "ICEV" recycling potential will peak at 60%, increasing at a rate of 0.9% each year.

While ICEVs and hybrids require platinum for autocatalysts, platinum in Fuel Cell Electric Vehicles (FCEV) is a crucial component in the electricity generation process. The higher content of platinum in fuel cells and the advanced state of regions that utilize them set the recycling rates at higher levels than ICEVs (Figure 3.11).

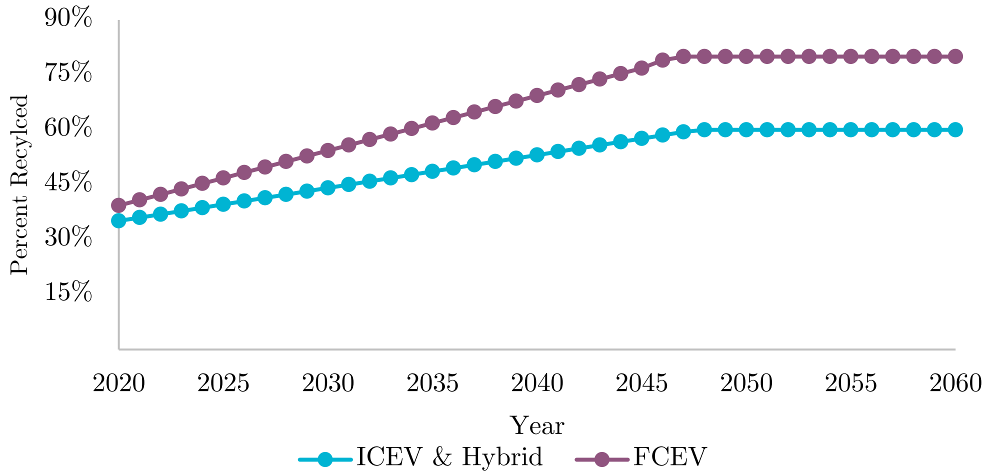

Figure 3.11 LDV PGM secondary production improvement over time

At an assumed range of 2.0-2.5 kW/g-Pt, most FCEVs need around 40-50 grams of platinum. Long term B2DS factors improvements in the platinum loading of FCEVs to around 8-12 kW/g-Pt by 2050. Figure 3.12 shows platinum loading reductions for FCEVs. Strict regulations maintain current loading levels for hybrids and ICEVs in both RTS and B2DS.

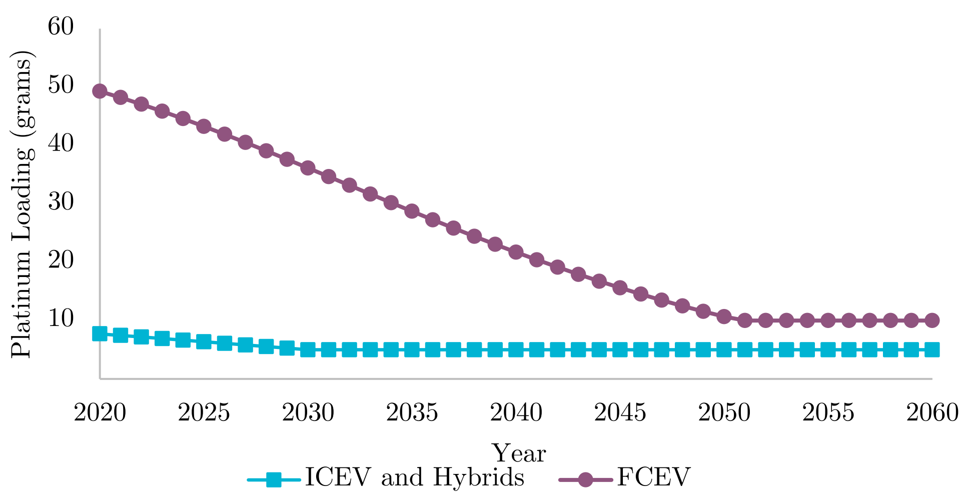

Figure 3.12 Platinum for FCEVs, ICEVs and hybrids in RTS and B2DS.

3.3 Forecasting Future demand

As mentioned in Sun, Delucchi, and Ogden (2011), the restrictions on supply and inelastic demand by sectors that cannot substitute platinum can make the prospect of forecasting long-term extracted supply possible. Based on the adoption of current trends (RTS) and innovative technologies (B2DS), the strain on extracted supplies is quantifiable.

Demand forecast drivers and improvements in recycling, allow the identification of the required extracted supply as below

Extracted Supply = Demand [Automotive + Non-automotive] – Recycling

3.3.1 Reference Technology Scenario incorporating announced policies

The components presented above give the total demand, and technological change with fleet turnover models provide the information on secondary production. Taking the secondary production out of the total demand will provide raw platinum extraction. Adding non-automotive and automotive forecasts gives the total demand under RTS (Figure 3.13).

The automotive sector is the main driving force for the future demand for platinum. RTS puts electric cars into the fold but developing countries will not have sufficient infrastructure and funds to accommodate an option that is more expensive and less reliable due limited range between recharging and refueling stops.

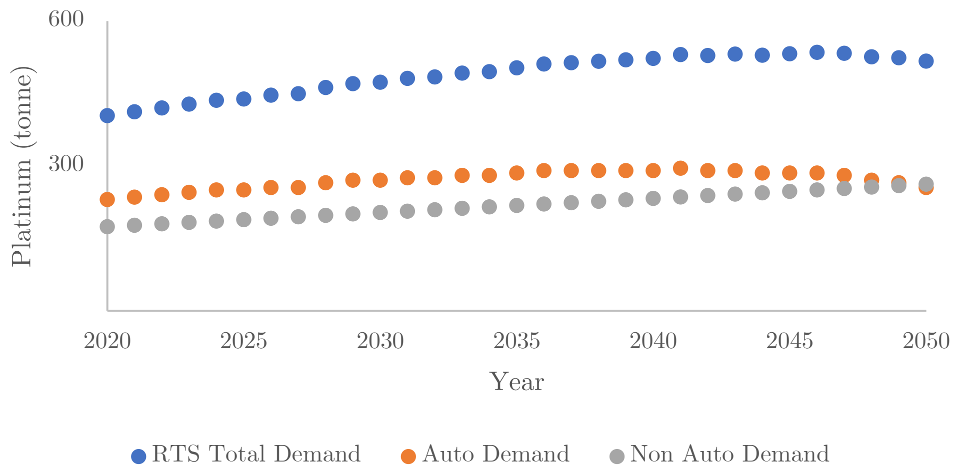

Figure 3.13 Total platinum demand in RTS until 2050.

RTS total platinum demand Figure 3.14 coincides with current forecasts of market trends. Eventually, in RTS, global markets retire ICEVs and transition into hybrids and fully electric vehicles. During this period automotive demand for platinum peaks but enhanced recycling efforts keep demand sustainable with extraction efforts. Therefore, in RTS there will be no platinum supply restrictions from automotive demand nor sustained growth in non-automotive sectors.

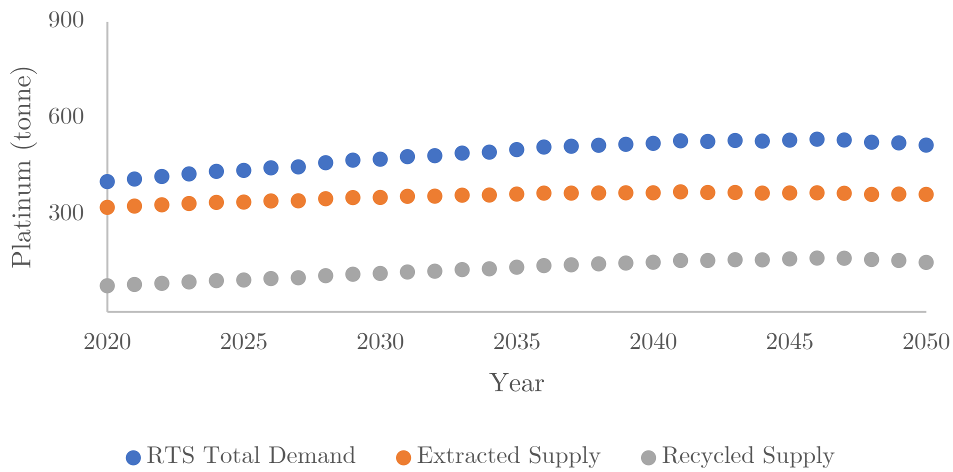

Figure 3.14 RTS total demand, extracted and recycled Supply

3.3.2 Beyond 2°C Scenario

In B2DS, global stock of vehicles shifts towards fully electric, hybrids and fuel cells. An assumption added to B2DS model, is that by 2050, 20 % of the vehicle stock is FCEVs, 50% EV, 20% hybrids and 10% ICEVs (Figure 3.9). Accomplishing the B2DS in LDVs will require doubling the current extracted supply of platinum.

In Figure 3.15, platinum extracted supply in B2DS is double RTS shown in Figure 3.14. If fuel cell electric vehicles start increasing the demand for platinum without additions to mined supplies, the price will escalate promptly, which leaves end consumers to choose cheaper alternatives.

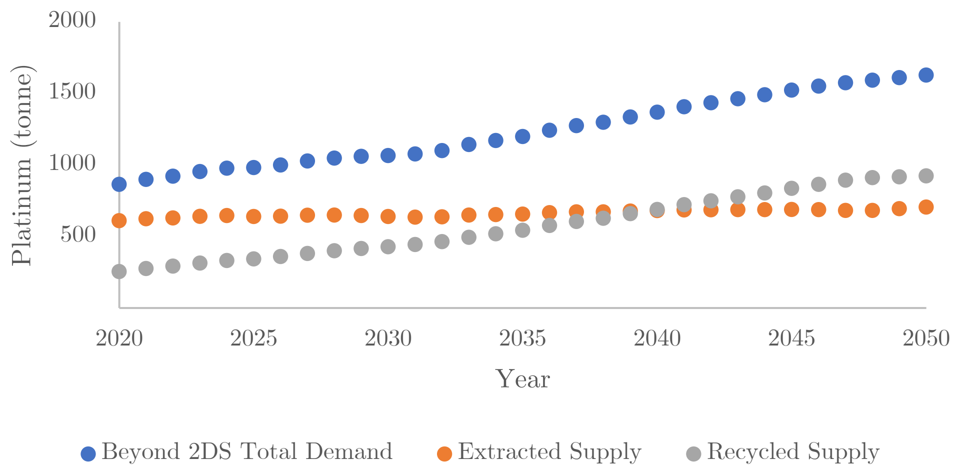

Figure 3.15 B2DS Platinum Total Demand, Extracted and Recycled Supply

In the future, technological change in platinum loading and recycling will overcome the extraction efforts. Nonetheless, reaching the intersection of primary and secondary supply is not possible with currently exploited deposits. Beyond 2DS total demand for putting the first 100 million FCEVs on the road requires an increase of approximately 35% tonnes over PGMs extracted from 2000-2014, (Figure 3.1). The world's entire platinum reserve can suffice the demand for 30 years. These reserves are inferred and are not economically feasible to extract due to low concentration (1-2 ppm) and/or positioning within the orebody.

The lack of accessible and sufficient supply of platinum adds another barrier to the mass adaptation of FCEVs. Therefore, asteroid mining for platinum can be of significant value to firms in new segments of an Established Market as it diminishes competition against conventional mining market share.

3.4 Optimal Placement in Established Markets

The mining of metal asteroids (M-type) has potential as a supply of platinum. With increasing demand, the supply provided from asteroids will offset the shocks in the market, removing the technological and strict chemical constraints on recycling and adds a new supply to the market that is not present in hydrogen economy literature.

Technological change facilitates the transition into FCEVs. If platinum recovery rate is 100%, then market penetration of FCEVs will stagnate behind other vehicles that require lower platinum loading and bring higher returns. The other half of introduced technological change is platinum loading declining over time. Reducing the content required in FCEVs and the hybrids will help automotive manufacturers reduce overhead costs and in turn pass the saving to consumers. The individual research and development approach in reducing platinum loading, without use in a mass-market removes competition and adds more risk to firms involved as time progresses. In addition, demand for automobiles will drop with the prospect of autonomous vehicles.

Hence, mining asteroid resources for Established Markets on Earth have no value unless there is the dire need for a commodity. Asteroid mining firms need to establish long-term partners, thereby ensuring price stabilization. The first firm to successfully mine an asteroid will not have to worry about selling the commodity in the markets. The firm will deliver the resource to companies that bided on their share of allocation of asteroid mined resources.

FCEVs are not the only goods dependent on platinum. Somarvia (2015) highlights a vital crossover between the demand for platinum and newly emerging private space companies. Significant investments in such firms are directly related to Multinational computer and internet firms. To list a few, Elon Musk (SpaceX, PayPal), Paul Allen (Strato Launch, Microsoft), Jeff Bezos (Blue Origin, Amazon.com), Eric Schmidt and Larry Page (Planetary Resources, Google). These investments are in direct relation to the high requirement of critical raw materials in the electronics industry, all of which will be affected by any significant shortage of the minerals.

Platinum is only one of many critical metals that are copiously present in asteroids and lacking in sufficient concentrations on Earth. The realization of asteroid mining in Established Markets will require connecting the abundant resources on asteroids with firms seeking them for mass adoption of innovative technologies.

4 Unestablished Market: Water

In Unestablished Markets, there has yet to be the initial exchange of goods between buyers and sellers. Unlike PGMs in Chapter 3, there is no prevailing price for exchange of asteroid resources in Space. There is no dispute regarding the presence of water on asteroids. Water on asteroids can be hydrated, trapped in a mineral or free form (Rietmeijer, 1998). The value of water in a new space economy would directly impact main cost restraints facing Deep Space operations, fuel and life sustainability.

The lack of a water market in Space is one reason some literature (Andrews et al., 2015; Sommariva, 2015) shifts the focus towards mining asteroid for high-value metals like platinum. In this chapter, we set a methodology for setting a prevailing price for water extracted from asteroids. Doing so allows valuation of the Unestablished Market along with potential short and long-term price paths.

Nonetheless, if water is successfully extracted from an NEA and delivered to Low Earth Orbit/Geostationary Orbit (LEO/GEO), water/oxygen resupplies will not be necessary and outbound spacecraft will not need to launch with additional propellant to reach their destinations. If the primary allocation target is LEO then even with the added Δv (3.3 km/s), the energy requirement is three orders of magnitude less than payload delivery from the Earth's surface (Sanchez & McInnes, 2012).

The case begins by setting up a way to evaluate the profitability of harvesting water from the applicable NEA population. This is followed by a cost-benefit examination on the first entity to fund and operate this venture. A simulation on the long-term dynamics of supply and demand offers insight on whether the water extraction and delivery are a one a time feat or if it has the necessary components to become an Established Market eventually.

4.1 Water Sources and Costs

The International Space Station (ISS) is currently the manned mission in Space. Different kinds of water are available for use on board the ISS (Russell & Klaus, 2007).

1. Ground-launched water
2. Wastewater
3. Recycled water
4. Other (reserves of water for conducting experiments)

Water recycling is at the forefront of innovation in sustaining manned missions. For long-duration manned missions, the risk will increase, a crew of 4 will need 3 tonnes of water over 12 months. Although recycling technology functions well, as it scales up, risk increases for the entire crew, and that is not acceptable for any time extensive manned missions (Moses & Bushnell, 2016).

Additionally, water can be used as a propellant (Solar Thermal Engines, liquid oxygen (LO_2) - hydrocarbon, LO_2- liquid hydrogen (LH_2)), agriculture and as a shield from radiation (Zacny et al., 2012). The prospect of obtaining a new supply of water tackles a significant hurdle in launch costs.

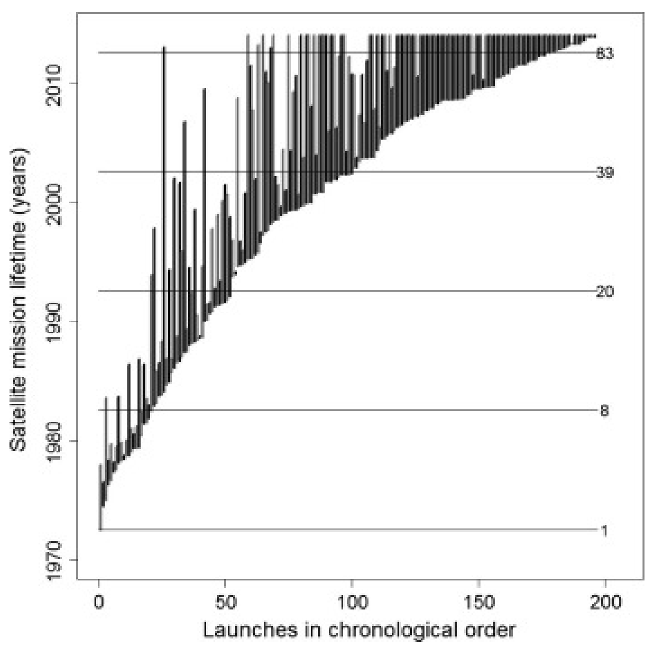

Figure 4.1: Orbit lifespan of most satellites (Belward & Skøien, 2015)

Water may find the use of refuelling satellites. Since 2000, satellite launches have exponentially increased (Figure 4.1), longevity is also on the rise with many launched in the 1990's still operational. Satellites with placement in low orbits suffer severe weathering, drag conditions and do not last as long or have better communications than others in higher orbits. However, costs to Geosynchronous Transfer Orbit (GTO) are almost double with half of the possible payload (Belward & Skøien, 2015). Perhaps if water is to be delivered from an NEA to LEO, it can be potentially applied for a new generation of satellites that can utilize this new resource, to elevate an improved location, increasing their longevity and reliability.

Estimates for shuttle costs range from $15,000 to $35,000 USD/kg to LEO-GTO (Table 4-1), a hefty price when compared to $5-15 USD/kg in airline shipping. If human passengers are on board, the weight requirement is five to ten times more than unmanned missions.

Vehicle	*Space Agency*	*Approximate Cost to GTO Orbit $USD/kg*	*Payload LEO-GTO (kg)*	*Success Rate*
Atlas V 401	NASA	≈ 28,000	9,800-18,810	98.6 %
Delta IV Heavy	NASA	≈ 25,000	9420-28,790	97.1%
Ariane 5	ESA	≈ 24,000	10,500	98.4 %
Ariane 5 ES	ESA	≈ 30,000	20,000	100.0 %
Proton-M	RFSA	≈17,000	23,000	89.8%

Table 4-1 Approximate Delivery Fees per Rocket (Belward & Skøien, 2015; Wilcox, Schneider, Vaughan, Hall, & Conference, 2009)

If shipping cost to the desired location is $20,000 USD/kg, then every kilogram placed will have the same value as, 2/3 Platinum, 1/2 Gold and 28 kilograms of Silver on Earth (Markets, 2017).

Therefore, if an ample supply of water is harvested and delivered from asteroids at a price equal or lower than surface shipping, firms will now have an option to optimize and reduce costs of mission payloads, in turn enabling energy-intensive space endeavours.

4.2 Valuation of an Unestablished Market

4.2.1 Extraction Approach

For terrestrial safety, the upper diameter limit for the tugging approach is around $\leq 20m \pm 3$ meters (Badescu, 2013). On site extraction, landing with proper gripping mechanism displays similar technological feasibility for NEAs > 100m diameter. The main issue with on-site extraction and return is the cycle time. If feasible tugging to a stable position will be a one-time feat, the rest is extraction efforts, making delivery rendezvous much shorter, more reliable and thus more profitable. Section 2.4 provides an account of possible extraction approaches and processing techniques.

Based on the approach, the extraction target would be a $\leq 20m \pm 3$ water-rich carbonaceous NEA, "$C_{\leq 20m\ H2O}$". Estimating the market value of $C_{\leq 20m\ H2O}$ requires knowledge of NEA diameters that are within extraction target and have the uppermost concentration of water.

4.2.2 Relevant Population

The techniques and equipment used in the discovery of NEAs are more inclined towards larger diameters. Approximately 95% of NEAs $\gtrsim$1 km have been catalogued, shifting the focus towards the 140+ m range (Chodas, 2017). Figure 4.2, shows a handful of relatively large NEAs $>$ 1 km and plenty more at a diameter of 100-1000 m.

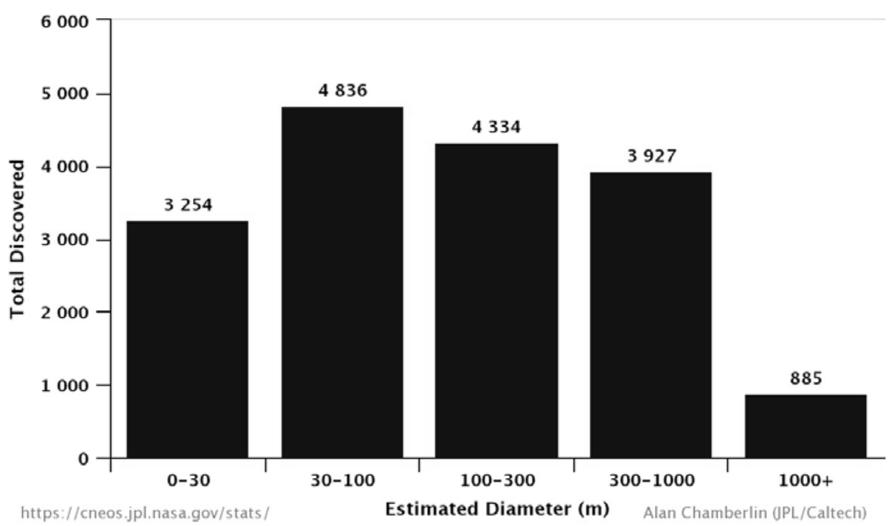

Figure 4.2 NEA discovered total per size bin (Chodas, 2017)

It is yet to be confirmed if the distribution trend of main belt asteroid prevails for NEAs below the 100-m limit (Mainzer et al., 2011). If the fit of the population trend extends below that range, it will imply the presence of substantially more NEAs at $<$100 m. Current estimates hint at 80,000 + at 50-100m and substantially more below that diameter threshold (Elvis, 2013).

Regardless, there are 36 NEAs that fit the extraction criteria for the tugging approach (Chodas, 2017). De-biased fractional abundance indicates that approximately 10 percent of NEAs are C-type with a density range between 0.8 to 1.5 g cm^{-3} (Stuart & Binzel, 2004). Therefore, the assumption is there are least 4 NEAs can be possibly tugged and harvested for water.

4.2.3 Water Content

The water content in retrieved CI and CM samples from meteorites ranges from 5 - 15 percent with an upper limit of 20 percent [34]. The odds are low for volatile-rich meteorites surviving entry through atmosphere and asteroid spectroscopy provides insight on surface mineralogy based on the ability of the surface to reflect light, advantageous for metal-rich asteroids.

In terrestrial drill operations, it is not always possible to determine the entire volume of water or oil. Specific characteristics of soil and rock are relevantly more attainable and are used concerning each other to determine the total targeted volume:

$$\text{Porosity} = \frac{V_{\text{air}} + V_{\text{water}}}{V_{\text{total}}} \qquad (8)$$

NASA's Near-Earth Asteroid Rendezvous (NEAR Shoemaker) space probe, passed within a close distance of a C-type asteroid, Mathilde. NEAR Shoemaker provides sufficient information to reverse the use of the porosity equation. Assuming no space is void of liquid, it is possible to approximate the quantity of water present (V_{water}).

For Mathilde:

- Dimensions from NEAR Shoemaker are 66 x 48 x 44 km^3
- Bulk density is 1.3 g cm^{-3}
- Water is assumed to be in the native form (ice) ∴ density is 1 g cm^{-3}
- Porosity will not alter with depth ∴ porosity is kept constant at 50%[a]
- Water abundance does not vary between Main belt asteroids and NEAs
- The vacuum of space dissipated trapped air, $V_{air} = 0$

[a] In terrestrial deposits, density increases and porosity decreases monotonically because of rising differential pressures with depth. However, it is well documented that C-type asteroids are undifferentiated and have not experienced igneous differentiation (Britt et al., 1987; Carry, 2012; Tholen, 1989).

Under the following assumptions and known variables for Mathilde, the volume of water as a function of a total volume can be up to 38%.

Now with $C_{\leq 20m\ H2O}$ total mass, upper-lower water content and price levels, a metric approach produces, the estimated total market value for $C_{20m\ [0-40\%]H2O}$ NEAs:

$$\text{Market Value}_{C_{20m\ [0-40\%]}} = P\left[M \sum C_{20m}\right][0\text{-}40\%] \quad (9)$$

Whereas:

P = price of shipping per kilogram, at $20,000 or $30,000 USD (Table 4-1).

$M \sum C_{20m}$ = sum of the spherical mass of discovered NEAs at 1.3 g cm^{-3}

$[0 - 40\%]$ = Range of retrievable water content.

Table 4-2 details the potential value of an Unestablished Market for water in Space for four $C_{20m\ [0-40\%]H2O}$ NEAs can generate anywhere between $40 to $260 billion USD.

		Market Value in Billion USD	
Indicator	*Water Content %*	*20,000 USD/kg*	*30,000 USD/kg*
Cl Chondrite	10	40	70
CI Chondrite	20	90	130
NEAR Shoemaker	30	130	200
NEAR Shoemaker	40	170	260

Table 4-2 Potential value of an Unestablished Market for water in Space (DeMeo et al., 2009; Stuart & Binzel, 2004)

4.3 Short-term Economic Feasibility

What follows the assignment of market value for water is a cost-benefit examination of the first operation to do so, including the risk on the return on investment. The operation will require prospecting, recapture and extraction machinery.

Asteroid recapture estimates are taken from the costs for conceptual spacecraft design of NEA "2008 HU4" tug to lunar orbit, with a mass of 1,000t, using a 40-KW SEP system costing approximately $2.6 Billion USD. The total time to return to cis-lunar orbit for 2008 HU4, is 6 to 10 years (J. R. Brophy & Oleson, 2012).

Prospecting for water-rich NEAs reduces critical uncertainties. High-resolution wavelength observations without interference from Earth's atmosphere are only possible with close spacecraft encounters with asteroids. This allows verification of theories and analysis from ground-based asteroid data. Moreover, capturing accurate geometric data is only possible with close encounters (Bertini, 2013). Adjusted for inflation, NEAR Shoemaker space probe (TRL 9) "prospector" costs $350 Million USD (Noor, Venneri, Paul, & Hopkins, 2000). There are conceptual designs and prototypes for "miners." Looking back, Apollo 15, 16 and 17's Lunar

Roving Vehicle (LRV) "Moon buggy" cost adjusted for inflation is around $145 Million USD to develop (Figure 4.3) (Dunham, McAdams, & Farquhar, 2002).

The LRV is the only manned operated machine that traversed a surface of another planetary body. It resembles the basics of a terrestrial hauler while having higher technological readiness levels than any other conceptual design as one has set foot on an extraterrestrial terrain. Miners will perform a single function, extract and store extracted ice. They will not need to be deployed until the NEA is tugged into a stable position. $1.5 Billion USD covers the prospecting and extraction machinery with backup units and contingency.

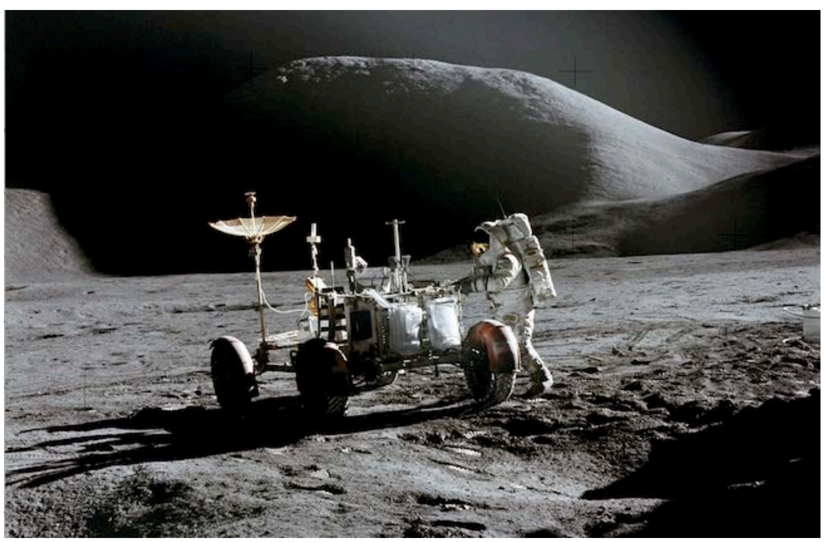

Figure 4.3 The U.S. Apollo Lunar Roving Vehicle, 1971 (NASA, 2016)

Put together, the historical prospecting, delivery and harvesting costs, accompanied by the equation of market value provides a cost-benefit structure for a firm's first operation. The venture might be funded by the private sector, governments or a combination of both. The principal financial risk is a failure to obtain the resource.

Table 4-3 depicts the Cost-Benefit of Tugging $C_{12m\ [30\%]\ H2O}$ as an example of what would these returns and risks would look like for the first tugged water-rich NEA. The risk on investment is taken to be at the critical juncture for the first operation, reaching and successfully initiating the tugging process (4 years).

The prospecting and extracting machinery are merely a capital expenditure set back while the financial uncertainty is from the wait time. Investors seek quick returns and low risk. Regardless of technology readiness levels, the early onset of the operation will be a setback in obtaining the necessary funds. Therefore, insurance premiums will go up as failure uncertainty rises.

Maximum Weight	1,000 tonnes	Density 1.3 g cm^{-3}
Diameter Retrievable Water Content Launch Vehicle Propulsion Time on Return	12 meters 30% Atlas V 521 Class 40 KW SEP 6 to 10 years	Time on Return Break Down: 1. Reach Earth Escape: 2 years 2. Journey to $C_{12m\ [30\%]\ H2O}$: 2 years 3. Return w/ $C_{12m\ [30\%]\ H2O}$: 2 to 6 years
	Billion USD	
NEA C Market Value Asteroid Recapture NEA "Water Harvesters" NEA "Prospectors" Contingency Insurance Premium	7.1 2.6 0.3 0.7 0.5 21%	Market Value C_{12}= P[M][30%] From cost estimates on tugging 2008 HU4 2x Moon Buggy $145 Million in 2017 USD 2x NEAR Shoemaker $350 Million in 2017 USD 50% of prospecting & mining 4 years of uncertainty

Table 4-3 Cost-Benefit of Tugging $C_{12m\ [30\%]\ H2O}$

In this scenario, the cost of tugging ($2.6 Billion USD), will have a four year wait period and the compounded interest rate over four years for zero-sum is defined as the risk on the return of investment, "insurance premium."

In terrestrial mining, the risk on investment depends on the payback period (duration and success of tugging) and the cut-off-grade (water content). Figure 4.4 Relation between insurance premium, water content and price, shows that the higher the water content and delivery price, the more likely it is to secure capital.

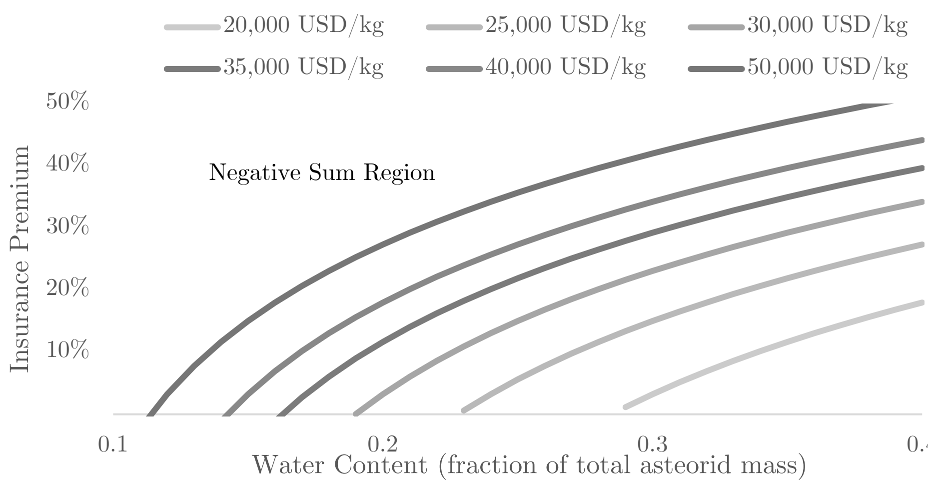

Figure 4.4 Relation between insurance premium, water content and price

However, the supply must be a better alternative than delivery from the surface. The breakeven on capital with no investment restraint is the value of the extracted water. The higher the water content, the lower the breakeven. For example. \$35,000 –\$ 20,000 USD/ kg at 0.15 - 0.30 fraction of water content from asteroid mass respectively.

Cost reduction and risk diversification will be critical targets for the actors behind the first operation. In this case, the higher insurance premium, the greater the likelihood of obtaining capital funding. Most importantly, the balance between the price level, insurance premium, and end users are completely dependent on the primary objectives of the entity in charge.

Figure 4.5 feasibility regions at different price levels, portrays the importance of setting the current price level for the extracted water. The higher the prevailing price, the lower water content required to extract.

The tugging and water extraction of a C-type water-rich NEA will not be a single feat; the insurance premium will drop upon the successful apprehension of water. Technological change eases the costs of development in prospecting, extracting and tugging spacecraft. Soon enough, other missions follow suit.

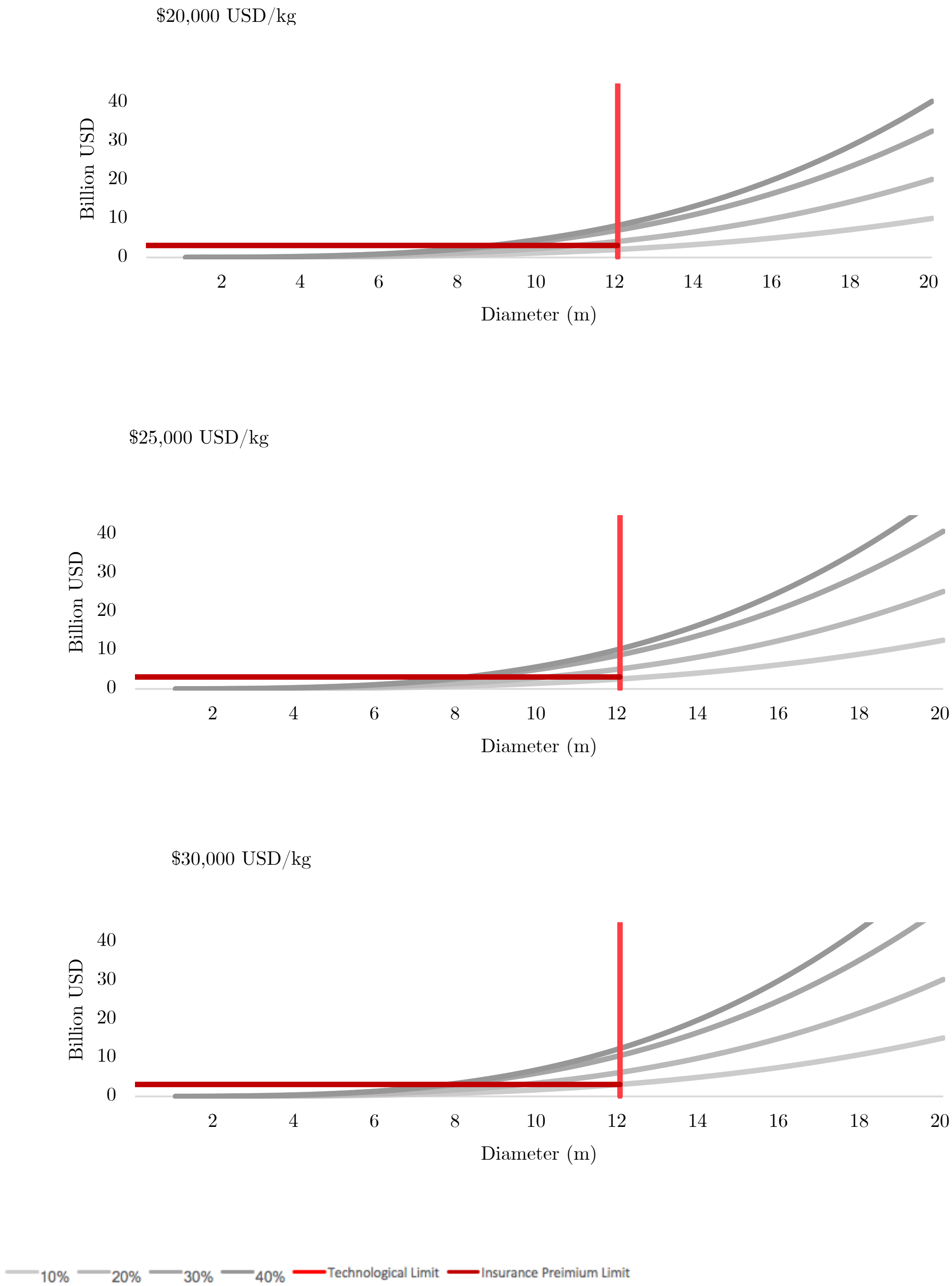

Figure 4.5 Feasibility regions at different price levels

4.4 Long-term Economic Feasibility

When market supply sharply increases, and there is no demand to match it, the price starts to diminish "over-supply(glut)" (Adelman, 1982). Similarly, in the case of water extraction of tugged NEAs, the propagation of subsequent NEA water extraction operations missions will eventually overwhelm the demand, decreasing the price of water per kilogram. Unlike terrestrial markets, we argue that the surge in supply will lead to major reductions in water intensive space-bound endeavours.

History is packed with commodities that were at a point scarce, later becoming abundant. Inspecting sharp fluctuations in commodity prices in relation to over or under supplies can provide insight in modelling the longevity of the soon to be water market. When looking at historical commodity prices, there is more than often a peak in price that substantially exceeds any previous value. There are multiple reasons for such hikes in pricing, but in some instances, it comes down to the commodity's own supply and demand.

One example is aluminum (Figure 4.6), during the 1970s demand for aluminum rose until the early 1980's during which the industry experienced a period of oversupply and declining demand, leading to lower pricing and a shutdown of excess capacity. Then the industry witnessed a sharp increase in demand from the aerospace industry that exceeded the restricted supply, which caused the price to increase yet again only to drop as capacities and inventories increased to meet the demand.

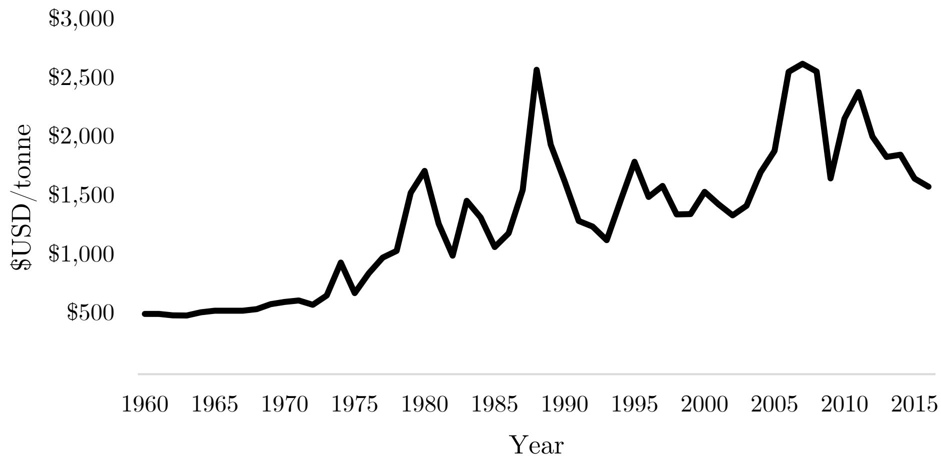

Figure 4.6 Historical primary aluminum prices USD

Another illustration with a similar commodity cycle is lead (Figure 4.7). Price control policies stabilized prices, when the controls were lifted alongside a demand increase, lead prices reached historic highs (1979).

Environmental production controls phased out lead in multiple industries, which lead to a dramatic decrease in demand, reducing the price to an all-time low. What brought the lead industry back to the fray was an increase in demand for lead-acid batteries. Lead-acid storage batteries represented 87% of US consumption of lead.

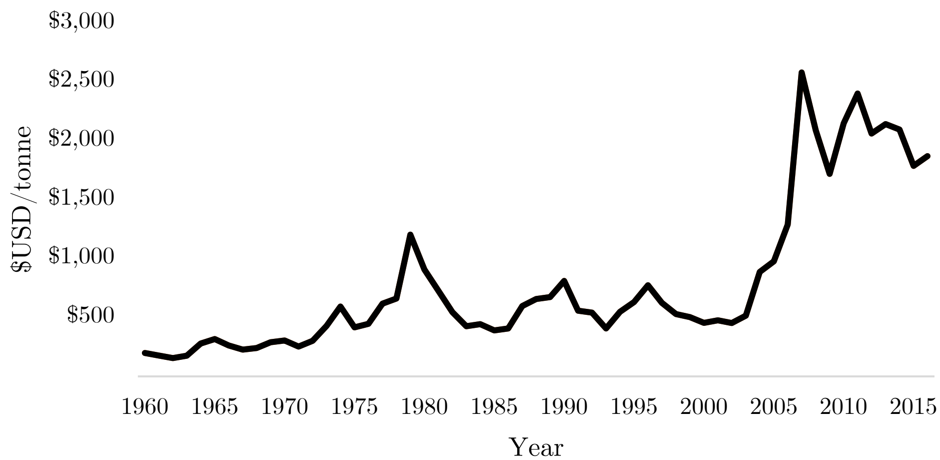

Figure 4.7 Historical Lead Prices USD

Oil experienced a well-known case of supply glut and by the 1980s, geopolitical restrictions in oil supply caused the price to reach an unprecedented peak. At that price level, offshore drilling operations became feasible, profits were initially made, but prices kept falling as demand failed to match excess capacity and inventories of supply (Yergin, 2011).

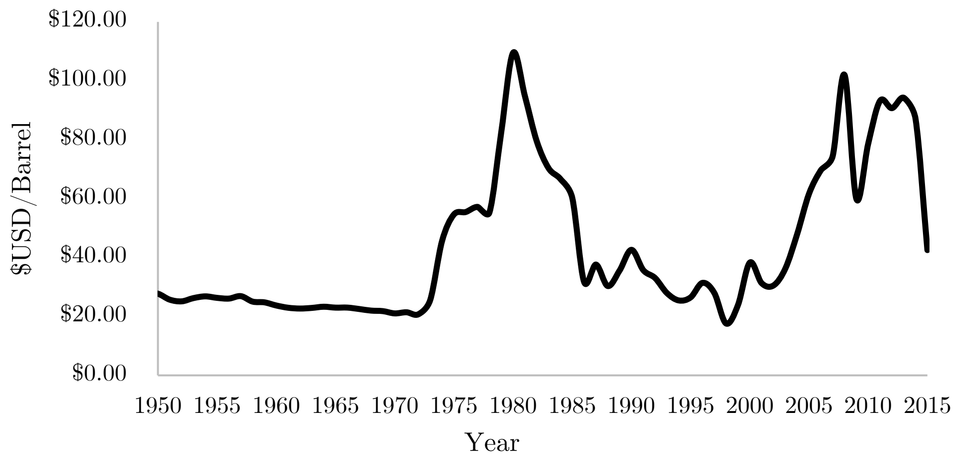

Figure 4.8 Historical Oil Prices with Moving Average Momentum

The Unestablished Market condition for water allows the assumption that the price of water will be the highest until the first successful extraction from an NEA. Therefore, until there is a new supply of water, the price is at peak and is equal to the cost of delivering 1 kilogram of water from the Earth's surface to the desired location.

In the examples mentioned, historical peak prices came about from a sharp increase in demand and some restriction in supply, a situation familiar to the space industry. For these commodities, when the price reached their peak it allowed means of access that were not feasible at lower prices. The analysis in Section 4.3 shows that the first operation is economically feasible.

If perfect competition conditions hold, the peak price of water extracted from an NEA will be at its highest during the first operation and peak price will drop following the second successful extraction from an NEA and it will keep dropping until it is no longer feasible to extract, which will further be impacted by the demand.

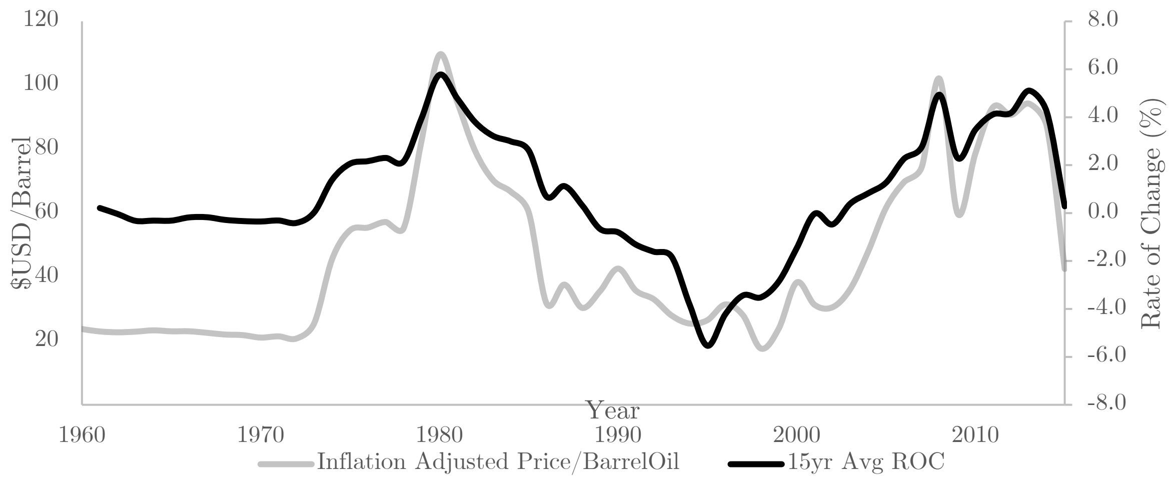

Figure 4.9 Rate of change in oil price on 15 yr moving the average

The scenario model incorporates the rate of change (ROC) in annual oil price from 1980 to 1998. If a commodity's ROC follows a path from peak (restricted supply, high demand) to trough (excessive supply, unchanging demand), the result is similar. In this model, ROC is a factor that indicates the pace of diminishing returns.

The following parameters allow the modelling of the profitability of succeeding missions:

- NEA recapture spacecraft launches in 2017
- No change in insurance premium (21%) until success in initiating tugging protocol (4 years)
  - Second successful initiation drops insurance premium to 15 %
  - Subsequently, insurance premium drops and remains constant at 5%
- Peak water price is $20,000 USD/kg
  - Price decreases using the trend of moving average of ROC (1980 to 1998) from Figure 4.8, begins after 8 years.
- Three scenarios for technological change: 2, 4 and 6 percent:
  - Miners and prospector's development costs will decrease annually after 6 years
  - Tugging spacecraft development costs will decrease annually after 4 years
  - Efficiencies in time and volume extracted are not included

Figure 4.10 presents the long-term economic feasibility of continuous tugging and harvesting of water-rich NEAs. Technological change and lower capital risk maximizes the returns on investment and slightly increases the longevity of the venture. Regardless of cost reductions, if supply no longer matches the demand and the market has suppliers willing to exchange water at lower prices, within a decade current operation capacity will no longer be feasible and after the market stabilizes, technological change will shift towards scale of economies.

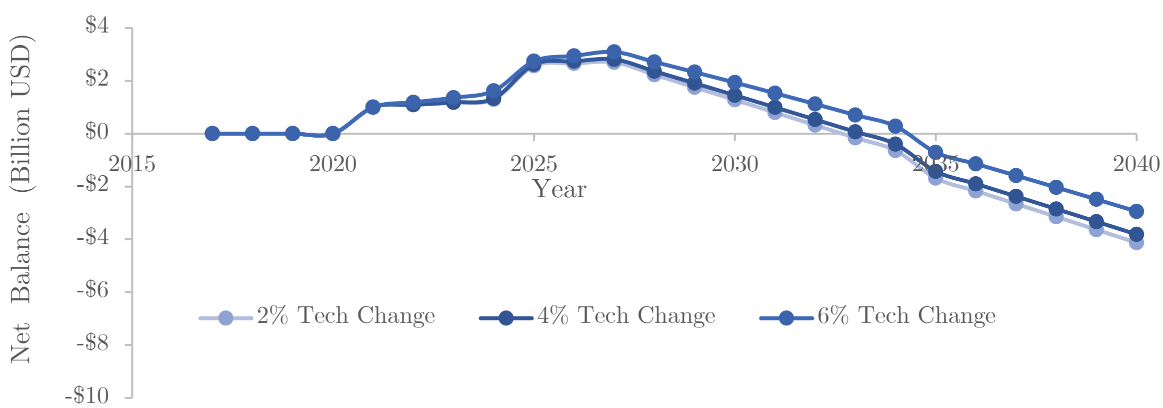

Figure 4.10 Technological change & the longevity of water extraction of tugged NEAs.

5 Conclusions and Future Work

The accessibility of Near Earth Asteroids and their immense resource potential can drastically alter Established Markets, and lay the cornerstone for Unestablished Markets particularly in space.

If current market trends hold, there will be no room for extracted metals from NEAs to enter Established Markets without causing price shocks. Nonetheless, the restricted supply of platinum sets back significant innovations that tackle climate change, healthcare and information technologies. The thesis emphasizes that Fuel Cell Electric Vehicles cannot become a significant mode of transportation with existing platinum supply. The platinum content in one FCEV alone costs more than an entire ICEV.

Nonetheless, an NEA smaller than 100 meters in diameter with mineral content similar to that H or LL Chondrite, can provide enough platinum to load into 100 million FCEVs. Therefore, a platinum supply from an NEA removes the technological and strict chemical constraints on recycling and adds a new supply to the market that is not widely considered in the hydrogen economy literature.

Long-term modelling displays economic feasibility for water harvesting from Near Earth Asteroids as it directly impacts costs and material restraint in space markets. However, water content and price levels are crucial in assessing the risk on the return on investment. The lifespan of unestablished market will depend on matching the new water supply with demand. Nonetheless, the realization of the first operation will bring a vital resource that is essential to all entities involved in the space economy.

The final argument for extracting water is that it will lead to an accelerated growth model and upon realization of abundant water, the space economy will experience a new rush, and from that point onwards commercial metal mining will start to emerge among other energy/volatile extensive manned/unmanned missions.

In summary, for parties interested in obtaining water from NEAs, the following must be considered:

I. Defining the underlying end objectives of the venture
II. Initiate talks with interested parties to establish price levels for extracted resources
III. Begin prospecting right after settling on an insurance premium rate
IV. Attempt to diversify the capital cost by bringing more partners into to the proposed project
V. Set up continuous supply chain upon first success to stay ahead of the market curve

Future work should not involve everyday metal commodities such as aluminum, copper and nickel, as justifiable end products from asteroid mining. Table 5-1 showcases the worldwide annual primary production of aluminium, copper, nickel and PGMs.

The infrastructure and technologies to require extracting common metals will not be able to compete with current production levels. Hence the focus on platinum in the thesis, even when combined with all other PGMs, primary production is orders of magnitude lower than the metals shown in Table 5-1.

	Year of mining				
Commodity (tonnes)	2011	2012	2013	2014	2015
Aluminum	46,000,000	49,500,000	52,200,000	54,200,000	57,000,000
Copper	16,100,000	16,800,000	18,300,000	18,500,000	19,200,000
Nickel	2,129,000	2,386,000	2,576,000	2,150,000	2,092,000
PGMs	492	443	455	337	459

Table 5-1 Tonnes Mined of Different Metals from 2011 to 2015

(Dataset: British Geological Survey, 2016)

However, water and platinum are not the only viable products from asteroid mining. Rather than targeting common metals, the list of critical raw materials (CRM) in Table 5-2, contain materials which reach or exceed limits for economic importance and supply risks.

Critical Raw Materials

Antimony	Fluorspar	LREEs	Phosphorus
Baryte	Gallium	Magnesium	Scandium
Beryllium	Germanium	Natural graphite	Silicon metal
Bismuth	Hafnium	Natural rubber	Tantalum
Borate	Helium	Niobium	Tungsten
Cobalt	HREEs	PGMs	Vanadium
Coking Coal	Indium	Phosphate rock	

Table 5-2 lists of Critical Raw Materials to the EU (EU Commission, 2018)

(HREEs = Heavy Rare Earth Elements, LREEs = Light Rare Earth Elements)

Technological progress and quality of life depend on the access to raw materials. Platinum is only one of the CRMs that are irreplaceable in solar panels, wind turbines, electric vehicles and energy-efficient lighting. Future work in assessing asteroid mining feasibility should consider the added value of a multitude resources in different sectors.

Resources from asteroid mining can be utilized in the electrical and electronic equipment (EEE) sector. The sector relies on a multitude of CRMs including antimony, beryllium, cobalt, germanium, indium, natural graphite, rare earth elements (REEs), silicon metal, and tungsten. Additionally, in recent years the battery market has seen a relative increase in the amount of cobalt: from 25% of global end uses of cobalt in 2005 to 44% in 2015.

In the renewable energy sector, markets for wind and photovoltaic (PV) energy technologies have been proliferating in recent years, as wind energy increases its presence in the electrical generation mix. Larger more efficient wind turbines will require then greater use of permanent magnets instead of the traditional gearboxes.

For example, the transition to permanent magnetic turbines will considerably increase the demand for rare earth elements, and since turbines have a lifetime of around 30 years, recycling will initially be limited. Similarly, PV modules can have recycling rates of up to 95%, but with a lifetime of over 25 years and current policies pushing towards more solar and wind in the energy generation mix will put a strain on the resources.

Future work would expand the scope matching resource scarcity to global issues, evaluating a combination of end products from a single asteroid concerning critical raw materials and their market conditions. Asteroid population is diverse in mineralogy, and the potential of extracting multiple products can showcase considerable value in NEA resource extraction.

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