UNIVERSITY OF CAPE TOWN – ECONOMICS MASTERS THESIS

Asteroid Mining and the Market for Platinum, a speculative analysis

Charles Kieck – KCKCHA002

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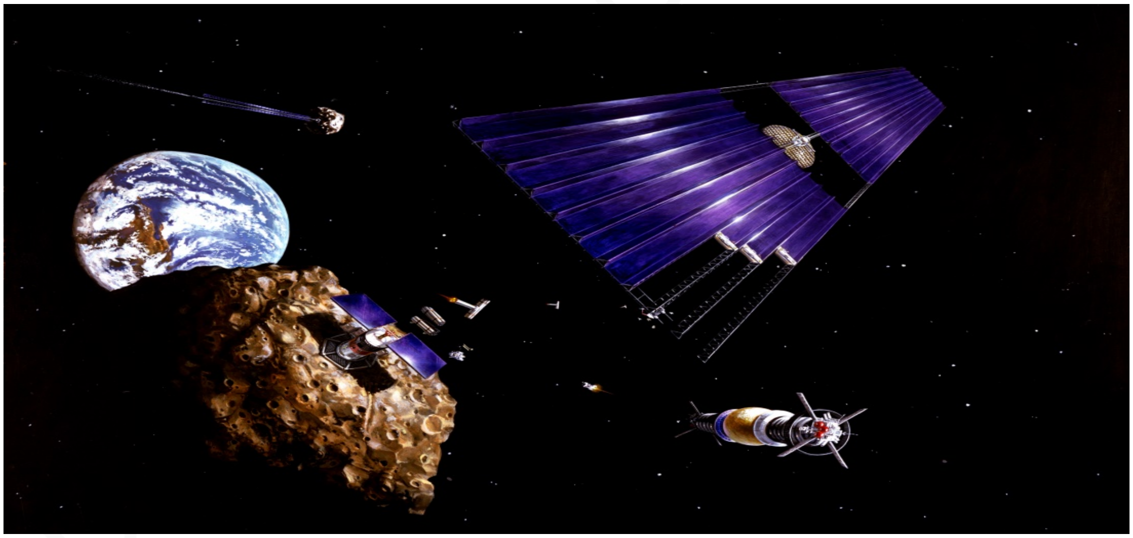

The potential existence of a high-volume asteroid-derived platinum production is examined from an economic perspective to assess the possible impact on long-term platinum supply. It is hypothesized that space-mined resources will increasingly become available over the next 30 years to 2050, driven by growing human activity in near-Earth space. Forecasted asteroid platinum supply under 3 scenarios is compared to forecasted terrestrial platinum supply. The thesis finds that, depending on the speed at which the size of an asteroid practical to mine up-scales, space-mined platinum has the potential to significantly impact on the terrestrial platinum market.

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Dedicated to Prof Emeritus Phillip Black

- Economist and inspiration

"Space, the final frontier"

Captain James T Kirk – The Starship Enterprise

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Glossary

Term	***Symbol/* Abrev.**	**Explanation**
Aphelion	*Q*	The point on an orbit that is most distant from the Sun.
Amors		Earth-approaching NEAs with orbits exterior to Earth's but interior to Mars's orbit.
Apollos		Earth-crossing NEAs with semi-major axis larger than Earth's.
Astronomical Unit	AU	The average distance of the earth from the sun; approximately 150-million kilometers.
Atens		Earth-crossing NEAs with semi-major axis smaller than Earth's.
Bushveld Igneous Complex	BIC	Main PGM ore bearing reef in South Africa containing the world's largest known reserves.
Carbonaceous asteroid	C-type	Water-bearing asteroid with very high contents of opaque, carbonaceous material.
Catalytic converter		Oxidation catalyst to treat automobile exhaust emissions.
China National Space Administration	CNSA	Agency responsible for China's national space program.
Cis-lunar Space		The volume of space with-in the Moon's orbit.
Delta-V	ΔV	Change in velocity required to change from one orbit to another.
Exchange-traded Fund	ETF	Securities backed by physical stocks, giving investors exposure to the underlying asset price without having to take delivery of the asset.
Geo-stationary Orbit	GEO	An orbit where the orbital period is the same as the rotation rate of the Earth; an object in GEO appears stationary in the sky to ground observers. GEO is at an altitude of approximately 36 000km above sea level.
European Space Agency	ESA	European inter-governmental organisation dedicated to the exploration of space, with 22 member states.
Fuel Cell		Device that generates electricity using an electro-chemical reaction, with the only emissions being water and heat.
High Lunar Orbit	HLO	The orbit of an object around the moon. Stable high-altitude lunar orbits are inclined at steep angles to the Moon's equatorial plane so they get far above the horizon at the lunar poles.
In-situ		Takes place "on-site" or "in position".
Japan Aerospace Exploration Agency	JAXA	Japan's national aero-space agency.
Lagrange Point		Lagrange points mark positions where the combined gravitational pull of two large masses provides precisely the centripetal force required to orbit with them. There are five such points in cis-lunar space labelled L1 to L5, with L1 positioned about 80% to the moon on a straight line from Earth.

Low Earth Orbit	LEO	An orbit around Earth with an altitude between 160km (orbital period of about 88 minutes) and 2 000km (about 127 minutes). Objects below LEO (sub-orbital space) will experience very rapid orbital drag and altitude loss.
Main Asteroid Belt		Countless asteroids in orbit around the sun between Mars and Jupiter.
Metallic asteroid	M-type	Asteroid with high radar reflectivity characteristic of metals.
National Aeronautics and Space Administration	NASA	United States government agency responsible for the civilian space program as well as aeronautics and aerospace research.
Near-Earth Asteroid	NEA	An asteroid that comes with-in 1.3 AU of earth.
Near-Earth Objects	NEO	Includes both NEAs and short-period comets.
NewSpace		The collection of entrepreneurial space companies currently establishing themselves across the globe.
Noril'sk-Talnakh		Main PGM ore-bearing geology in Russia.
Outer Space Treaty	OST	Main international treaty governing space activities, signed in 1967 by 102 countries including the US and Russia.
Parts per million	ppm	Concentration of a substance; equals *grams per tonne*.
Perihelion	Q	The point on an orbit which is closest to the Sun.
Platinum Group Metals	PGMs	Group of precious metals consisting of platinum, palladium, ruthenium, rhodium, osmium, and iridium; are often contained in the same ore body and mined together.
Potentially Hazardous Asteroid	PHA	NEA larger than 150m that comes with-in 0.05 AU from Earth.
Regolith		Surface fragmented rocky debris blanketing the Moon and small solar system objects.
Reserves		Mineral tonnage estimated following an economic feasibility study.
Resources		Mineral tonnage and grade estimates based on geological information only.
Semi-major axis	A	The radius of an orbit at the orbit's two most distant points.
Space-based Solar Power	SPS	SPS systems generate electricity from solar arrays in orbit around the Earth. Power is beamed along microwaves.
Stillwater Complex		Main PGM ore-bearing geology in Montana, USA.
Sudbury Basin		Main PGM ore-bearing geology in Ontario, Canada.
Stony asteroid	S-type	Anhydrous rocky asteroid, consisting of silicates, sulphides, and metals.
Synodic period	A	Interval that it takes for an object to reappear at the same point in relation to two or more other objects.
Terrestrial		On or relating to the Earth.
Volatiles		Gases that can be released from solar body cores by heating, e.g.: water and its parts oxygen and hydrogen, carbon dioxide and monoxide, methane, and ammonia.

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1. Introduction

This thesis explores the potential impact of asteroid mined platinum on long-term platinum supply on Earth. The economic theory of the optimal extraction of exhaustible resources, such as mined resources, suggests that there is an optimal path of extraction of non-renewable resources which will eventually lead to the complete exhaustion of the resource. The theory also introduces the idea of a backstop resource, which can act as a direct substitute for the exhaustible resource; this backstop could be another resource, a new technology, or a new ore body. One such possible ore body is the countless platinum-rich asteroids floating in space.

This thesis argues that commercial space mining is both an economic and technical possibility, and could become a reality as demand for resources in space grows over the next few decades. With the future exploitation of asteroid mineral resources assumed, it is the central hypothesis of this thesis that asteroid platinum supply could become a reality from 2030 onwards. Three scenarios are used to forecast potential supply of asteroid platinum to 2050, and these forecasts are then compared to projected terrestrial supply. The thesis finds that, depending on the rate at which the size of an asteroid practical to mine increases, space-mined platinum could significantly impact on the terrestrial platinum market.

The thesis proceeds as follows:

The next section, *Section 2: The economics of exhaustible resources* presents an overview of economic theory for the optimal extraction of exhaustible resources, introducing the seminal work of Harold Hotelling. The section introduces the idea of a "backstop" resource.

Section 3: The outlook for terrestrial platinum supply to 2050 investigates whether the platinum market has evolved as the economic theory of exhaustible resources would suggest. It then reviews the potential for terrestrial platinum supply and provides a forecast for platinum supply from both mining production and recycling to 2050 under 3 different growth rates; this is then compared to known resources and reserves.

Section 4: The outlook for asteroid mining first presents a brief review of asteroid mining literature and then outlines the rational for asteroid mining. The section concludes with a review of the current state of the asteroid mining industry and related projects.

Thereafter, *Section 5: The outlook for asteroid platinum supply to 2050* investigates the potential platinum supply from asteroids with reference to asteroid geology. It presents a forecast for asteroid platinum supply to 2050 based on the mining of 10 different asteroids under 3 different scenarios.

In *Section 6: Potential impact of asteroid supplied platinum* the forecasted asteroid platinum supply (calculated in *Section 5*) is compared to the forecasted terrestrial supply to 2050 (calculated in *Section 4*). The section then analyses the potential impact of asteroid platinum supply on the terrestrial market.

Final remarks are given in *Section 7: Conclusion*.

2. The economics of exhaustible resources

2.1. Introduction

The links between the demand, sources of supply, and market price for a mineral commodity are complex. Basic economic theory suggests that, over the longer term, higher prices tend to dampen demand for a resource and lower prices tend to stimulate it. Prevailing prices also have a longer term impact on mine production: mineral exploration activity is generally heightened when there is the expectation that future demand for a commodity will be higher than the anticipated supply (Wilburn, 2012). Economic theory also argues that there is an optimal path of extraction for these resources.

Following on from earlier work by LC Gray (1913 & 1914) (Crabbe, 1983), Harold Hotelling's theory on the optimal depletion of exhaustible resources (Hotelling, 1931) provides the foundation of mineral economics. Hotelling showed that economic variables, such as extraction costs and interest rates, influence the spot price, rate at which a mineral is extracted, and when the stock will be exhausted. He argued that profit maximising extraction programmes will be different in perfectly competitive and monopolistic resource markets, and that the extraction path would also be influenced by the existence of a backstop technology or resources.

The following sections explore Hotelling's ideas in more depth.

2.2. The optimal extraction path

In his 1931 article, Hotelling didn't set out to model a mine; rather, he was trying to show that the general rule that competition enhances welfare, is as true of mining as it is of other sectors. In order to do this he needed to identify the profit maximizing extraction behaviours of mines.

He argued that the economic problem is to determine the appropriate quantities of the mineral to be extracted in each period to maximize the present value of profits available from the stock (Hotelling, 1931). In the optimal solution, the sum of the amounts extracted in each period must exactly equal (and cannot exceed) the total stock of the resource in order to not forego any potential profits (Hotelling, 1931).

An optimal solution should therefore fully deplete the stock just as the demand for it falls to zero (the "terminal condition") (Hotelling, 1931).

In Hotelling's model, the profit maximization, stock constraint, and terminal conditions are used simultaneously to determine a unique optimal inter-temporal extraction profile for the resource from a single mine as well as at an industry level.

2.3. The price of an exhaustible resource

Hotelling assumed that mineral prices adjust so as to maintain a market clearing equilibrium at all points in time (Hotelling, 1931).

As the ore body is mined, the thicker and easier access seams are depleted first. Thereafter more waste rock must be removed to access increasingly thinner seams. Costs of extracting and processing each ton of ore rise because the mean metal content of the ore diminishes while the rock content increases (Hotelling, 1931). An important implication of this is that the resource's "economic rent" (or, the price net of costs) must rise over time if extraction of lower-quality, higher-cost ore is to occur (Hotelling, 1931).

The "*Hotelling r-per cent rule*" states that the price[1] of an exhaustible resource (or value of an exhaustible resource in the ground) must grow at the market rate of interest[2] (Hotelling, 1931). The Hotelling rule is an inter-temporal efficiency condition which must be satisfied by any efficient process of resource extraction (Perman et al, 2003). It is true even under monopoly, in which case it is not the net price (P-MC) but the marginal profit (marginal revenue less marginal extraction cost) that rises at the rate of interest (Hotelling, 1931).

An important implication of a continuously rising price is that the demand for the resource is slowly choked off while the quantity extracted is simultaneously falling. Eventually the price becomes so high that demand is altogether eliminated. In Hotelling's model, this "choke price" is reached precisely when the resource stock is also completely exhausted (Hotelling, 1931).

2.4. Extraction under a monopoly

Hotelling viewed the problem of how to extract a fixed stock of a natural resource from the vantage point of a government social planning agency (Hotelling, 1931). He then showed that a competitive industry facing the same extraction costs and demand curve as the government, and having perfect information about resource prices, will arrive at exactly the same extraction path for the mineral[3], and will not result in an overly rapid (and therefore social sub-optimal) rate of depletion (Hotelling, 1931).

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[1] Price here is considered to be the net price received after paying the cost of extraction and placing upon the market (Hotelling, 1931).

[2] In a perfectly competitive environment with no uncertainty, all assets must, in a market equilibrium, have the same rate of return (Hartwick & Olewiler, 1986). Unless the rental value of the mine is growing at exactly the same rate as the value of other assets extraction will either be as fast as possible or deferred as long as possible. If prices rose more slowly than the interest rate the entire stock of ore would be extracted in the initial period and the proceeds of the sale invested in some other assets whose value would rise at the rate of interest. If prices rose faster than the rate of interest, the entire stock of ore would be held in the ground until the last moment in time and then extracted. In this case, the mine is worth more un-extracted because the rate of return on holding ore in the ground exceeds the return on alternative investments (Hartwick & Olewiler, 1986).

[3] What these arguments require is that all mines operate with perfect foresight about the price of the mineral in all periods. To be able to see that it will be profitable to shift production from one period to the other, individuals must know what the price will be. Given that mines can produce for several decades, it is difficult to imagine that perfect foresight characterizes the centralized or decentralized operation of mineral markets. Some economists have argued that market forces will ensure that a perfect foresight equilibrium will be achieved in a decentralized situation, even if some participants in the market have deficient information. If a person I's foresight is deficient relative to person j's, j could make a profit by signing a contract to buy or sell, from i in the future at specific conditions. The informational deficiencies will be competed away by the forces of profit maximization and free entry into the industry (Hartwick & Olewiler, 1986).

The profit maximising solutions in monopolistic and competitive markets will however differ. Under perfect competition, the market price is exogenous to (fixed for) each firm (Hotelling, 1931). However, in a monopolistic market, price is not fixed, but will depend upon the firm's output choice (Hotelling, 1931). There is an incentive for a monopoly or a partial monopoly to keep production below the optimum rate and to slow the production rate as the resource is depleted to extract excessive prices from consumers (Hotelling, 1931). A monopolistic exploitation of an exhaustible resource is therefore likely to be protracted, taking place over a longer period than competition or maximisation of social value would require (Hotelling, 1931).

2.5. Backstop technologies/resources and the "choke" value

The conventional view is that exhaustion of most minerals is followed by the production of a substitute product (Hartwick & Olewiler, 1986). This alternative, or "backstop" resource will then be available in fairly large quantities so that its rate of price increase will initially be low.

Substitution will take place if the price of the resource rises to such an extent that it makes alternatives economically more attractive (Hartwick & Olewiler, 1986). The "choke price" is that price at which demand for the resource is driven to zero or is 'choked off' and the users of the resource switch entirely to the use of the substitute good (Hartwick & Olewiler, 1986). At the moment of exhaustion, prices would have risen to the cost of production of the back-stop resource (Hartwick & Olewiler, 1986). Thus, the cost of the backstop technology provides a ceiling price for the natural resource (Minnitt, 2007).

Physical exhaustion will occur in any industry if the marginal cost of extracting the final ton is less than (or equal) to the choke price. If, however, there are ore qualities with extraction cost in excess of the choke price, *economic* exhaustion occurs (Hartwick & Olewiler, 1986).

3. The outlook for terrestrial platinum supply to 2050

3.1. Introduction: A bird in the hand

Platinum-group metals (PGMs) include platinum, palladium, rhodium, ruthenium, osmium, and iridium. PGMs are among the least abundant of the Earth's elements and are unusual in that they are heavily concentrated in a single location, Southern Africa (i.e. South Africa and Zimbabwe) (Johnson Matthey). PGMs occur naturally in close association with one another as well as with nickel and copper (Cawthorn, 2010). Platinum and palladium are found in the largest quantities and have the greatest economic importance (Johnson Matthey).

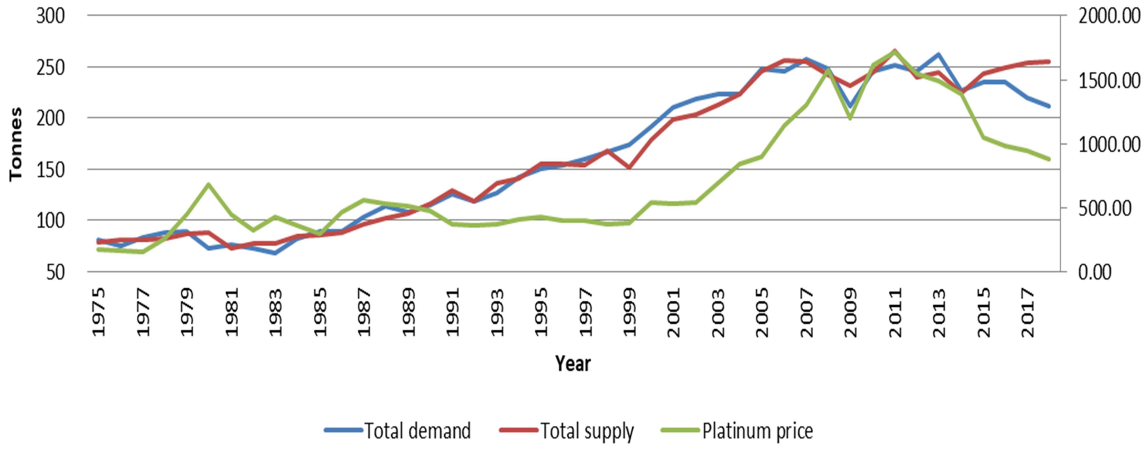
This section first investigates whether the platinum market has evolved as the economic theory of optimal extraction would predict. It then presents a forecast for terrestrial platinum production to 2050. The forecast is based on the assumption, as outlined in the economics of exhaustible resources section above, that platinum prices will adjust to ensure that the supply of platinum resources equals the global demand for platinum.

To conclude the section, the supply from both mining production and recycling is forecasted on the basis of 3 different growth rates, and is compared to known resources and reserves. Simple projections suggest that, unless alternative uses for PGMs arise, currently known resources will be sufficient to meet demand growth well into the 2nd half of the 21st century.

3.2. Platinum prices

Figure 1: Platinum Price, Demand & Supply below illustrates the relationship between the price, demand and supply (including recycled production) of platinum over the period 1975 to 2018.

FIGURE 1: PLATINUM PRICE, DEMAND & SUPPLY (1975 - 2018)



Source: Johnson Matthey

The trends illustrated in the graph can for most of the period be explained by the theory for the optimal extraction of exhaustible resources presented in the previous section. As the theory predicts, supply closely matched demand over the period 1975 to 2009, suggesting that Hotelling was correct in assuming that mineral prices will adjust to ensure that the market would at any given point in time be in equilibrium where supply always equals demand.

With demand and supply in balance, the theory would ascribe the increasing annual average platinum prices[4] to rising costs due to shrinking economically viable deposits as more metal is taken out of the ground. The platinum market is also a de facto oligopoly. These factors suggest that prices should have continued to rise sharply.

However, real prices have been in decline since 2009, with declines in nominal prices from 2012 onwards. This is contrary to Hotelling's theory, which predicts that prices should continue rising towards its choke price, where demand reaches zero and resources are depleted. The fact that demand has remained relatively strong, if declining, while resources have not yet been depleted, suggests that a price of around $900[5]/0z is still well short of platinum's choke price.

Some of these price movements can be easily explained. The sharp decline in prices in 2009 and subsequent recovery in 2010/11 was common to many minerals due to the impact of the global financial crises.

However, average annual prices again declined from 2012 to 2018. The World Platinum Investment council (WPIC) ascribes the decline up to 2015 on the sale of over 2mn ounces from above ground stocks despite a fundamental deficit in the market each year (WPIC, March 2016).

The declining prices could however also be explained by the fact that the market believes that platinum is not going to be a long-term scarce resource, either due to a falling off of demand (due to a decline in the sale of diesel vehicles following the "Diesel-gate" revelations in 2015 – see next section) or the potential for a viable (i.e. cheaper) backstop resource to emerge – either a strong increase in recycled supply (as experienced after 2004) or a large new ore body (such as asteroids).

The following sections explore the outlook for platinum demand and the potential for platinum supply to keep pace with demand growth, to determine whether the possibility of an oversupplied market exists.

3.3. The outlook for global platinum demand to 2050

Platinum is used in several applications due to its chemical and physical properties. It is soft, malleable, ductile, resistant to oxidation and high temperature corrosion, and is widely used as a catalyst (WPIC Platinum Perspectives, January 2018). Other distinctive properties include resistance to chemical attack and electrical stability (USGS, 2016). Platinum is often used with the addition of other metals, including other PGMs (WPIC Platinum Essentials, January 2018).

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[4] Although the annual average platinum price was the highest in 2011, the price reached its all-time high of $2 263/oz on 6 March 2008.

[5] The platinum price averaged $880/oz in 2018.

3.3.1. Drivers of platinum demand

Due to its attractive properties platinum has several uses in industrial (autocatalysts, manufacturing, electronics) and consumer applications (medical, jewellery), and in investments (bars, coins, other investment products) (WPIC Platinum Essentials, January 2018). A small amount of platinum is currently used in fuel cells (Johnson Matthey, May 2018); the fuel cell market however offers great growth potential and may ultimately become the most important dynamic in the platinum market (USGS, 2016).

Table 1: Platinum Demand below summarises the demand for platinum for the period 2013 to 2018 per major category of use, both in tonnes consumed and its share in total use. The leading drivers of consumption over the period continued to be catalytic converters (~40%), jewellery (30-35%), industrial applications (~20%) and investment (~5%). Fuel cells (included in *Industrial demand*) made up less than 1% of demand over this period. Platinum demand on average grew 4.1% per annum over the period 1980 to its peak in 2007, but in 2018 was 18% below the 2007 level.

TABLE 1: PLATINUM DEMAND (2013 - 2018)

Demand driver	2013		2014		2015		2016		2017		2018	
	Tonnes	**Share**	**Tonnes**	**Share**	**Tonnes**	**Share**	**Tonnes**	**Share**	**Tonnes**	**Share**	**Tonnes**	**Share**
Auto-catalysts	91.2	35%	93.8	41%	96.0	41%	98.4	42%	94.5	43%	88.2	42%
Year-on-Year % growth	-7%		3%		2%		3%		-4%		-7%	
Jewellery	92.8	35%	85.0	37%	80.5	34%	71.0	30%	69.7	32%	68.2	32%
Year-on-Year % growth	7%		-8%		0%		-12%		-2%		-2%	
Investment	27.2	10%	4.3	2%	8.6	4%	15.2	6%	7.5	3%	3.5	2%
Year-on-Year % growth	96%		-84%		100%		77%		-51%		53%	
Industrial	50.6	19%	44.3	19%	50	21%	50.4	21%	48.1	22%	51.8	24%
Year-on-Year % growth	7%		-12%		13%		1%		-5%		8%	
Total	**262**		**227**		**235**		**235**		**220**		**212**	
Year-on-Year % growth	**-6.5%**		**-13.1%**		**3.4**		**0%**		**-6%**		**-4%**	
Average annual growth rate: 1980 – 2018											**2.6%**	

Source: Johnson Matthey

The next section covers the outlook for each of these main sources of demand. The markets for autocatalyst and fuel cells are covered in greater detail because of the former's current large influence in the market and the latter's significant growth potential:

3.3.1.1. Auto-catalysts

Since 1979, the automotive industry has been the principal consumer of platinum, where it is used as an oxidation catalyst in catalytic converters to treat automobile exhaust emissions[6] (USGS, 2016). Stricter vehicle emissions standards in established markets such as Europe[7] and the US[8] have led to

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[6] Autocatalysts convert over 90% of hydrocarbons, carbon monoxide and oxides of nitrogen from gasoline engines into less harmful carbon dioxide, nitrogen and water vapour (Johnson Matthey).

[7] Since September 2015, Euro 6b emissions limits have been enforced on all new passenger cars registered in Europe (Johnson Matthey, Nov 2015).

mandatory use of pollution controlling devices such as catalytic converters, while expanding markets, such as China and India[9] have also introduced emission controls (Wilburn, 2012).

Different powertrains (e.g. diesel, gasoline hybrid, and battery electric vehicles (BEVs)) have significantly different loadings of platinum, palladium and rhodium; only BEVs contain no PGMs. Given platinum is the dominant PGM in diesel vehicle catalysts (USGS, 2019), a higher diesel market share would lead to higher platinum demand (and vice versa) (WPIC Platinum Essentials, January 2018).

The outlook for diesel vehicle sales has however become clouded since September 2015 when Volkswagen admitted to using software to circumvent EPA emissions standards for certain air pollutants (in particular, nitrogen oxides (NOx[10])) during testing, while the effectiveness of these vehicles' pollution emissions control devices is greatly reduced during normal driving situations. This approach results in cars meeting emissions standards in the laboratory or testing station, but during normal operation, emit NOx at up to 40 times the standard (US EPA, September 2015).

The "Diesel-gate" crises deepened in 2017 following allegations that major German auto-makers, including Volkswagen, Audi, BMW, Porsche, and Daimler, colluded to coordinate their exhaust gas treatment systems and fix technology, costs and suppliers (Der Spiegel, July 2017). In April 2019 the European Commission formally accused Volkswagen, BMW and Daimler of colluding to impede the roll-out of emissions limited technology (EUC, April 2019).

To make matters worse, a German court in February 2018 permitted driving bans for certain diesel vehicles in cities to enforce EU clean air rules (Wacket & Wissenback, Feb 2018), with a number of cities subsequently instituting or contemplating bans of varying degree[11].

Public uncertainty over emissions legislation, discrepancies between real world driving and test bed emissions and the risk and timing of possible diesel bans continue to dent sales of diesel cars in Europe, the largest diesel vehicle market, where the share of diesel in new passenger car sales has shrunk from above 50% in 2015 (ACEA) to 35% in January 2019 (WPIC, March 2019).

Platinum consumption in autocatalysts has also been hit by a decline in average platinum loadings, primarily due to a reduction in the PGM content of European diesel catalytic systems (Johnson Matthey, May 2019).

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[8] The US Environmental Protection Agency's National Low Emission Vehicle (NLEV) Program was implemented in 1997 as a voluntary program and Federally mandated by 2001 (Wilburn, 2012).

[9] India introduced the Bharat Stage III emissions legislation, equivalent to Euro 3, in 12 major cities across India in 2005 and enforced nationwide from April 2010. Bharat Stage IV, equivalent to Euro 4 emissions legislation, was introduced in 2010 in 14 major cities across India and set to be enforced nationwide from April 2017 (WPIC, November 2015).

[10] NOx pollution contributes to nitrogen dioxide, ground-level ozone, and fine particulate matter. Exposure to these pollutants has been linked with a range of serious health effects, including increased asthma attacks and other respiratory illnesses that can be serious enough to send people to the hospital. Exposure to ozone and particulate matter has also been associated with premature death due to respiratory-related or cardiovascular-related effects (US EPA, September 2015).

[11] In May 2018 Hamburg became the first city to impose a ban in its city centre (Chazan, May 2018). Stuttgart has announced that it will implement a ban in parts of the city from 2019 (Cremer & Chambers, May 2018). Courts have also ruled that Frankfurt (Wissenbach, Sept 2018) and Cologne and Bonn (Invaradi, Nov 2018) must implement bans for older diesel vehicles.

Diesel car shares seem unlikely to recover in Europe (WPIC, March 2018), but the outlook for diesel vehicles and platinum use in autocatalysts is however not all doom and gloom. There are three reasons for this: 1) efforts by auto-makers and legislators to repair diesel's image 2) increasingly stringent global emission standards, 3), substitution of other PGMs for platinum in autocatalysts.

Efforts by carmakers and legislators

Automakers are trying to win back consumers' trust in diesel vehicles by retrofitting hardware to existing on-the-road diesel cars to make them less polluting (with potential for additional demand for platinum) (WPIC, March 2018) and launching scrappage schemes that can help boost diesel sales[12].

As per Johnson Matthey (May 2019), automakers are also devoting enormous technical resources to meeting tightening legislation:

> *"the introduction of real driving emissions (RDE) testing in major markets is inciting the adoption of more conservative emissions strategies that prioritise compliance (i.e. necessitating more platinum) over cost."*

Automakers are increasingly using independent testing to present on-road NOx emissions in an attempt to address car buyer concerns, with recent results, widely publicised in Germany and the UK, showing diesels in a very positive light (WPIC, May 2019), supporting sales.

The World Platinum Investment Council (WPIC, May 2019) points out that:

> *"…several automakers now appear better disposed towards diesel and are considering retaining diesel engine options in their product ranges for longer, rather than removing them from production at the earliest opportunity… [This] renewed vote of confidence in diesel is driven largely by the need for automakers to meet very challenging CO_2 emissions targets, particularly for larger and higher mileage vehicles; diesels remain around 15%-20% more fuel efficient than their petrol equivalents, so a sizeable diesel share can help automakers avoid substantial fines and damage to their reputation."*

German authorities have also stepped in to limit the impact of diesel driving bans, in October 2018 amending federal emission laws to prevent bans in cities where cars have been successfully retrofitted, with all diesel cars with the emission standard EURO6 also excluded (BMU, October 2018).

Global emissions legislation

The major impetus for higher PGM loadings in autocatalysts is increasingly stringent emissions regulation on the CO_2, NOx and particulates that can be emitted from vehicles (WPIC Platinum Perspectives, January 2018). Regulation is currently most stringent in developed countries with developing countries following a similar trend (WPIC Platinum Perspectives, January 2018).

All else being equal, a higher volume of PGM content is needed to achieve lower emissions from a vehicle (WPIC Platinum Perspectives, January 2018). Technological improvements can go some way

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[12] Several automakers, including VW, Mercedes, BMW, Ford and Toyota, have launched scrappage schemes in Western European markets where drivers are offered incentives purchase new cars (any powertrain) in exchange for trading in an old diesel vehicle (WPIC, November 2017).

to offset this; autocatalyst manufacturers have got better at making small incremental reductions to PGM volumes (and maintaining the same emissions performance) (WPIC Platinum Perspectives, January 2018).

Since 2017, there has been a revolution in European light vehicle emissions legislation (Johnson Matthey, May 2019)[13]. The roots of these changes date back over ten years, but much of the shakeup was triggered by the 2015 emissions scandal (Johnson Matthey, May 2019).

Johnson Matthey forecasts that the demand for platinum in heavy duty catalysts rise significantly over the 2019–2021 period, as:

> *"…the implementation of China 6 and then India's BSVI emissions regulations results in the addition of advanced platinum containing catalytic systems for trucks…In the past, many vehicles sold in these countries were not equipped with PGM-containing catalytic systems, while those which did carry catalysts typically had low platinum loadings."*

Johnson Matthey (May 2019) also points out that this increasing toughness in emissions legislation is not just a question of degree, but also of kind:

> *"Previously, the legislation focused on reducing emissions by tightening limits. While tightening emissions limits will continue in future, the key changes are currently to the way vehicles are tested"*
>
> *"From 1 September 2018 all new vehicles sold in the EU must be emissions tested under the new Worldwide Harmonized Light Vehicles Test Procedure (WLTP), which replaced the outdated New European Driving Cycle (NEDC). This was done to ensure that laboratory tests more closely reflect the on-road emissions of a car, with the secondary aim of reducing various loopholes in vehicles testing. The new protocol (or parts of it), will be used in several major automotive markets: Japan adopted the test from 2018; China will adopt the WLTP 2020[14]."*
>
> *"In addition to the WLTP lap tests, "Real Driving Emissions" (RDE) mandates on-the-road testing of new vehicles for the first time in Europe. It is being implemented in two phases under Euro 6d."*

According to the WPIC (Platinum Perspectives, November 2018), the step up in standards means that manufacturers will need to improve their emissions technology, which should also boost PGM demand.

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[13] The phase-in of Euro 6d-TEMP regulations began in September 2017 and will apply fully to all passenger cars sold in Europe from September 2019 and to all light commercial vehicles a year later (Johnson Matthey, May 2018). China's 6a and 6b standards, to be fully implemented by 2020 and 2023, respectively, represent a significant tightening of emissions requirements, while India will adopt the Bharat Stage VI (BSVI - Euro 6-equivalent) in 2020 (WPIC Platinum Perspectives, Nov 2018).

[14] The US Environmental Protection Agency has been involved in all WLTP discussions but at this stage has no plans to adopt it, as it believes the current US test procedures are more representative of real driving conditions than the test cycles in use elsewhere (Johnson Matthey, May 2019).

While these innovations are unlikely to fully restore diesel's market share, they might help rehabilitate diesel's reputation and popularity to some extent.

Substitution of other PGMs

Platinum demand may also increase as a result of currently high palladium prices, and palladium supply concerns, which could boost platinum use in diesel catalysts at the expense of palladium (Johnson Matthey, May 2019), but substitution in petrol applications is more challenging (Johnson Matthey, May 2019).

In the late 1990s, palladium demand outstripped supply, resulting in a short term price premium over platinum. The result was substitution away from palladium and a significant demand increase for less expensive platinum (WPIC Platinum Perspectives, October 2018).

Palladium's latest price premium to platinum emerged in late 2017, with palladium prices setting new records in the first quarter of 2019, and with the premium over platinum widening to over $600/oz on average, there has been increased speculation about the potential to move away from palladium and towards platinum in the light duty diesel sector (Johnson Matthey, May 2019).

In the longer term, there may also be some potential for substitution in petrol applications. A number of US and European automakers are believed to be testing increasing platinum loadings on petrol auto-catalysts and in the last year several new test programmes on platinum-containing three-way catalysts for petrol vehicles have been initiated (Johnson Matthey, May 2019). Although there are technical challenges to overcome, there may be potential for additional platinum use in petrol applications within a two- to three-year timeframe (Johnson Matthey, May 2019).

Rhodium's recent rapid price increase also supports the use of more platinum for NOx reduction. Fabricators cannot share loading strategies of their automaker customers, making it difficult to verify this trend (and confirm increased platinum loadings) (WPIC Platinum Perspectives, January 2019).

3.3.1.2. Jewellery

Platinum's wear and tarnish resistance characteristics are well suited for making fine jewellery (USGS, 2016). Gold has traditionally been the metal of choice for jewellery in Asia, but platinum has established a secure niche and brand presence in urban markets (Jollie, Jan 2016). China is now easily the largest single market for platinum jewellery after a surge in demand from the 1990s on the back of its economic expansion (Johnson Matthey). India has also become an important market in the last decade; the market is much smaller, but has achieved double digit growth over the last few years (Johnson Matthey, May 2019).

Growth in the Chinese market has slowed over the past few years, but bridal demand in Tier 3 and 4 cities is a potential growth area (WPIC, March 2019), while the rate of urbanisation, long-term growth in disposable income and the effectiveness of jewellery promotion will continue to drive Chinese platinum jewellery sales growth in the medium term (WPIC, Nov 2017). India is expected to make the largest contribution to platinum jewellery demand growth as the young market remains in its growth phase (WPIC, May 2019). To date, platinum jewellery sales have mainly been confined to southern cities such as Chennai and Bangalore, with marketing activities focusing on the self-purchase and bridal gift markets, targeting younger, wealthier consumers (Johnson Matthey, February 2019).

3.3.1.3. Industrial use

Platinum is widely used in industrial applications due to its relative inertness and its ability to catalyze specific chemical reactions (Elshkaki & Van der Voet, 2006). Its main applications are in chemical catalysts and coatings (the largest industrial market), dental alloys, electronic components and computer hard discs to increase storage capacity, glassmaking equipment, medicines, and petroleum catalysts for gasoline refining (USGS, 2016).

Generally, there is a positive relationship between platinum industrial demand and global GDP (WPIC, January 2018). Even as some applications in each subsector becomes less widely used; platinum's physical properties make it likely that others will be found, leading to robust industrial usage over time (WPIC Platinum Perspectives, January 2018).

3.3.1.4. Investment

Like other precious metals, platinum is used as a medium for financial investment in the form of exchange-traded funds (ETFs), as well as physical bars and coins (such as the Platinum Eagle, the official platinum bullion coin in the US) (USGS, 2016). Short term price movements and macroeconomic events influence buying or selling in a given period with some dramatic year-on-year changes related to the launch of new ETF products in particular (Jollie, Jan 2016).

Platinum ETF balances have grown steadily since 2007 and there are now 16 platinum backed ETFs listed in listed in North America, Europe, Asia and South Africa (WPIC ETF, May 2019). New coin and bar launches from the South African Mint and Royal Mint are also increasing retail investment demand (WPIC, May 2019).

3.3.1.5. Fuel cells

Fuel cells generate electricity using an electro-chemical reaction, with the only emissions being water and heat (FCHEA, 2015). There are various types of fuel cells, but only the proton exchange membrane fuel cell (PEM) contains a platinum catalyst (Johnson Matthey).

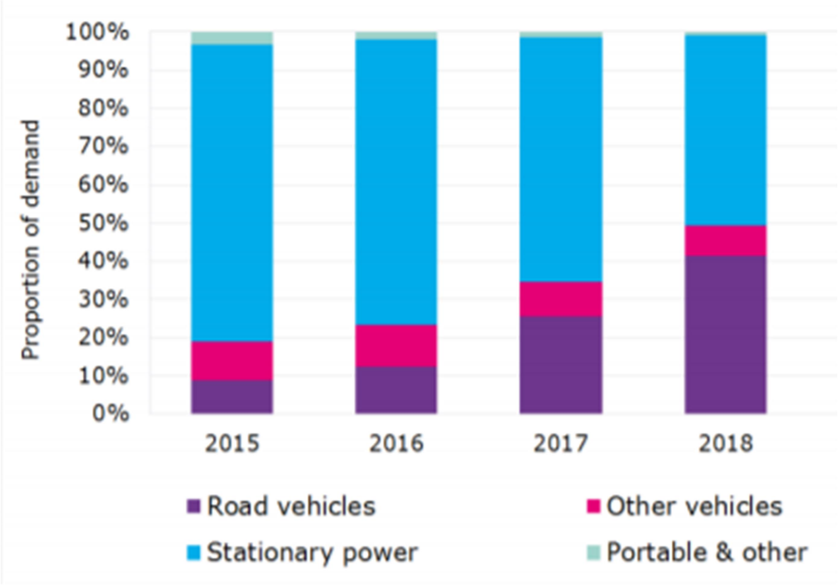
PEM fuel cells can be used in stationary power generation for buildings, in portable equipment instead of batteries or generators, and as replacements for vehicle internal combustion engines (FCHEA, 2015).

Platinum demand for fuel cells has grown from around 10 000oz to 15 000oz (0.42t) per annum in 2015 (Johnson Matthey, Nov 2015) to 25 000oz (0.71t) in 2014, and to 40 000oz (1.13t) in 2017 (Johnson Matthey, May 2018). The most significant source of demand for platinum in fuel cells is currently the large stationary sector, but demand for fuel cells in vehicles represents an ever-increasing share, now approaching 50% of demand (Johnson Matthey, February 2019), as shown below in *Figure 2: Platinum demand for fuel cells by application*, with annual fuel cell vehicle (FCV) platinum demand growing at over 150% per annum since 2015 (WPIC Platinum Perspectives, May 2018).

Although PEMs provide only a relatively small contribution to the levels of global deployment of large scale stationary fuel cells, a number of important projects (particularly in Europe and Korea) is expected to continue supporting platinum demand (Weidmeir et al, April 2019).

At present, the main application for PEM fuel cells is transportation, with more than 90% of the 490MW of PEM fuel cell systems deployed globally in 2017 for the transport sector (Weidmeir et al, Apr 2019). Indeed, fuel cell vehicles (FCVs) are considered the application with potentially the greatest impact on future platinum demand.

FIGURE 2: PLATINUM DEMAND FOR FUEL CELLS BY APPLICATION



Johnson Matthey, Platinum Perspectives, March 2019

The global FCV fleet today remains modest at about 10 000 vehicles, over half of which are in California (WPIC Platinum Perspectives, March 2019), but is growing rapidly. Johnson Matthey (Feb 2019) notes that:

> *"…sales of fuel cell cars (mainly in California and Japan) more than doubled in 2017, while several hundred fuel cell buses were deployed in China. The fuel cell sector continued to record strong growth in 2018, especially in China, where the government's New Energy Vehicle (NEV) programme has stimulated the market for electric vehicles, including FCVs."*

The FCV market is poised for even greater expansion, driven by endeavours to achieve zero on-road emissions (WPIC, May 2019), with growth centred in Asia[15]. In terms of zero emission vehicles, FCVs

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[15] Asia dominates the outlook for FCV growth. China's technology roadmap envisions 50 000 FCVs by 2025 and 2mn by 2030; fuel cell and hydrogen technology is named in both the 13th Five-Year Plan and the 'Made in China 2025' initiative (Johnson Matthey, May 2018), while several local governments have recently announced plans to provide support for the FCV sector (Johnson Matthey, May 2019). In March 2019, one of the revisions included in China's Government Work report was to promote the development and construction of fuelling stations for hydrogen fuel-cell cars. (Minter, March 2019). China is reducing NEV subsidies for battery electric and plug-in hybrid vehicles, but incentives for FCVs have been maintained (Johnson Matthey, February 2019); this has encouraged investment in fuel cell stack production capacity, and in the development of new FCV

offer advantages above battery electric vehicles (BEVs) in terms of driving range and charging time (WPIC Platinum Perspectives, March 2019). BEVs however at this stage have a cost advantage[16]. KPMG's 2018 Global Automotive Executive Survey found that fuel cell vehicles have replaced battery electric vehicles as the top key trend until 2025 (KPMG, 2018).

FCVs are not the only mode of transport adopting fuel cells, which are also being designed for rail[17] and water transport[18].

Rapid growth in fuel cell sales in the transport sector bodes well for future platinum demand, although, as with PGM loadings in autocatalysts, platinum loadings in fuel cells are being significantly thrifted (Johnson Matthey, May 2018). Current loadings are 30-80g per vehicle (WPIC Essentials, January 2018), but are expected to fall over time[19], with the US Department of Energy setting a platinum loading target of 12.5g (WPIC, January 2018); this is still materially higher than the platinum contained in a conventional internal combustion engine vehicle (3-10g for diesel) (WPIC, January 2018). Further, the US Department of Energy's Argonne National Laboratory in late 2018 identified a new catalyst that uses only about a quarter as much platinum as current technology by maximising the effectiveness of the available platinum, which at least keeps platinum in contention (Chong et al, December 2018).

Non-platinum solutions are currently still in the fundamental research stage and platinum is likely to remain the main catalyst used over the next decade (Bernhart et al, December 2013).

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platforms, including passenger cars, buses, logistics trucks and trams (Johnson Matthey, February 2019). Japan targets 40 000 FCVs by 2020 and 200 000 FCVs by 2025 (WPIC Platinum Perspectives, March 2019). South Korea in January 2019 unveiled its hydrogen roadmap, which targets 6.2m FCVs and 1 200 refuelling stations by 2040 (Hyun-woo, January 2019). Europe and the US take a different approach, focusing on hydrogen refuelling infrastructure to foster FCV ownership rather than setting specific fleet targets (WPIC Platinum Perspectives, December 2018), aiming for 400 stations by 2021 and 1 000 stations by 2030 respectively (WPIC Platinum Perspectives, December 2018).

[16] The Toyota Mirai – the Japanese company's signature fuel-cell vehicle – sells for around $70,000 (unsubsidized); Chinese battery-electric vehicles can sell for less than $10,000 (Minter, March 2019).

[17] Most of the global fuel cell train market development activities are currently concentrated in Europe (Ruf et al, April 2019). The world's first two hydrogen trains have already been in regular passenger service in the Elbe-Weser network since September 2018 (Alstom, May 2019), while French manufacturer Alstom in May 2019 announced that it will deliver 27 hydrogen fuel cell trains in the central German state of Hesse by 2022 (Alstom, May 2019). Fuel cell and hydrogen (FCH) technology is a promising option for replacing diesel combustion engines in rail transportation and that by 2030, one in five newly purchased train vehicles in Europe could be powered by hydrogen (Ruf et al, April 2019).

[18] Hyundai Motor will verify application of its fuel cells to coastal vessels by the end of 2022, improve the performance of its fuel cell systems by 2025 and apply the technology to real ships after 2030 (Min-he, May 2019).

[19] Mercedes Benz reported a 90% reduction in platinum content from its B-Class F-Cell (available first in 2010), to the current GLC F-Cell SUV. GM stated that in its latest generation FCV, the ZH2 military pick-up truck, it achieved a platinum loading "in the 12-gram range" and model further reductions, reaching about 10g before 2030 (WPIC Platinum Perspectives, March 2019). Hyundai Motor Co has cut the amount of platinum needed for the fuel cell stack in the latest edition of its NEXO, released in 2018, to 56g from 78g previously (Onstad, May 2019). Toyota's Mirai, is expected to cut platinum by two-thirds to around 10 grams per vehicle in its next version, down from 30 grams in the current model (Onstad, May 2019).

3.3.2. General demand forecast for platinum to 2050

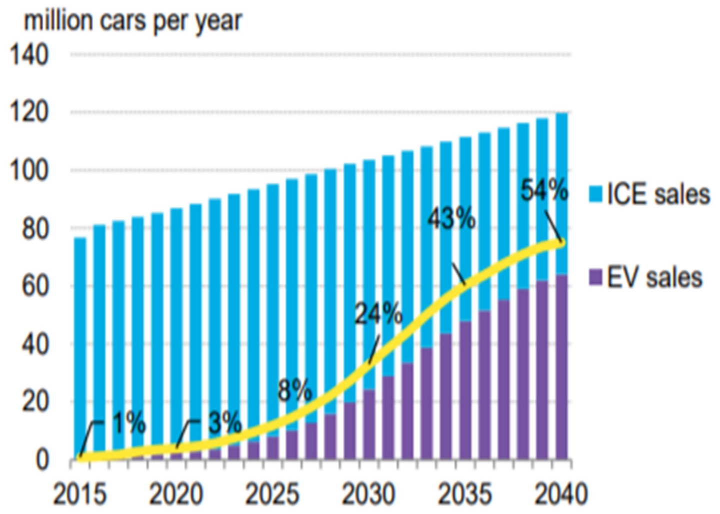
Jollie (January 2016) suggests four main factors that should drive future platinum demand: global economic and population growth, increases in the requirements for platinum from existing applications, and the development of new end uses.

Vehicle, jewellery and industrial demand should generally expand along with GDP growth, with population growth providing an additional boost. Forecasts for world growth to 2050 are modest, generally in the region of 3%[20]. The global population is forecasted to grow from 7.3bn in 2015 to 9.8bn in 2050 (UNWPP, 2017), an increase of 33%.

Automotive demand should reflect both increased vehicle sales and higher platinum loadings per vehicle to achieve stricter environmental standards, especially in the developing world, where increasing diesel sales should offset declines in Europe. Although fuel efficient lean-burn engines, particularly diesels, are expected to remain an essential part of the vehicle mix over coming decades (Johnson Matthey, November 2015), they are expected to cede some market share to petrol and electric vehicles due to concerns about diesel emissions.

Whilst this impact may substantially retard the growth in diesel vehicle sales, the growth in global vehicle production could help compensate for this – as shown by *Figure 3: Vehicle sales forecast*, combustion engines are expected to still represent a significant portion of global vehicle sales to at least 2040.

FIGURE 3: VEHICLE SALES FORECAST



Bloomberg New Vehicle Finance, May 2019

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[20] Forecast from major global institutions include: 2% - 2.5% by the EIU (EIU, 2015), just over 3% per annum by PWC (PWC, 2015) and the OECD (OECD, 2012) and between 2% (rich nations) and 3.3% (in low- and middle-income countries) by the World Bank (World Bank, 2006).

Thrifting is expected to continue, albeit at a reduced rate with smaller incremental improvements (IPGMA).

Investment growth should be driven by the broader global growth in savings and retirement funds and increasing new platinum investment products and interest over time (Jollie, January 2016).

Fuel cells offer the best potential for a new market. Transport and energy infrastructures will come under increasing pressure to reform their emissions profiles. This is likely to stimulate significant growth in fuel cell adoption over the next few decades, provided the cost and refuelling obstacles can be overcome (Adamson, 2015). Significant growth in FCV demand will of course cut into catalytic converter demand.

Recognizing these issues, this thesis considers an average growth in platinum demand of 2% per annum to 2050 to be reasonable (lower than the 2.6% achieved over the past 35 years). A growth of 4% per annum is considered to be an optimistic forecast, while a growth of 6% would be achieved only under exceptional circumstances.

3.4. Global platinum supply

PGMs are recovered from 3 sources: primary PGM deposits, as by-products of nickel and copper recovery and from secondary (recycled) resources. The section first reviews the available global platinum resources and reserves, briefly covering the major producer regions. It then shows that over the last 40-years, the growth in supply has generally followed the growth in demand and that supply has the potential to absorb a moderate growth in demand over the next 30 years.

3.4.1. Global platinum resources and reserves

In most classification schemes, “resources” refer to tonnage and grade estimates based on geological information; “reserves” indicate an economic feasibility study has been complete (Zientek et al, 2014).

Table 2: Total Terrestrial Resources & Reserves presents a break-down of PGM and platinum reserves by major producing regions and provides for each an estimate of the life-time of resources and reserves based on 2018 production. The proportion of PGM reserves attributable to platinum is calculated as the average of annual platinum production to the sum of platinum, palladium and rhodium[21] production for the period 2000 to 2018.

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[21] No detailed historic production data for the other PGMs are available; platinum, palladium and rhodium however represent the bulk of PGM production.

TABLE 2: TERRESTRIAL PLATINUM RESOURCES & RESERVES

Country	PGMs			Platinum (Pt)					
	Tonnes		% of global	% Pt	Tonnes		% of global	Years Pt resources at 2018 production	Years Pt reserves at 2018 production
	Resources	Reserves			Resources	Reserves			
South Africa		63 000	91%	60%		37 779	96%		272
Russia		3 900	6%	22%		852	2%		40
North America		1 210	2%	27%		321	1%		31
Others[1]		1 200	2%	49%		592	1%		30
Total	**> 100 000**				**> 45 000**	**39 544**		**> 237**	**208**

Source: USGS 2019, Johnson Matthey

1 Includes Zimbabwe

3.4.1.1. Global platinum resources

“Resources” are defined as: a concentration of naturally occurring solid, liquid, or gaseous material in or on the Earth’s crust in such form and amount that economic extraction of a commodity from the concentration is currently or potentially feasible (USGS, 2019). Resources must be continuously reassessed in the light of new geologic knowledge, of progress in science and technology, and of shifts in economic and political conditions (USGS, 2019).

The US Geological Survey 2019 estimates global PGM resources in mineral concentrations currently or potentially economic to mine at more than 100 000 tonnes[22]. These resources represent more than 237 years of platinum supply at 2018 production levels.

Economically recoverable concentrations[23] of PGMs are not found in many places. PGMs resources occur primarily in igneous intrusions such as the *Bushveld Igneous Complex*[24] (BIC) in South Africa (by far the largest), the *Great Dyke* in Zimbabwe, and in Russia’s *Noril’sk-Talnakh* district (Zientek et al, 2014). Most of the PGMs recovered from mining in Canada are by-products of nickel-copper ores in the *Sudbury Basin* in Ontario (Johnson Matthey). Virtually all the PGM production in the US comes from the *Stillwater Complex* in Montana (Johnson Matthey). PGM resources in other areas are viewed as negligible, although sizeable PGM resources have been identified in Australia and Finland, where initiating production would require substantial capital investment (Wilburn, 2012). Extensive exploration during the early 2000 has produced no new major targets or mines (Cawthorn, 2010).

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[22] This estimate has remained unchanged since 1996.

[23] Average crustal abundances for PGMs range from a few 10s to a few 100s parts per trillion (Zientek et al, 2014). The BIC contains up to 3ppm of PGMs (Cawthorn, 2010). The Great Dyke has a lower PGM content than the BIC, with head grades generally below 4ppm (Johnson Matthey). Although Russia’s reefs are thicker than the ones mined in South Africa, they are more variable in grade and PGM composition (Wilburn, 2012). Platinum has a concentration of 5 part per billion (ppb) in the earth crust (Elshkaki & Van der Voet, 2006).

[24] The Bushveld Complex has been subdivided into three areas, the Northern limb (hosting the Platreef) and the Eastern and Western limbs (each hosting the Merensky Reef and UG2 seam). The Merensky Reef has been a principal source of PGMs since it was first worked in 1925 because of its shallower depth and generally higher PGM content than the UG2; in addition, the Merensky Reef has a lower chromite content, which makes it easier and less costly to process ores than from the UG2 seam. Production from the UG2 seam began in the 1970s and has steadily increased (Wilburn, 2012).

3.4.1.2. Global platinum reserves

Conceptually, “reserves” may be considered a working inventory of mining companies’ stock of an economically extractable mineral commodity. Importantly, the concept is dynamic. Reserves may be reduced as ore is mined and/or the extraction feasibility diminishes, or, they may continue to increase as additional deposits (known or recently discovered) are developed, or currently exploited deposits are more thoroughly explored and/or new technology render viable ore bodies that were previously sub-marginal (USGS, 2016). As such, the magnitude of that inventory is necessarily limited by many considerations, including cost of drilling, taxes, commodity prices, and the demand for the commodity (USGS, 2016); in any given ore-body, the extent of the reserve is therefore simultaneously determined by the marginal extraction cost, and the demand for the commodity. The term reserves need not signify that extraction facilities are in place and operative (USGS, 2016).

The USGS 2019 declares a total of 69 000 tonnes PGM reserves from six regions: South Africa (91%), Russia (6%), North America (2%), and “Other” (incl Zimbabwe) (1%). These reserves represent 208 years of platinum supply at 2018 production levels (also assuming South African reserves can accommodate any short-fall from depleted reserves in other countries).

3.4.2. Terrestrial platinum production

Platinum supply includes both that extracted from the ground as well as from secondary sources, mostly recycling. Large strati-form PGM deposits, such as the *BIC*, *Great Dyke* and *Stillwater*, typically contain PGMs of sufficient grade to be considered the primary products. PGMs are recovered as by-products from Canadian and Russian nickel and copper deposits (Wilburn, 2012).

Table 3: Terrestrial Platinum Supply summarises platinum supply from both mined and recycling production for the period 2013 to 2018 from each major producing region, given for each the total volume produced at its share of the global total. Production is dominated by South Africa (~75%), with Russia (~12%), Zimbabwe (~8%), and North America (~5%) the other noted producers. Recycling accounts for around 25% of terrestrial supply and comes mostly from auto-catalysts (~65%) and jewellery (~35%) (Johnson Matthey). Supply grew by an average of 3.1% per annum since 1980. Most of the increased primary production was from established areas South Africa, Russia, Canada, and Zimbabwe (Wilburn, 2012).

TABLE 3: TERRESTRIAL PLATINUM SUPPLY (2013 – 2018)

Source	2013		2014		2015		2016		2017		2018	
	Tonnes	Share	Tonnes	Share	Tonnes	Share	Tonnes	Share	Tonnes	Share	Tonnes	Share
Mined production		**74%**		**71%**		**78%**		**76%**		**75%**		**74%**
South Africa	130.9	72%	110.3	69%	142.2	75%	136.6	72%	138.4	73%	138.9	73%
Year-on-Year % growth	2.4%		-15.7%		28.9%		-3.9%		1.3%		0.4%	
Russia	22.9	13%	21.8	14%	20.8%	11%	22.2	12%	22.4	12%	21.4	11%
Year-on-Year % growth	-8.0%		-4.8%		-4.6%		6.7%		0.9%		-4.5	
Zimbabwe	12.7	7%	12.5	8%	12.4	7%	15.2	8%	14.5	8%	14.7	8%
Year-on-Year % growth	21.0%		-1.6%		-0.8%		22.6%		-4.6%		1.4%	
North America	9.9	5%	10.5	7%	9.8	5%	10.5	6%	10.2	5%	10.3	5%
Year-on-Year % growth	4.2%		6.1%		-6.7%		7.1%		-2.9%		1.0%	
Other	5.4	3%	5.2	3%	4.7	2%	5.0	3%	4.9		4.8	3%
Year-on-Year % growth	38.5%		-3.7%		-9.6%		6.4%		-2.0%		-2.0%	
Total - mined production	**181.8**		**160.3**		**189.9**		**189.5**		**190.4**		**190.1**	
Year-on-Year % growth	**-3%**		**-12%**		**18%**		**-0.2%**		**0.5%**		**-0.2**	
Secondary sources		**26%**		**29%**		**22%**		**24%**		**25%**		**26%**
Recycling	62.6		64.0		53.3		60		64		65	
Year-on-Year % growth	-1%		2%		-17%		13%		6%		3%	
Total supply	**244.4**		**224.3**		**243.2**		**249.7**		**254.0**		**255.5**	
Year-on-Year % growth	**2%**		**-8%**		**8%**		**3%**		**2%**		**0.6%**	
Average annual growth rate: 1980 – 2015											**3.1%**	

Source: Johnson Matthey

3.4.3. Potential to meet future demand

Demonstrated reserves and resources published by mining companies make detailed calculations up to a maximum of about 20 years ahead, but there is abundant and adequate geological evidence that these deposits continue far beyond where mining companies have proven according to rigorous international reporting codes (Cawthorn, 2010). It is also likely that any potential shortage of terrestrial supply will push up PGM prices, thereby enlarging the pool of economically viable resources.

Various studies suggest that there are sufficient PGM resources positively identified by mineral exploration to meet projected platinum demand well into the middle of the 21st century (Zientek et al, 2014). Exploration patterns at the larger, long-established operations suggest that, even when exploration does not delineate large new deposits, exploration often better defines potential new ore zones. The longevity of some global PGM mines is proof of this (Wilburn, 2012). Mining will therefore not deplete the identified mineral resources and reserves or potential undiscovered mineral resources for many decades (Zientek et al, 2014).

Most of the global PGM capacity expansion will continue to come from established areas in South Africa[25], Russia[26], Zimbabwe[27], and North America (Wilburn, 2012).

The availability of recycled supply should increase as the introduction of stricter vehicle emission standards boosts the amount of PGMs available from recycled automobile catalysts as diesel cars from the early and mid-2000s with higher platinum loadings enter the recycling stream in greater numbers (Johnson Matthey, Nov 2015). Growth should slow down later in the period as scrapped loadings diminish because of thrifting.

3.5. Forecast of terrestrial platinum supply under 3 growth rates

While PGM supply will likely be affected by short-term economic, social, environmental and political factors (Zientek et al, 2014), this thesis demonstrates that there are sufficient reserves of PGMs and platinum in particular to meet a strong increase in platinum demand to 2050.

Table 4: Forecast of Terrestrial Platinum Supply to 2050 presents the forecasted numbers calculated by this thesis for both primary and recycled production to 2050 under 3 different growth rates, 2%, 4% and 6% respectively. Recycling supply is assumed to grow at the same rate as demand and primary mined production is the difference between total demand and recycled supply.

As shown in the table, terrestrial reserves would only come under threat by 2050 if mined production from now till then were to grow at 6% per annum. The resource estimates used in the calculation are however the minimum known quantity and it is likely that the global reserves would by then far exceed the 34 years calculated here as reserves keep expanding as prices rise.

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[25] A greater amount of new South African PGM production is likely to come from deeper, higher cost Upper Group Reef (UG2) and Eastern Bushveld deposits as the shallower, lower-cost mineralized portions of the Merensky Reef in the Western Limb becomes depleted (Wilburn, 2012).

[26] Future Russian PGM capacity is likely to come from ore zones with generally lower PGM content and different platinum-to-palladium ratios than the nickel-rich ore that dominated PGM supply in the 1990s (Wilburn, 2012).

[27] Zimbabwe also holds some potential to be a more meaningful producer of platinum over the longer term. However, a complex political and operating environment makes it unlikely that any significant additional investment will be made in the platinum mining sector there in the next few years (Jollie, Jan 2016).

TABLE 4: FORECAST OF TERRESTRIAL PLATINUM SUPPLY TO 2050

Assumed annual average growth rate	2015		2020		2025		2030		2035		2040		2045		2050	
	Tonnes produced	Years resources at current production	Tonnes produced	Years resources at current production	Tonnes produced	Years resources at current production	Tonnes produced	Years resources at current production	Tonnes produced	Years resources at current production	Tonnes produced	Years resources at current production	Tonnes produced	Years resources at current production	Tonnes produced	Years resources at current production
Annual growth rate in demand	2%															
Mine production	190	237	152	293	168	261	186	232	205	205	226	181	250	159	276	140
Recycled supply	53		68		75		83		92		101		112		123	
Total terestrial supply	**243**		**220**		**243**		**268**		**296**		**327**		**361**		**399**	
Annual growth rate in demand	4%															
Mine production	190	237	158	282	193	228	234	183	285	146	347	115	422	90	513	70
Recycled supply	53		71		86		105		127		155		189		229	
Total terestrial supply	**243**		**229**		**279**		**339**		**412**		**502**		**610**		**743**	
Annual growth rate in demand	6%															
Mine production	190	237	164	272	220	199	294	144	394	104	527	73	706	51	944	34
Recycled supply	53		73		98		132		176		236		315		422	
Total terestrial supply	**243**		**238**		**318**		**426**		**570**		**763**		**1 021**		**1 366**	

Source: own calculations based on parameters outlined in thesis.

4. The outlook for asteroid mining

4.1. Introduction: To boldly go

There is a rapidly growing body of work covering the economic viability, technical requirements, legal considerations and environmental impacts of asteroid mining. The idea of exploiting asteroid resources dates back almost a hundred years (see Tsiolkovskyi below), but only now is the technology becoming available to make asteroid mining a reality. Significantly, three operating companies have roadmaps for launch, exploration of targets and the eventual extraction of space resources.

Asteroid miners target *near-Earth asteroids* (NEAs), whose orbits make them relatively accessible from Earth. NEAs are potentially rich in useful volatiles such as water, oxygen and hydrogen, base metals such as iron ore and nickel, as well as precious metals including platinum group metals (PGMs) and gold.

While asteroid-mined precious metals, such as PGMs, may compete in Earth-based markets, it is postulated that the huge cost of transporting materials (for life support, fuel and construction) from Earth into space to supply a spaced-based economy would also result in a space-based market for asteroid mined materials.

NEAs also pose a pending threat to Earth and contain valuable information about the formation of the universe, providing a security and scientific incentive to study asteroids.

This thesis argues that the economic, security, and scientific interests together will attract the necessary investment to explore and exploit NEAs. While it assumes that asteroid mining kicks off at a very small scale in 2030, the outcomes of the analysis, and the conclusions drawn, do not materially differ if mining starts at any time before 2050.

The next section presents a brief review of asteroid mining literature and then outlines the rational for asteroid mining. The section concludes with a review of the current state of the asteroid mining industry and related projects, followed by a brief overview of the main challenges faced by asteroid miners.

4.2. A brief review of asteroid mining literature

The notion of asteroid mining is far from new. Tsiolkovskyi (1926) included the “exploitation of asteroids” as one of his 16 points for the conquest of space in *Plan of Space Exploration* (Keck, 2012). Asteroid mining was first discussed in concept by Cox and Cole (1964) and in more detail by O'Leary (1977). An early study for NASA by Johnson and Holbrow (1977) proposed the feasibility of retrieving a main belt asteroid for mining; however, because of the very long travel times, Billingham, Gilbreath & O'Leary (1979) and O'Leary (1982) suggested instead the mining of asteroids with orbits closer to Earth.

John Lewis (1996) describes in more detail routes for accessing and processing extra-terrestrial resources, either for use on Earth or for enabling space colonization. Lewis postulates that colonies built with the natural resources of the asteroid belt alone could eventually support a vast civilization of "several tens of quadrillions (10^{16})" of people.

Mark Sonter in his seminal 1997 (updated 2012) thesis *The Technical and Economic Feasibility of Mining the Near Earth Asteroids* argues that future space industrialization and exploration will prompt the search for in-space resources to use in construction and as propellant mass. He concludes that NEAs are the most likely targets and that robotic resource recovery from NEAs is technically feasible in the near term. His findings are supported by, inter alia, Gerlach (2005), Casini (2011), and Cutright (2013).

Few papers deal explicitly with platinum supplied from asteroids. Kargel[28] (1994) estimated that a 1km metallic asteroid of "good platinum PGM enrichment" (in the 90th percentile) could yield 117 000t of platinum (615-times total 2018 production on earth). His prediction that extra-terrestrial sources of PGMs would become available in the global market-place was echoed by Blair (2000) and Ross (2001). They all concluded that, while platinum would not be economic to mine on its own, the potential for other materials would justify a multi-product operation.

Considering the technical feasibility of asteroid mining, a 2012 study sponsored by the *Keck Institute for Space Studies*[29] (Keck, 2012) suggests that it should be possible to return a ~7m diameter, ~500t NEA to high lunar orbit by 2025, using technology that is or could be available with-in a decade. Buet et al (2013), Zhoa et al (2013), and Janhunen & Merikallio (2015) agreed that the retrieval of asteroid resources using simplified mining techniques seems quite possible within the next few decades. All of these papers proposed a mission designed for a single space-craft to either capture and haul an asteroid back to the earth's orbit for mining operations, or mine the asteroid remotely and return the mined material to earth-space.

Papers are also now addressing the economic feasibility of asteroid mining: Hein et al (2018) finds that the economic viability of an asteroid platinum mining venture depends greatly on the development costs and mining throughput rate, but would ultimately only be profitable in a very narrow set of values for price elasticity and substitution, when the quantity of platinum from space would substitute an equal quantity of terrestrial platinum. Both Hein et al and Calla et al (2018) (who consider the feasibility of mining water in space) conclude that an economically feasible operation is more likely if swarms of smaller spacecraft are used to perform the mining.

The preconditions for asteroid mining are not, however, all technical or economic. In their reviews of the legal aspects of asteroid mining Lee (2008), Feinman (2014) and Leterre (2017) all conclude that a new international legal framework outlining property rights and regulatory authority in more detail would be required to incentivise asteroid mining. More recently, Hennig (2016), MacWhorter (2016) and Hein et al (2018) have introduced environmental arguments for asteroid mining, in particular with regards to platinum group metals.

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[28] Jeffrey S Kargal has been an Adjunct Professor and Senior Research Scientist at University of Arizona since 2005, specialising in Earth and Planetary Science and obtained a doctorate in Planetary Science in 1990.

[29] The Keck Institute for Space Studies aims to develop new planetary, earth, and astrophysics space mission concepts and technology. The institute was established at the California Institute of Technology in 2008 and draws on external experts from academia, government, and industry - http://kiss.caltech.edu/mission.html.

4.3. The rational for asteroid mining

There are two potential motivations for asteroid mining:

1) Expanding activity in space in the future will require resources that will be more cheaply obtained from asteroids than from earth; and
2) Existing mining on earth continues to a point where prices are high enough to justify a switch of technique to asteroid mining.

This section outlines the 1st rational for asteroid mining, discussing the market for space resources and the potential of space-mined resources to jumpstart a nascent space-based economy. Thereafter it outlines the attraction of NEA to harvest resources from and briefly examines the additional advantages of asteroid mining and challenges faced by asteroid miners.

The 2nd rational is discussed in more detail in *Section 5: The potential impact of asteroid mined platinum*.

4.3.1. The market for space resources

At present, the development of large-scale tourism, habitation, and manufacturing in near-Earth space is hampered by Earth-launch costs of several thousand dollars per kilogram (Buet et al, 2013). The overriding requirements for a sustained human presence in space are therefore energy and materials outside of Earth's gravity that can be exploited. Future space industrialization will therefore prompt the search for and provide the market for in-space resources (Sonter, 2012).

4.3.1.1. The cost advantage of in-space resource supply

Because of the immense amount of energy required to escape from Earth's gravity, the viability of a space-based economy is limited by launch costs (Accenture, 2015). For many years, the private sector was unable to improve on the US space shuttle transport system's initial launch costs of $15 000 - $20 000/kg into low-earth orbit (LEO) (Cutright, 2013).

Launch costs have, however, come down over the past few years as dozens of private companies race to reduce them (Tartar & Qiu, Jul 2018). This market is dominated by SpaceX, the first company to successfully land its rocket safely back on earth (Bloom-ed, Feb 2018); other major players include United Launch Alliance (a joint venture between the aerospace arms of Boeing and Lockheed Martin), and European launch service provider Arianespace (Tartar & Qiu, Jul 2018). Blue Origin is also developing its own reusable orbital vehicles and successfully launched and landed its New Shepard rocket in July 2018 (Stone, Jul 2018).

Some outfits have lowered launch costs by developing smaller rockets designed to carry just a few hundred kilograms into LEO; other companies are achieving lower costs through economies of scale with heavier rockets (Tartar & Qiu, Jul 2018).

But the biggest factor in the drive to lower costs is "reusability"- the capacity to employ components of launch vehicles and spacecraft multiple times (Tartar & Qiu, Jul 2018). SpaceX's successful demonstrations of reusability for its launch vehicle (in 2016), its cargo capsule (in 2017), and most recently its heavy-launch vehicle (in 2018) are seen as watershed moments in both aerospace technology and the commercialization of space (Tartar & Qiu, Jul 2018).

Table 5: Space rocket launch costs set out the cost to transport 1kg of material from earth into LEO and GTO respectively.

TABLE 5: SPACE ROCKET LAUNCH COST

Rocket	Launch Service Provider	2018 launches	Cargo capacity to LEO - kg	LEO launch cost/kg ($)	Cargo capacity to GTO - kg	GTO launch cost/kg ($)
Falcon Heavy*	SpaceX	1	63 800	$1 400	26 700	$3 400
Falcon 9 (Re-used)*	SpaceX	20	22 800	$2 100	8 300	$5 900
Proton M	VKS/Roscosmos/ILS	2	23 000	$2 800	6 270	$10 400
Ariane 6*	Arianespace		20 000	$4 700	4 500	$20 900
H3*	MHI Launch Services		10 000	$5 000	6 500	$7 700
Long March 3B/E	PLA/CGWIC	11	12 000	$5 800	5 500	$12 700
Soyuz FG	VKS/Glavkosmos	5	7 800	$6 400	N/A	
PSLV	ISRO/Antrix	4	3 250	$6 500	1 425	$14 700
Long March 4C	PLA/CGWIC	4	4 200	$7 100	1 500	$20 000
Long March 4B	PLA/CGWIC	2	4 200	$7 100	1 500	$20 000
Long March 2C	PLA/CGWIC	6	3 850	$7 800	1 250	$24 000
Long March 3A	PLA/CGWIC	2	8 500	$8 200	2 600	$26 900
Long March 2D	PLA/CGWIC	8	3 500	$8 600	N/A	
Ariane 5	Arianespace	6	20 000	$8 900	10 500	$17 000
H-IIA/B	Mitsubishi Heavy	4	10 000	$9 000	4 000	$22 500
GSLV	India Space Research	2	5 000	$9 400	2 500	$18 800
Long March 11	PLA/CGWIC	3	530	$10 000	N/A	
Antares	Orbital ATK	2	6 200	$12 900	N/A	
Atlas V	ULA	5	8 123	$13 400	2 690	$40 500
Soyuz 2.1a/2.1b	VKS/Roscosmos/ILS	10	4 850	$16 500	3 250	$24 600
Delta IV	ULA	2	9 420	$17 000	4 210	$38 000
Vega	Arianespace	2	1 963	$18 800	N/A	
Electron	Rocket Lab	3	225	$21 800	N/A	
Rockot	VKS/Eurocot	2	1 820	$23 000	N/A	
LauncherOne*	Virgin		500	$24 000	N/A	
Minotaur IV*	Orbital ATK		2 600	$23 100	860	$69 800
*First launched since 2017 or in development						

Source: FAA, 2018

These innovations have led to lower costs for the launch industry as a whole - launch costs have dropped by between 10-15% in real terms since 2010, driven in part by SpaceX, whose costs has dropped by about 25% (Tartar & Qiu, Jul 2018), putting pressure on rivals such as Arianespace and ULA to also drop prices (Tartar & Qiu, Jul 2018).

However, the further away from Earth material is launched, the greater the costs. Among geostationary or geosynchronous transfer (GTO) missions, which need to achieve a specific orbit of around 36 000km and are therefore better suited for direct comparison, average launch costs are down about 20% from 5 years ago (Tartar & Qiu, Jul 2018), but still, as the table above shows, average over $20 000/kg. It costs roughly $35 000/kg to launch material to a high lunar orbit (Kutter & Sowers, 2016).

Sustainable operations in space are therefore not feasible if all supporting supplies and materials must be launched from Earth. Raw materials retrieved from non-terrestrial sources however need not attract the high "airfreight" costs because the energy requirement to return material from many NEAs is much less than the energy requirement to launch the material from Earth (Sonter, 2012).

To illustrate the cost advantage, consider the following example: at $35 000/kg it would cost $17.5bn to launch 500t of material to a high lunar orbit. In contrast, the Keck study (2012) estimated the full cost of delivering a 500t asteroid to high lunar orbit at $2.6bn, a 7th of the cost of launching the material from Earth.

4.3.1.2. Jumpstarting the space-based economy

Komerath[30] (2011) defined a "space-based economy" as one where the majority of suppliers, value-adders and customers are located beyond Earth, and trading between them occurs for the most part without transiting Earth. This thesis extends this description of a space-based economy by including the shipment of space-mined resources back to earth.

Although no such market exists at present, Weinzierl (2018) conceives a:

> *"self-reinforcing virtuous cycle of space development that would support the space economy. For example, cheaper and more frequent rocket launches might facilitate short-term space tourism as well as both industrial and scientific experimentation on suborbital and orbiting spacecraft. If these activities become routine, demand might rise for commercial habitats to support longer flights and micro-gravity factories. In turn, these habitats could generate demand for resources in space, both material inputs and fuel."*

Other authors develop this concept. Cutright (2013) postulated that an active and expanding in-situ resource development program could jumpstart a self-sustaining space-based economy. Accenture (2015) argues that starting a space mining industry early in the space development phase can dramatically reduce commercial space-development costs. Similarly, Casini (2011) insisted that after an initial phase to build up space infrastructures with material sent up from Earth, it would be essential to start using space resources. Not only would space resources have to provide the critical fuel, air and materials needed to expand and maintain a space industry (as argued by Janette, May 2014), but as Craig et al (Dec 2014) make clear, a certain level of pre-existing space industry would also be required to provide fuelling services and/or energy sources for the mining operations, as well as a market for the raw materials.

In a 2005 conference paper, Gerlach suggested that this sort of feedback loop could accelerate the economic development of space. He envisioned early materials being used to support space-based operations that would be able to acquire and process additional materials more cost-effectively.

A space-based resource economy could produce, transport, and store resources at distributed locations such as Earth and lunar orbits or Lagrange points[31] (Grogan & De Weck, 2012). Transportation, mission operations, and habitation systems capabilities would be expected to evolve

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[30] Dr Narayanan Komerath lectures in fluid and aero dynamics, space concepts and micro renewable energy systems at GIT's School of Aerospace Engineering. He has served as Fellow of the NASA Institute for Advanced Concepts and Chair of the Aerospace Division of the American Society for Engineering Education..

[31] Lagrange points mark positions where the combined gravitational pull of two large masses provides precisely the centripetal force required to orbit with them. There are five such points in cis-lunar space labelled L1 to L5, with L1 positioned about 80% to the moon on a straight line from Earth.

from the use of space-resources and build upon each other to enable a phased transition from operations in low earth orbit, to missions beyond this and ultimately to cis-lunar space, the Moon, and Mars (NASA, June 2012).

4.3.1.3. The potential for space-based resource demand

The uncertainties and imponderables relating to the economics of development in space mean that much of the discussion about it appears conjectural. However, Weinzierl (2018) makes the point that, though economists should treat the prospect of a developed space economy with healthy scepticism, it would be irresponsible to treat it as science fiction.

Weinzierl (2018) further stresses that:

> *"…there is general agreement on the technologies essential for the commercialization of space: low-cost, frequent launch capabilities, advanced spacecraft power and propulsion capabilities, in-space resource extraction and energy collection, in-space manufacturing, in-situ resource utilization (ISRU), and long-term cryogenic fuel storage, and scalable habitats."*

Many of these technologies are now being developed by the fast growing global industry of private companies and entrepreneurs generally known as *NewSpace*.

NewSpace companies seek to profit from innovative products or services developed in or for space (Newspaceglobal, 2019). In contrast to the traditional model of large government-run programs, *NewSpace* enterprises are typically private companies backed by personal finance or risk capital, which primarily target commercial customers (David & Strevy, August 2014). Since 2000, start-up space ventures have attracted around $21.8bn in investment, with a record $3.2 being invested during 2018 (Bryce, 2019).

Companies like *Space Exploration Technologies Corporation* (SpaceX), *Orbital Sciences* and *Virgin Galactic* offer a range of products and services, including, but not limited to, building rockets, mission planning services, freight carriage to space, and monitoring of planetary risks (Nordrum, April 2015), while some aim to offer human space travel and habitation (NASA, Sept 2014). Several companies plan to provide more than one type of service (NASA, September 2014).

There are signs that the current government-aided phase of *NewSpace* is leading to a thriving private sector space economy (Silber, May 2014). For now, a major focus of *NewSpace* remains government funding for projects, such as NASA contracts to *SpaceX*, *Orbital Sciences*, *Sierra Nevada* and *Boeing* for resupplying the International Space Station (ISS) and ferrying astronauts[32] (Silber, May 2014). However, in 2014 it was already being argued that next generation launch systems, and in-situ resource extraction, would so revolutionize the space industry as to allow *NewSpace* to supplant government legacy programs by the next decade (Janette, May 2014).

Governments will nevertheless remain important contributors to the space economy. China, India, Russia, Japan, South Korea, Israel and multiple European nations, have announced plans or initiated missions to send spacecraft into lunar orbit and to the surface of the Moon by 2030; many nations,

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[32] Since the retirement of the space shuttle program in 2011, the US has relied on Russia to transport their astronauts to the ISS at a cost of about $74m per seat (Silber, May 2014).

including the US and China, are also planning missions to Mars's orbit and surface in the 2030s (NASA, Sept 2018).

This thesis assumes that the rapid development in space-based commerce over the next few decades will set sufficient demand for fuels for use in satellites and space-craft, volatiles for life-support, structural materials to construct platforms for space tourism, in-space manufacturing, and solar power stations, as well as regolith for radiation-shielding.

4.3.2. The attraction of near-Earth asteroids

There are countless asteroids circling the sun. Most lie inside the *main asteroid belt* between Mars and Jupiter[33], however, some have been pushed from the main belt into Earth-crossing orbits (Gerlach, 2005). NEAs are those that come within 1.3 astronomical units (AU) from Earth i.e. 1.3 * 150m km (the average distance of the Earth from the sun) (Sonter, 2012). Roughly 20% of NEAs have orbits that come within 0.05 AUs of the Earth's orbit (Keck, 2012).

More than 20 000 NEAs have been catalogued thus far (JPL, May 2019), however, the existence of about 25 000 000 NEAs with a diameter of ~100m has been inferred from mathematical models (Libourel & Corrigen, 2014). The Keck institute posits that there are millions of NEAs larger than 10 meters in diameter, and billions larger than 2 meters.

Cutright (2013) suggests that the two most persuasive arguments in favour of NEAs as the primary source for space resources are, their relative accessibility from Earth orbit, and the wide variety of resources they contain. These issues had been recognised far earlier by O'Leary (1977), who argued that the exploitation of NEAs could allow greater flexibility in mission design propulsion systems and would greatly reduce the cost of space industrialisation during the early stages.

This section develops his view, first outlining accessibility to asteroids in terms of energy required to reach them; this is followed by a comparison of asteroid resources to those of other space bodies.

4.3.2.1. The energy advantage

Energy is likely to dominate the extraction costs incurred when mining asteroids. Even if the ores are rich, the resource has to be accessed and retrieved (O'Leary, 1977). In space, the parameter which determines how easy or difficult it is to deliver mass from one orbit to another, is not distance, but the required velocity change (Delta-V or Δv), measured in km/s, needed to perform the transfer (Sonter, 2012). The required Δv is dictated by the orbital positions of the departure and destination objects relative to each other (Zacny et al, 2013). It is this issue that make NEAs so attractive.

Table 6: Mission Velocity Requirement below shows the Δv requirements to depart and reach objects within the solar system – the smaller the number, the less energy is required:

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[33] There are over 700 000 known asteroid in the main belt, ranging in size from 1m to 1 000km in diameter (JPL, Aug 2015). Many are left to be discovered. An estimated 1 to 2 million objects in the main asteroid belt are greater than 1km in diameter (Cutright, 2013).

TABLE 6: MISSION VELOCITY REQUIREMENT	
Transfer	**Delta-V (km/s)**
Earth surface to Low Earth Orbit (LEO)	8.5
Earth surface to escape velocity	**11.2**
Earth surface to Geo-synchronous Orbit (GEO)	11.8
LEO to highly-elliptical Earth orbit (HEEO)	2.5
LEO to escape velocity	3.2
LEO to GEO	3.5
LEO to Mars transfer orbit	3.7
LEO to Near Earth Asteroid (NEA) – Average	**4.0**
LEO to Moon landing	6.3
NEA to Earth transfer orbit – Average	**1.0**
Moon surface to LEO (aero-braking)	2.4
The moons of Mars: Phobos/Deimos to LEO	8.0

Source: Sonter 2012

NEAs are attractive for resource utilization due to the relatively low Δv required to reach them and to return resources from them (Gerlach, 2005). The table shows that it requires less energy to transfer from LEO to nearly anywhere in the inner solar system than it is to get into orbit from the Earth's surface. Most NEAs require less Δv than a round-trip mission to Mars, many of them require less energy than is required to reach than the surface of the Moon. Similarly, a few NEAs have Δvs for return departure on the order of 1 km/s, less Δv than required for a return trip from the Moon (NASA, February 2015).

4.3.2.2. Asteroid resources

Asteroids not only contain a wide variety of resources, but are also considerably more research rewarding than other potential sources of space bodies such as the Moon or Mars.

Asteroids contain many of the materials necessary for space development: mass in orbit for life-support, fuel, construction, conducting, insulation, chemical processes and radiation-shielding (Sonter, 2012). Furthermore, certain types of asteroids contain rich endowments of precious metals that could be shipped back to earth.

Table 7: Asteroid Resource Use below summarizes the materials available from asteroids and their potential uses[34].

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[34] Volatiles will be the easiest products to extract and process (Accenture, 2015). Initially, processing would concentrate on the extraction and purification of water, followed by electrolysis to split the water into hydrogen and oxygen and the liquefaction of both gases. Strong "baking" forces auto-reduction of the major mineral magnetite (Fe3O4), leading to a release of more water, carbon monoxide (CO), carbon dioxide, and nitrogen. The released CO is used as a reagent for the extraction, separation, purification, and fabrication of iron and nickel products via the Mond process. The residue from Mond extraction would be a dust of cobalt, PGMs, and semi-conductor components such as gallium, germanium, selenium, and tellurium. Metals can be transformed into usable alloys using industrial processes perfected on Earth (Keck, 2012).

TABLE 7: ASTEROID RESOURCE USE	
Primary use	**Molecule**
Volatiles	
Life support	Water (H_2O), Nitrogen (N_2), Oxygen (O_2)
Propellant	Hydrogen (H_2), Oxygen (O_2), Methane (CH_4), Methanol (CH_3OH)
Agriculture	Carbon dioxide (CO_2), Ammonia (NH_3)
Oxidizers	Hydrogen peroxide (H_2O_2)
Refrigerant	Sulphur dioxide (SO_2), Nitrogen (N_2)
Metallurgy	Carbon monoxide (CO), Hydrogen sulphide (H_2S), Nickel carbonyl ($Ni(CO)_4$)), Iron penta-carbonyl ($Fe(CO)_5$), Sulphuric acid (H_2SO_4)
Radiation-shielding	Water (H_2O)
Metals and semi-conductors	
Construction	Iron (Fe), Nickel (Ni), Cobalt (Co), Titanium (Ti)
Semi-conductors	Silicon (Si), Aluminium (Al), Phosphorus (P), Gallium (Ga), Germanium (Ge), Cadmium (Cd), Copper (Cu), Arsenic (As), Selenium (Se), Indium (In), Antimony (Sb), Tellurium (Te)
Precious metals	Gold (Au); PGMs: Platinum (Pt), Palladium (Pd), Osmium (Os), Iridium (Ir), Rhodium (Rh), Ruthenium (Ru), Rhenium (Re), Germanium (Ge)
Non-metals	
Radiation-shielding	Regolith[35]
Agriculture	Regolith

Source: expanded on Ross, 2001

Compared to asteroids, the material on the lunar surface is poor in volatiles and metals, being similar in composition to the slag discarded in metallurgical processing on Earth (Ross, 2001). The Moon has metals and trace quantities of water but no organics (Cutright, 2013) and is thought to contain little if any carbon, nitrogen or oxygen (O'Leary, 1977); free metal concentrations in lunar regolith are typically only a few hundred ppm (compared to about 20% in stony asteroids) (Ross, 2001).

Mars has metals, an atmosphere, and plentiful water, but it is unlikely that it has any viable organic resources necessary to sustain life (Cutright, 2013).

4.3.3. The other advantages of mining asteroids

The section will provide a brief review of the other stated advantages of mining NEAs: 1) synergies with planetary defence, 2) scientific research, and 3) protecting the Earth's environment:

4.3.3.1. Synergy with planetary defence

More than 100 tons of asteroid fragments hit the Earth's atmosphere every day (NASA, 15 Sept 2014). Although the vast majority disintegrate before reaching the surface, those larger than 100 meters may survive and cause major destruction[36] (NASA, 15 Sept 2014).

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[35] Surface fragmented rocky debris blanketing the Moon and small solar system objects.

[36] The *Alvarez Hypothesis* blames the extinction of the dinosaurs on a massive asteroid that struck Mexico's Yucatan Peninsula 65m years ago (Dean, November 2015). In June 1908 an asteroid 36m in diameter exploded over Tunguska in Siberia, releasing the energy of 185 Hiroshima bombs (Dean, November 2015). Then, in

The mining of NEAs would provide valuable information on the small perturbations that affect asteroid trajectories, their internal makeup and structural integrity, as well as the technology to avert a potential asteroid impact (Keck, 2012).

4.3.3.2. Scientific Research

Studying asteroids would expand our understanding about the origins of life as well as terrestrial geology.

NEAs are remnants of the early solar system and contain information that has been lost in the planets through large-scale planetary processes such as tectonism and vulcanism (Casini, 2011).

Exploring NEAs may help us discover whether asteroids delivered to earth life sustaining microbes (NASA, Jun 2012), ores in Earth's crust and water in our oceans (Elvis, May 2012). Importantly, asteroids offer the opportunity to study material with a known origin (Elvis, May 2012).

4.3.3.3. Protecting the Earth's environment

There is a very strong environmental and sustainability argument for space-based mining. Exploitation of Earth's accessible resources has had profound environmental costs. It has forced humans to dig deeper for lower grade materials that are more costly to produce, to use more energy and produce more waste (Elshkaki & Van der Voet, 2006). The environment may be severely impacted by the use of hazardous substances during the extraction process (Hein2 et al, Oct 2018). Toxic mine water and leachate from dumps are also problems. Lastly, there is growing pressure to target sensitive areas such as national parks, the Great Barrier Reef, the deep sea-bed and Antarctica (Lee, 2008).

Relocating a part of Earth-based mining activities to space would reduce the environmental impacts and consumption of energy, mineral, and water resources on Earth (Cutright, 2013).

Hein et al (Hein2 et al, Oct 2018) concluded that the global warming effect of Earth-based mining is several orders of magnitude larger than a space-based equivalent would be, even allowing for the manufacture and launch of rockets etc.

4.4. Challenges faced by asteroid miners

Although challenges remain, great strides have been made in discovering and characterizing NEAs that may be targeted for asteroid mining. The legal framework for asteroid mining is also undergoing an overhaul to provide the necessary security for investors.

This section briefly outlines each of these issues.

4.4.1. Asteroid target selection

Currently, there are a limited number of targets around which primary and backup opportunities can be planned (Keck, 2012). Good outbound opportunities do not generally fit with good return opportunities (Sonter, 2012) and many accessible asteroids mission opportunities are 10- to 40-years

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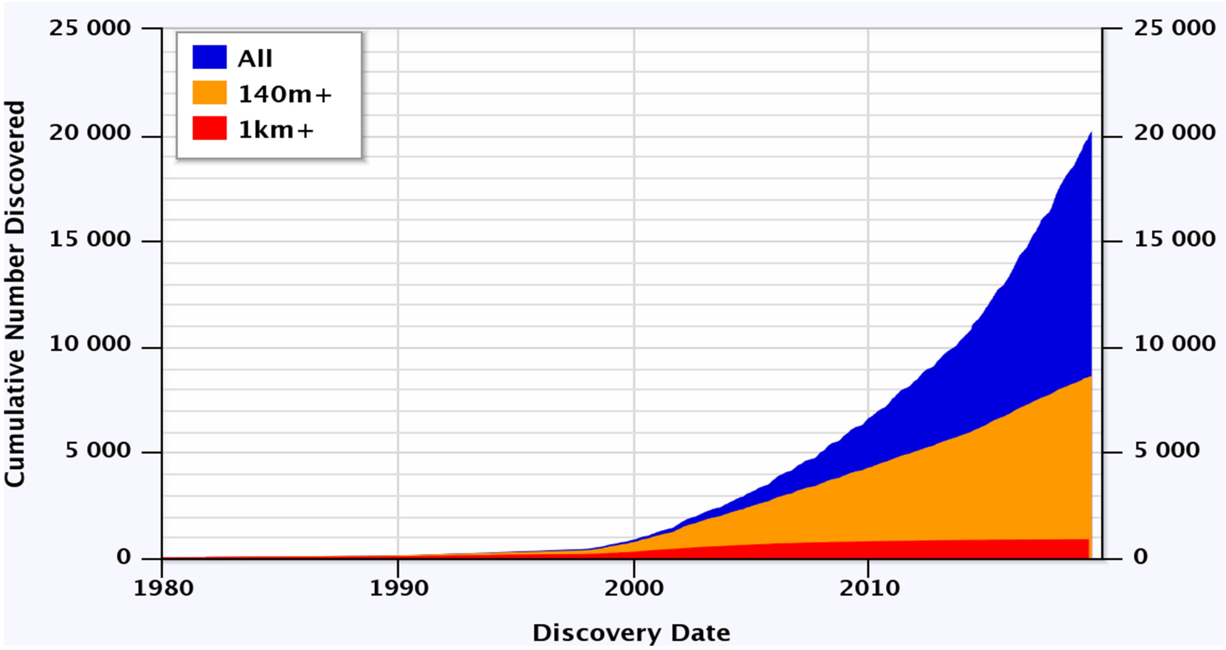
February 2013 an asteroid approximately 18 meters in diameter burnt up over the Russian city of Chelyabinsk with the force of 500 kilotons of TNT (Dean, November 2015).

apart[37] (Hopkins et al, 2010). However, the number of asteroids with favourable orbits is rapidly increasing as more asteroids are discovered (Hopkins et al, 2010).

Larger asteroids are easier to discover and characterize; small asteroids are faint and can only be discovered by ground-based observatories on the rare occasions they make a very close approach to Earth (Keck, 2012). Despite the limitations[38] of ground-based telescopes, modern asteroid survey systems are automated and new asteroids are being located in ever-increasing numbers (Libourel & Corrigen, 2014). Detection rates were also boosted by NASA's redeploying of the NEOWISE[39] space-based telescope, which has discovered 285 NEAs since reactivation in September 2013 (JPL, May 2019).

Just over 20 300 NEAs have been discovered to date, with more than 1 500 new ones currently being discovered per year (JPL, May 2019). 90% of the near-Earth objects larger than one kilometer in diameter have already been discovered; the NEO Program is now focusing on finding 90% of the NEO population larger than 140 meters (JPL, May 2019). *Figure 4: Known Near-Earth Asteroids* depicts the growth in the number of asteroids discovered since 1980 (as of May 2019), delineated by size:

FIGURE 4: KNOWN NEAR-EARTH ASTEROIDS



Source: NASA

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[37] Launch windows to Jupiter (5.2 AU) occur every 13 months and to Mars (1.5 AU) every 26 months (Hopkins et al, 2010).

[38] Detection is possible only at night, there is no coverage in much of the southern hemisphere, and weather, moonlight, and atmospheric distortion make detection much more difficult than it is from outer space. Furthermore, searching for asteroids from Earth makes it very hard to find asteroids in orbits similar to our own (Tomblin et al, Aug 2015).

[39] NEOWISE was previously known as the *Wide-field Infrared Survey Explorer* (WISE) space-based telescope (NASA, 11 Nov 2015). WISE's mission was to create infrared images of 99% of the sky.

4.4.2. Legal considerations

Much of the ownership of space is regulated by The *Outer Space Treaty*[40] of 1967 (UNIDIR, 2015); however, the treaty did not anticipate the commercial exploitation of space resources, and the mining of space materials was left unregulated (Lee, 2008). The US stepped into the void and adopted the *Commercial Space Launch Competitiveness Act* in November 2015. This granted US space firms the right to extract, own and sell resources extracted from an asteroid (but not claim ownership over the asteroid itself) (Molloy, Nov 2015). Many have however questioned whether the US has the power to confer these rights under the limitations of the *Space Treaty* (Fecht, Sept 2015).

Luxembourg passed a similar law, the *Asteroid Act* in August 2017 (Pheifer, Sept 2018). Luxembourg is positioning itself as a hub for asteroid mining, launching a €100m fund to back space technology start-ups (Pheifer, Sept 2018). Both of the leading asteroid mining companies - Planetary Resources and Deep Space Industries – have opened offices in Luxembourg.

Given the inadequacies of international law and the ambiguities of the US and Luxembourg acts, an overhaul of international regulations is needed to provide investors with greater certainty.

In economic terms, new laws will need to establish a property right regime for asteroids, as well as how profits will be taxed and how security concerns will be addressed (Accenture, 2015). New laws could considered asteroids to be chattels rather than celestial bodies because they are moveable objects that can be claimed by a single owner and held against other parties (Feinman, 2014) and might require that ownership is granted only once a resource has been worked for a certain amount of time (Lee, 2008). An international governing body needs to be established to administer the law, issue exploration and mining permits, and resolve disputes (Lee, 2008). Over time, it is possible that space will see the development of a code of conduct similar to maritime law and the system of convention and regulation that governs use of the seas (Oxford Analytica, 2008).

4.5. Asteroid projects

This section gives a brief overview of the 3 existing asteroid mining companies and then provides a brief summary of current and planned government asteroid related projects.

4.5.1. Asteroid mining companies

Private asteroid mining firms *Planetary Resources*, *Deep Space Industries* and *Kepler Industries* have invested heavily in the design, development and construction of asteroid prospecting probes and automated robotic mining mechanisms.

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[40] The *Outer Space Treaty* was adopted by 102 nations, including the US and Russia, and proclaims that celestial objects are part of the "common heritage of mankind" (not defined), and that "outer space, including the Moon and other celestial bodies, shall be free for exploration and use by all States" (UNIDIR, 2015). Furthermore, activities in outer space would be governed by the principle of International Law and would not be subjected to any domestic legislation of any country (Sharma & Dari, 2012).

4.5.1.1.Planetary Resources

Planetary Resources was founded in 2011, with the purpose of transforming asteroid water into rocket fuel for orbital refuelling stations within a decade, and eventually to harvest PGMs (Wall, Aug 2015).

The company has raised more than $50mn in investments and successfully sent two satellites into orbit over the course of the past 6 years. The company in January 2016 managed to print the first ever 3D object from actual asteroid materials (Planetary Resources, Jan 2016).

In July 2015, Planetary Resources deployed its Arkyd-3 Reflight (A3R) from the International Space Station. A3R was critical to the development of several core technologies required to build more advanced spacecraft (Planetary Resources, May 2019).

Planetary Resources in January 2018 launched its Arkyd-6 spacecraft, designed as a technology demonstrator for future missions to explore and categorize asteroids for eventual resource mining. Its demonstration mission was declared a success in April 2018 (Planetary Resources, May 2019).

Assuming that funding is found, the next step in Planetary Resources' timeline is to develop more advanced asteroid-prospecting satellites known as the Arkyd 301. Such satellites could identify and potentially sample water. The program is an extensive data-gathering series of missions in deep space that will visit multiple near-Earth asteroids (Planetary Resources, May 2019).

Planetary Resources was acquired by block-chain software technology company ConsenSys in October 2018 (Bryce, 2019).

4.5.1.2.Deep Space Industries

Deep Space Industries (DSI) was founded in 2012, its aim being to invest in the technical resources, capabilities and system integration required to prospect for, harvest, process, manufacture and market in-space resources. It proposed carrying these out using small spacecraft the company planned to develop – *FireFly* prospector space-craft would first conduct initial survey work from 2017. After confirming targets, *DragonFly* space-craft would collect samples (25–50kg (Harris, 2013)) for detailed analysis on Earth (2019/20). *Harvester* space-craft would then mine the minerals for processing in Earth's orbit (Lu, Apr 2015).

DSI has however failed to achieve its initial *Firefly* targets and has more recently focussed on smallsats, as well the production of a propulsion system called Comet that uses water as a propellant (Foust, Jan 2019). In addition to selling these propulsion systems to other satellite developers, the company is incorporating them into its own smallsat bus, Xplorer, specifically designed for missions beyond Earth orbit (Foust, Jan 2019).

In January 2019 DSI was acquired by Bradford Space Group, a space technology company, which has not ruled out again pursuing asteroid mining (Foust, Jan 2019).

4.5.1.3.Asteroid Mining Corporation

Asteroid Mining Corporation (AMC) was founded in 2016 (AMC, May 2019).

AMC's first mission is the Asteroid Prospecting Satellite One (APS1), which aims to conduct a compositional survey of 5 000 NEAs in order to identify those rich in PGMs, and to produce a Space

Resources Database (AMC, May 2019). The dataset will be commercialised to fund the development of space mining hardware (AMC, May 2019).

The dataset will then guide the target selection for AMC's second mission planned for 2023, the *Asteroid Exploration Probe One* (AEP1), which will visit the asteroid identified as having the highest concentrations of platinum. AEP1 will produce a global surface map of metallurgical, mineralogical and molecular components of the asteroid in order to select mining sites, while also examining the surface conditions of the asteroid in order to determine which attachment mechanisms and extraction techniques will be required to recover platinum from the asteroid (AMC, May 2019).

AMC's longer term goal is launching the *Asteroid Mining Probe 1* (AMP-1) in 2028. AMP-1 will be designed to recover 20tons of platinum. AMP-1 will also be used as a test-bed for in situ resource utilisation technologies and additive manufacturing techniques (AMC, May 2019).

4.5.2. Other space projects relevant to asteroid mining

There are a number of government asteroid missions related to the testing of deep space capabilities, scientific research and planetary defence underway or in the pipeline. These projects are test-beds for asteroid mining operations, demonstrating capabilities for deep space robotic missions, ISRU identification, characterization, extraction, processing, capturing, containment, and EVA tools for exploring low-gravity bodies (NASA, Oct 2015). Outlined in *Table 8: Government asteroid missions* are brief detail of these planned missions:

TABLE 8: GOVERNMENT ASTEROID MISSIONS

Mission	Agency	Target	Year	Details
Hayabusa2	JAXA	Ryugu	2014 - 2020	Hayabusa2 launched in December 2014 and arrived at C-type asteroid Ryugu in June 2018. It will survey the asteroid until December 2019 and collect samples. It successfully touched down on the asteroid in February 2019 and collected its first sample and in April 2019 it used explosives and a copper projectile to create an artificial crater from which it will potentially collect a second sample. The probe will return the samples to Earth around the end of 2020.
OSIRIS-REx	NASA	Bennu	2016 - 2023	The Origins, Spectral Interpretation, Resource Identification, Security-Regolith Explorer (OSIRIS-REx) mission launch in Sept 2016 and arrived at asteroid *Bennu* in August 2018. It aims to return a 60g sample to Earth in 2023.
Asteroid Impact & Deflection Assessment	NASA & ESA	Didymos	2020 – 2022	NASA "Dart" craft will launch in mid-2021 and arrive at double asteroid Didymos, arriving in 2022 and fire a probe into the asteroid. The ESA "Hera" craft will launch in 2023 and arrive at Didymos in 2026 to observe the impact of the Dart's probe at to put down its own lander on the smaller of the two asteroids.
Psyche	NASA	Psyche	2022 – 2027	Psyche is a nickel-iron asteroid in the main asteroid belt. The mission is scheduled to launch in 2022, arrive at the asteroid in 2026 and remain in its orbit for 2 years. The mission aims to determine whether Psyche has a molten core, or if it is un-melted material, as well as if it contains the same light elements as are

				expected in the Earth's high-pressure core.
Asteroid Retrieval Mission (ARM)	NASA	TBC	N/A	ARM was designed to launch a robotic mission to a greater than 100m diameter NEA, collect a multi-ton boulder from its surface along with regolith samples, and return the material to a stable orbit around the Moon for exploration. The mission was cancelled by Pres Trump in 2018.

Source: Compiled from the relevant space agency’s information presented on their respective websites.

5. The outlook for asteroid platinum supply to 2050

5.1. Introduction: All that glitters

Headlines proclaiming "*Asteroid with platinum core worth £3.5 trillion set to pass Earth*", "*Single asteroid worth £60 trillion if it was mined – as much as world earns in a year*", and "*Trillion Dollar Baby*" greeted asteroid *2011 UW-158* on its Earth fly-by in July 2015. Few studies have however explicitly investigated the potential platinum supply from asteroids.

This section first provides a general background on asteroid geology, classification and composition. It then outlines how the amount of platinum contained in an asteroid can be calculated and presents figures for potential platinum supply from various sizes of the 3 main asteroid types. The section then calculates potential asteroid platinum supply to 2050 under 3 different scenarios.

5.2. Asteroid geology

Asteroids are an amalgam of proto-planetary debris[41] that range from essentially undifferentiated solar nebula material (minus the lightest volatile compounds) to melted and differentiated planetary mantle and core material composed mostly of elemental iron, nickel, and cobalt (Cutright, 2013).

This section presents a review of asteroid geology, first outlining the various methods with which to determine asteroid composition and then gives more detail regarding the geological classification of asteroids. The composition of the 3 main types of asteroids is then presented.

5.2.1. Determining asteroid geology

The study of asteroid composition began in 1970 with asteroid Vesta, supported by spectral studies of minerals and meteorites (Gaffey et al, 2002). There are now over 100 000 asteroids which have had some measurement of their surface composition (De Meo et al, 2015).

Methods to constrain the surface mineralogy of asteroids include: 1) Spectral analysis[42], 2) meteorites[43], 3) samples and 4) asteroid fly-bys. Since the 1980s, there have been considerable

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[41] The geological characteristics of asteroids are governed by the environment in which they formed. Most asteroids condensed just after the formation of the solar system, approximately 4.7bn years ago (Gerlach, 2005). The environment allowed larger bodies, especially planets, to differentiate gravitationally - pulling iron and nickel as well as PGMs to the core (Blair, 2000). Bodies forming at the edge of the solar system cooled more rapidly, slowing or stopping this differentiation process. Smaller bodies did not develop sufficient mass for gravity separation and reflect the original distribution of elements from the supernova event (Gerlach, 2005).

[42] The principal of reflectance spectra is simple: different minerals observe light at different wavelengths, producing reflectance spectra with characteristic, wavelength-dependent absorption features (Nelson et al, 1993).

[43] Fragments of comets or asteroids that enter the Earth's atmosphere are known as meteors. Most meteors are small and vaporize in the Earth's atmosphere as "shooting stars" before reaching the planet's surface. A meteor that reaches the Earth's surface is known as a meteorite (NASA, 15 Sept 2014).

advances in laboratory spectral calibrations[44], and meteor studies and interpretive methodologies have been validated by several spacecraft rendezvous (Reddy et al, 2015).

However, spectral analysis tells us only about the composition of an asteroid's surface[45] (Carry, 2012), which is constantly being altered by an array of "space weathering" processes (Janette, May 2014). The majority of meteorites are derived from asteroid interiors, which are not subject to the same space weathering (Nelson et al, 1993) and therefore better reflect the bulk make-up of the asteroid. Tens of thousands of meteorite samples[46] have been collected and remain the primary source of data on asteroid chemical composition (Reddy et al, 2015).

Meteorites are therefore the only "ground truth" available, but selection biases are large and not well known. For example, volatile and structurally weak or friable objects (such as carbonaceous chondrites) will generally not survive entering the upper atmosphere (Sonter, 2012). The processes that deliver meteorites from the asteroid belt to the Earth are also strongly biased toward sampling the inner zones of the asteroid belt (Nelson et al, 1993).

The only direct sample of asteroid material ever returned to earth was by the Japanese spacecraft *Hayabusa* of the asteroid *Itokawa*[47]. As outlined in *Table 8*, two more sample return missions to NEAs are currently underway – JAXA's Hayabusa2 and NASA's OSIRIS-REx.

Space agencies from the US (NASA), Japan (JAXA), Europe (ESA) and China (CNSA) have all successfully completed robotic spacecraft rendezvous missions with asteroids (Keck, 2012). These mostly high-speed fly-bys (Gerlach, 2005) have provided detailed information on chemical and physical properties of the visited NEAs. However, they also confirmed that the characterization of the inner part of NEOs cannot be understood just by observing their surface (Casini, 2011). A brief outline of all asteroid fly-by missions (comet missions excluded), including the two planned asteroid sample retrieval missions, is given in *Table 9: Asteroid fly-by missions* below.

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[44] Since the early 2000s there have been numerous advances in the mineralogical characterization of asteroid surfaces using visible/near-infrared (VIS/NIR) and mid-IR spectra, as well as in our ability to model and interpret the data allowing for more accurate interpretations of asteroid surface mineralogies (Reddy et al, 2015).

[45] Gamma-ray spectroscopes unveiled end 2015 however promises the ability to measure sub-surface elemental abundance accurately (Griffin C, 20 Nov 2015).

[46] The number of meteorites catalogued for science has increased exponentially over the past few decades from fewer than 10 000 to more than 50 000 (Pearlman, May 2013). Approximately 5 000 chemical analyses of meteorites provide a large database of the chemical makeup of asteroids (Cutright, 2013).

[47] Although the sampling mechanism did not work, thousands of 10-100μm particles were found in one of the sample containers, apparently introduced during the spacecraft impact into the surface of the asteroid. The sample was returned to Earth aboard the *Hayabusa* in June 2010 and confirmed that *Itokawa* is indeed an LL chondrite as suggested by Binzel et al. (2001) (Reddy et al, 2015).

TABLE 9: ROBOTIC ASTEROID RENDEZVOUS				
Asteroid	**Space Agency**	**Spacecraft**	**Year**	**Description**
Phobos and Deimos	Various	Various	1970s – 2010	Several Russian, US, and European Mars missions, mostly recently by the ESA Mars Express orbiter in 2010.
Gaspra	NASA	Galileo en route to Jupiter	1991	Entered asteroid belt, passing about 1 600km from Gaspra.
Ida and Dactyl	NASA	Galileo en route to Jupiter	1993	Galileo flew by Ida on 28 August 1993, with its closest approach at 2 390km.
Mathilde	NASA	NEAR en route to asteroid Eros	1997	Passed within 1 200km of main belt asteroid, acquiring more than 500 images. First close observation of a C-type asteroid.
Braille	NASA	Deep Space 1 fly-by	1999	Spacecraft flew past asteroid, but camera problems limited the data received during this encounter.
Eros	NASA	NEAR-Shoemaker	2000 - 2001	Most extensive asteroid mission to date; orbited for a year and landed on this main belt S-class asteroid. Extensive analysis of surface. Most detailed knowledge to date of an asteroid.
Itokawa	JAXA	Hayabusa	2005	Arrived at Itokawa in September 2005 and landed on the asteroid in November 2005, collected samples in the form of tiny grains of asteroidal material, which were returned to Earth aboard the spacecraft on 13 June 2010.
Steins	ESA	Rosetta fly-by	2008	The Rosetta space probe flew by Steins on 5 September 2008 at a distance of 800 km and a relatively slow speed of 8.6 km/s.
Lutetia	ESA	Rosetta fly-by	2010	On July 10, 2010, the Rosetta space probe flew by Lutetia at a minimum distance of 3 162km.
Vesta and Ceres	NASA	Dawn	2011 - current	Dawn entered Vesta orbit on 16 July 2011, and completed a 14-month survey mission before leaving for Ceres in late 2012. It entered Ceres orbit on 6 March 2015 and is predicted to remain in orbit perpetually after the conclusion of its mission.
Toutatis	CNSA	Chang'e 2	2012	Chang'e flew by Toutatis on 13 December 2012, coming as close as 3.2km, the closest a space-craft has ever been to an asteroid.
Ryugu	JAXA	Hayabusa2	2014 - 2020	Hayabusa2 launched in December 2014 and arrived at C-type asteroid Ryugu in June 2018. It will survey the asteroid until December 2019 and collect samples. It successfully touched down on the asteroid in February 2019 and collected its first sample and in April 2019 it used explosives and a copper projectile to create an artificial crater from which it will potentially collect a second sample. The probe will return the samples to Earth around the end of 2020.
Bennu	NASA	OSIRIS-Rex	2016 - 2023	The Origins, Spectral Interpretation, Resource Identification, Security-Regolith Explorer (OSIRIS-REx) mission launch in Sept 2016 and arrived at asteroid *Bennu* in August 2018. It aims to return a 60g sample to Earth in 2023.

Source: table based on Gerlach, 2005; updated from various sources

5.2.2. Asteroid classification

The composition of the main asteroid belt varies systematically from the inner to the outer edge (Nichols, 1993) and mineralogical studies have confirmed that mineral composition of NEAs reflects the diversity of the main belt (Casini, 2011).

Asteroids are categorized into broad classes according to their reflective spectra following several taxonomic classification schemes (Carry, 2012). Asteroid taxonomy has evolved as the quantity and quality of observational data improved and as the appreciation of the variety and complexity of asteroid spectra has increased (Gaffey et al, 2002).

The most widely used classification is the *Tholen* system[48], which recognizes 14 different asteroid types, with the majority of asteroids falling into one of three broad categories (Janette, May 2014).

Despite such diversity, three categories of asteroids dominate the main belt and the NEA population: carbonaceous (C-type), stony (S-type) and metallic (M-type) asteroids (Libourel & Corrigen, 2014):

5.2.2.1. Carbonaceous (C-type) asteroids

Carbonaceous (C-type) asteroids represent around 75% of known asteroids (Buet et al, 2013). They dominate the main belt's outer regions (closer to Jupiter’s orbit) (Libourel & Corrigen, 2014) and around 75% of the large (>100km) main belt asteroids are C-type (Nichols, 1993). C-types make up only about 20% of the known NEA population, but this may underestimate the true figure as they are difficult to detect in optical surveys because of their generally low albedo (Keck, 2012).

C-type asteroids are compositionally diverse. They have a very high content of opaque, carbonaceous material (Casini, 2011) containing a high grade source of volatiles (Nichols, 1993), complex organic molecules, dry rock, and metals (Keck, 2012). Water in both free and chemically bound forms may comprise up to 30% of the C-type asteroids (Cutright, 2013). C-types are poor in PGMs (Tagle & Berlin, 2008).

5.2.2.2. Stony (S-type) asteroids

Stony (S-types) asteroids are the second most common in the main-belt (inner regions closer to Mars’s orbit), accounting for 15% - 17% of the total identified (Cutright, 2013). S-types appear to be the dominant class among NEAs (Sanchez et al, 2013), though this dominance may partly be caused by a selection effect, as their higher albedos make them easier to discover (Sanchez et al, 2013).

The S-type asteroids are composed predominantly of the oxides of iron, nickel, other metals, and magnesium silicates, with olivine and pyroxene minerals common. These asteroids are relatively rich in PGMs and rare-earth elements (Cutright, 2013).

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[48] Other widely accepted classifications include SMSSII system, the Barucci system (split into 9 classes (Sonter, 2012)), Bus-De Meo (15 classes grouped into 3 complexes and 9 additional “end-member” classes (Carry, 2012)) and the Howell system (Casini, 2011).

5.2.2.3. Metallic (M-type) asteroids

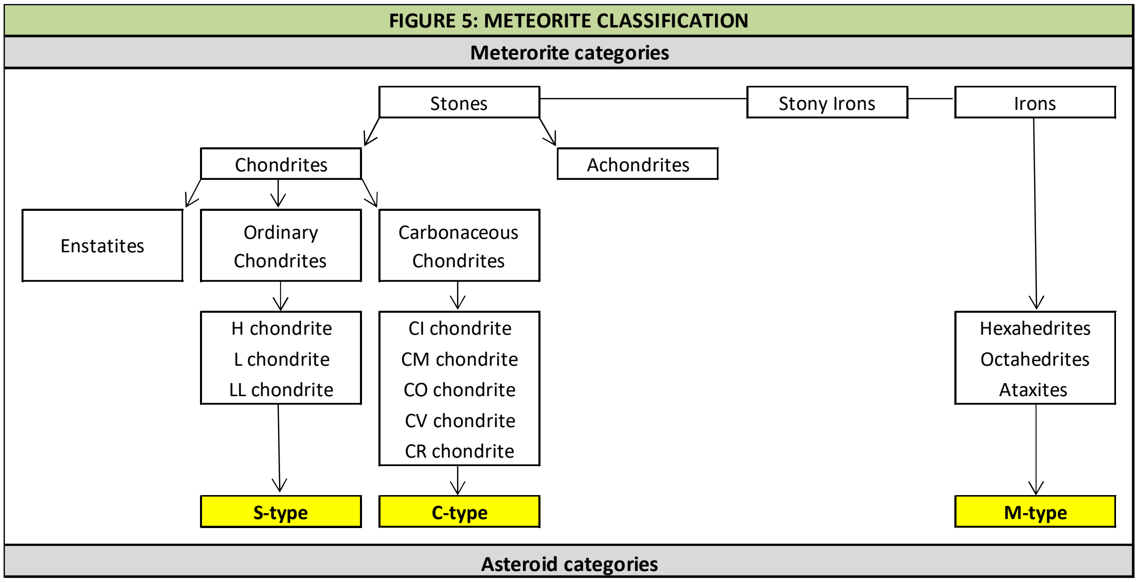
Metallic (M-type) asteroids account for only about 5% of known asteroids (Libourel & Corrigen, 2014) and are scattered throughout the central part of the belt (Buet et al, 2013). They also comprise only a small percentage of NEAs.

M-types are composed of 10% - 60% of elemental (non-oxidized) iron, nickel, and cobalt, with lesser amounts of other metals and some rocky material (Cutright, 2013). The metallic asteroids are sources of primary structural steel and rare-earth elements (Cutright, 2013). M-type asteroids are also rich in precious metals, with concentrations of several hundred ppm of gold and PGMs (Harris, 2013).

5.2.3. Asteroid composition

The 3 classes of asteroids described in *Section 3.2.2* above can each be traced to a certain class of meteorites. Meteorites are classified into *Stones*, *Stony-Irons*, and *Irons* (Sonter, 2012). The Stones comprise two subclasses, the *chondrites* and the *achondrites* (Sonter, 2012). Chondrites are further subdivided into *Enstatites*, *Ordinary Chondrites*, and *Carbonaceous Chondrites* (Sonter, 2012). These classes can be further sub-categorization as shown in *Figure 5: Meteorite Classification* below.

FIGURE 5: METEORITE CLASSIFICATION



Source: compiled from: Britt et al, 2002; Carry, 2012; Nelson et al, 1993; Sonter, 2012,

The link between the carbonaceous chondrite sub-categories CR, CM and CI and the C-type asteroids seems well established (Carry, 2012). The overwhelming majority of meteorites (some 75%) are ordinary chondrites (Britt et al, 2002); the majority of S-type NEAs have compositions most similar to the "LL" ordinary chondrite sub-category (Reddy et al, 2015). The M-type asteroid's composition is similar to that of iron meteorites (Nelson et al, 1993).

Table 10: Mineralogical Composition of Asteroids below depicts the mineral composition of four representative asteroids based on their four different analog meteorite types. Note that individual meteorites vary dramatically in composition, and this table presents samples from within only four categories (Gerlach, 2005). The table shows only the most prominent elements along with platinum and do not add to 100%.

TABLE 10: MINERALOGICAL COMPOSITION OF ASTEROIDS					
Mineral	**Symbol**	**C1-type***	**C2-type****	**S-type**	**M-type**
Free metals					
Iron	Fe	0.1%	10.7%	6% - 19%	88%
Nickel	Ni		1.4%	1% - 2%	10%
Cobalt	Co		0.11%	0.1%	0.5%
Volatiles					
Carbon	C	1.9% - 3%	1.4%	3%	0.1% - 23%
Water	H_20	12%	5.7%	0.15%	2.6%
Sulphur	S	2%	1.3%	1.5%	0.1% - 7%
Mineral oxides					
Iron	FeO	22%	15.4%	10%	3% - 15%
Silicon	SiO_2	28%	33.8%	38%	21% - 54%
Magnesium	MgO	20%	23.8%	24%	5.9% - 31.9%
Aluminium	Al_2O_3	2.10%	2.4%	2.1%	1.4% - 10.6%
Sodium	Na_2O	0.30%	0.55%	0.9%	0.12% - 1.8%
Potassium	K_2O	0.04%	0.04%	0.1%	0.01% - 0.22%
Phosphorus	P_2O_5	0.23%	0.28%	0.28%	0.03% - 1.39%
Calcium	CaO	1.36%	1.15% - 2.00%	3.36% - 11.00%	1.09% - 8.12%
Titanium	TiO_2	0.07%	0.11% - 0.13%	0.31% - 1.23%	0.11% - 0.77%
Precious metals					
Platinum	Pt	~0.0001%	~0.0001%	~0.0031%	~0.006%

Source: Cutright, 2013 - *Data from C2 meteorite Murchison and average Cl-C2 types, ** Data from metal-rich C2 meteorite *Renazzo*; Pt data added for illustration.

5.3. Potential asteroid platinum supply

Most asteroids are undifferentiated bodies that have never separated into core, mantle and crust. For this reason, there is no need to seek out mineral deposits because the entire body is an ore (Harris, 2013). To calculate the platinum contained in an asteroid it is necessary to know the concentration of platinum contained as well as the asteroid's mass.

5.3.1. Platinum concentration in asteroids

Distributions of PGM concentration for various meteorite groups are not widely available (Elvis, 2013). Initially, no analysis of PGMs contained in meteorites was done, it being difficult to identify elements only present in very low concentrations. However, with improved analytical techniques, the available data has steadily increased (Tagle & Berlin, 2008).

Carbonaceous chondrites (analog to C-type asteroids) contain very low concentrations of PGM, average from 3.35ppm to 5.07ppm for the various subclasses (Tagle & Berlin, 2008). Higher PGM concentrations of 50 – 60ppm are found across a variety of meteorite samples attributed to the LL Chondrites (analogs to S-type asteroids) (Blair, 2000), but some have *PGM* concentrations as high as 105ppm (Kargel, 1996). The PGM content of iron meteorites (analogs to M-type asteroids) is significantly greater, with total concentrations of as high as 181ppm in the best (98th percentile) of meteorites (Kargel, 1996). This is considerably higher than found on earth: the BIC contains up to 3ppm of PGMs (Cawthorn, 2010). The Great Dyke has head grades generally below 4ppm (Johnson Matthey). Russia's reefs have a concentration of only 5 part per billion (ppb) (Elshkaki & Van der Voet, 2006).

The average concentration of *platinum* can range from 1ppm in carbonaceous chondritic meteorites, to 30ppm in LL chondrites, and up to 60ppm in good metallic meteorites (Blair, 2000). Up to 63.8ppm of platinum is found in the top 2% of iron meteorite samples (Kargel, 1996).

Concentrations of PGMs in typical asteroids inferred from the chemical composition of meteorite finds on Earth are given in *Table* 9: *Concentration of PGMs in Meteorites* below. These values are used in all calculations of asteroid platinum supply in this paper.

TABLE 11: ESTIMATED CONCENTRATIONS OF PGMs IN ASTEROIDS

Asteroid class		**C-type**	**S-type**	**M-type**
		Meteorite analog		
Metal	**Symbol**	**Carbonaceous Chondrites* (ppm)**	**Ordinary Chondrites** (ppm)**	**Iron meteorite*** (ppm)**
Iridium	Ir	0.64	15.00	33.00
Osmium	Os	0.68	15.20	9.00
Palladium	Pd	0.67	17.50	1.30
Platinum	**Pt**	**1.19**	**30.90**	**35.00**
Rhodium	Rh	0.17	4.20	4.80
Ruthenium	Ru	0.96	22.20	13.00
Total PGMs		**4.30**	**105.00**	**96.10**

Sources:

* Tagle & Berlin, 2008 - Average of 5 carbonaceous sub-classes

** Kargel, 1996 (reported by Cutright, 2013) - Concentration in average LL Chondrite

*** Kargel, 1996 (reported by Cutright, 2013) - Concentration in good iron meteorite (90th percentile in Pt)

5.3.2. Asteroid mass

Asteroid mass is calculated as the product of its volume (V) and density[49] (ρ): $M = V \times \rho$. The volume of an asteroid is simply a function of its diameter[50].

The densities of meteorites vary widely, from ~1 g/cm^3 for a high-porosity carbonaceous chondrite to ~8 g/cm^3 for solid nickel-iron meteorites (Keck, 2012). Meteorites are strong enough to survive atmosphere entry and should be considered upper bounds for density (NASA, 2015); most asteroids will be significantly less dense than those that survived to reach earth as meteorites (Casini, 2011).

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[49] Our knowledge of the density of small bodies has undergone a revolution, from 17 objects examined by Britt et al (2002), to 40 by Consolmagno et al (2008), to 287 in Carry (2012) (Carry, 2012).

[50] Many different observing techniques and methods of analysis have been used to evaluate the diameter of small bodies (Carry, 2012). The diameter estimates are intrinsically precise and estimates from different techniques generally agree (Carry, 2012).

This paper relies on the density values for various meteorites estimated by Carry (2012) and set out in *Table 12: Meteorite Average Densities* below. Calculations of asteroid mass of the various asteroids are based on the calculated average densities presented in the table: C-type – 2.6 g/cm^3, S-type – 3.3 g/cm^3 and M-type – 6.2 g/cm^3:

TABLE 12: METEORITE AVERAGE DENSITIES

Meteorite		**Density (ρ) - g/cm^3**
C-type analogs		
Carbonaceous chondrite	CI	1.60
Carbonaceous chondrite	CM	2.25
Carbonaceous chondrite	CR	3.10
Carbonaceous chondrite	CO	3.03
Carbonaceous chondrite	CV	2.79
	Average	**2.6**
S-type analogs		
Ordinary chondrites	H	3.42
Ordinary chondrites	L	3.36
Ordinary chondrites	LL	3.22
	Average	**3.3**
M-type analogs		
Irons	Hexahedrites	4.01
Irons	Octahedrites	7.37
Irons	Ataxites	7.14
	Average	**6.2**

Source: Carry, 2012

5.3.3. Potential platinum supply from various asteroids

Table 11: Potential Platinum Supply from Various Asteroids presents the potential platinum supply from various sizes of the 3 different types of asteroids calculated in this thesis, based on the platinum concentrations and densities outlined in *Section 3.3.1* and *Section 3.3.2* respectively:

TABLE 13: POTENTIAL PLATINUM SUPPLY FROM VARIOUS ASTEROIDS (tonnes)							
Asteroid:	C-type		Density: 2.6 g/cm^3		Pt concentration: 1.2 ppm		
Diameter (m)	**10**	**20**	**50**	**100**	**200**	**500**	**1 000**
Volume (m^3)	524	4 189	65 450	523 599	4 188 790	65 449 847	523 598 776
Mass (tonnes)	1 361	10 891	170 170	1 361 357	10 890 855	170 169 602	1 361 356 817
Contained Pt (tonnes)	**0.0016**	**0.0131**	**0.204**	**1.6**	**13.1**	**204**	**1 634**
% Pt of total weight	0.0001%	0.0001%	0.0001%	0.0001%	0.0001%	0.0001%	0.0001%
Asteroid:	S-type		Density: 3.3 g/cm^3		Pt concentration: 30.9 ppm		
Diameter (m)	**10**	**20**	**50**	**100**	**200**	**500**	**1 000**
Volume (m^3)	524	4 189	65 450	523 599	4 188 790	65 449 847	523 598 776
Mass (tonnes)	1 728	13 823	215 984	1 727 876	13 823 008	215 984 495	1 727 875 959
Contained Pt (tonnes)	**0.1**	**0.4**	**6.7**	**53.4**	**427**	**6 674**	**53 391**
% Pt of total weight	0.0031%	0.0031%	0.0031%	0.0031%	0.0031%	0.0031%	0.0031%
Asteroid:	M-type		Density: 6.2 g/cm^3		Pt concentration: 35.0 ppm		
Diameter (m)	**10**	**20**	**50**	**100**	**200**	**500**	**1 000**
Volume (m^3)	524	4 189	65 450	523 599	4 188 790	65 449 847	523 598 776
Mass (tonnes)	3 246	25 970	405 789	3 246 312	25 970 499	405 789 051	3 246 312 409
Contained Pt (tonnes)	**0.1**	**0.9**	**14.2**	**114**	**909**	**14 203**	**113 621**
% Pt of total weight	0.0035%	0.0035%	0.0035%	0.0035%	0.0035%	0.0035%	0.0035%

Source: own calculations based on parameters outlined in thesis.

Since the volume and mass of an asteroid increase with the cube of its diameter, asteroids become massive much faster than their diameter increases (Keck, 2012).

It can be noted that for C-type asteroids, the platinum supply becomes significant (> 100t – vs 190t produced globally in 2018) only for the very large asteroids with diameters bigger than 500m. For S-type asteroids, supply becomes significant only for asteroids 200m in diameter and larger. The M-type asteroids, which have the highest concentration of platinum, contain a significant amount of platinum in asteroids of 100m in diameter and larger.

5.4. Forecast of asteroid platinum supply to 2050 under 3 scenarios

This section presents a forecast of asteroid platinum supply to 2050 under 3 different scenarios related to how fast the size of the asteroids mined scales up: 1) slow up-scale, 2) modest up-scale and 3) fast up-scale.

This analysis is set up as a heuristic, to demonstrate the extent of asteroid mining that would be necessary before the process could begin to impact on terrestrial PGM markets. The analysis will show that under the 'reasonable' assumptions outlined below, the impact of asteroid supply will not be as rapid in the way that a new large terrestrial discovery might.

The timeline of the number of asteroids that become available to mine, the type of asteroids selected, as well as the platinum concentrations and densities of the various asteroid types are applied consistently across all 3 scenarios. The sizes of the asteroids selected however differ under the scenarios.

It is assumed that supply from the first asteroid starts in 2030. This date is selected for convenience, but the key results are independent of the starting date.

Currently, the overlap between the smallest NEA that can reasonably be discovered and the largest that could be captured and transported appears to be around 7m in diameter (Keck, 2012). It is assumed under all 3 scenarios that experience and improved technology will allow for increasingly large asteroids to be exploited. The scenarios, however, differ in the rate at which the size of an asteroid practical to mine scales up.

As experience is gained and technology continues to improve, more asteroids become available to exploit: mining on 2 more asteroids starts in 2035, on 3 more in 2040 and on 4 more in 2045. This is a total of 10 asteroids.

The earliest demand for asteroid material will be for water and it is assumed that the early targets will be C-type asteroids, as they have the highest concentration of volatiles; C-types are also fairly abundant. The next targets are assumed to be M-type asteroids because of their high metal content to be used in the construction of space infrastructure as well as the extraction of PGMs. Although S-type NEAs are the most abundant and have a higher metal content than C-types, they are volatile poor and their metal content is considerable lower than M-types; S-types are therefore considered poor targets.

Elvis (2013) presents a simple formalism to assess the number of ore-bearing NEAs. Initial (conservative[51]) estimates give very low values for M-type asteroids, and larger, but still modest, numbers for C-types. It is however assumed that detection and characterization techniques will improve sufficiently for an adequate number of C- and M-type targets to be identified.

The rate of through-put of the mining operations is a key variable in the forecast. Both Sonter (2012) and Ross (2001) estimate a mass throughput ratio (kilograms per day per kilogram of equipment mass) of well over 200 may be achievable, allowing 200t to be mined per day with 1t of equipment. These estimates are based on analysis of terrestrial operations and, given the complexities of mining in space, seem optimistic for early operations. This thesis is more conservative and assumes that 100t – 1 000t of material can be mined per year for early operations. It then assumes that space mining operations become more efficient with experience, improved technology and increasing mining infrastructure in space, allowing mass through-put to scale up in line with the size of asteroids.

Table 14: Forecasted Asteroid Platinum Supply provides a summary of forecasted platinum supply under each of the scenarios as calculated based on the parameters as outlined in the thesis. The size of the asteroid and the mining through-put rate used in the calculations are highlighted in blue.

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[51] *Elvis* only considers targets with a ΔV of 4.5km/s or less, which includes only a small fraction of known NEAs, and stresses that an order of magnitude increase in the number of targets would occur if the ΔV is increased to 5.7km/s.

It is clear from the tables that not until much larger asteroids (>100m) become practical to mine would asteroid mining have the potential to significantly impact on terrestrial platinum markets. It can also be noted that, in the modest and fast up-scale scenarios, asteroid supply actually decreases between 2045 and 2050 as asteroids mined from earlier in the period become depleted:

Source: own calculations based on parameters outlined in thesis.

TABLE 14: FORECASTED ASTEROID PLATINUM SUPPLY (tonnes)

SLOW UP-SCALE SCENARIO

Parameter	Asteroid #1	Asteroid #2	Asteroid #3	Asteroid #4	Asteroid #5	Asteroid #6	Asteroid #7	Asteroid #8	Asteroid #9	Asteroid #10
Type	C-type	C-type	M-type	C-type	C-type	M-type	C-type	C-type	M-type	M-type
1st year of production	2030	2035	2035	2040	2040	2040	2045	2045	2045	2045
Diameter (m)	10	10	10	20	20	20	50	50	50	50
Volume	524	524	524	4 189	4 189	4 189	65 450	65 450	65 450	65 450
Density (g/cm^3)	2.6	2.6	6.2	2.6	2.6	6.2	2.6	2.6	6.2	6.2
Mass (tonnes)	1 361	1 361	3 246	10 891	10 891	25 970	170 170	170 170	405 789	405 789
Pt concentration (ppm)	1.2	1.2	35.0	1.2	1.2	35.0	1.2	1.2	35.0	35.0
Pt reserves (tonne)	**0.002**	**0.002**	**0.11**	**0.01**	**0.01**	**0.9**	**0.2**	**0.2**	**14.2**	**14.2**
Mining volume (m^3/yr)	**100**	**100**	**100**	**1 000**	**1 000**	**1 000**	**10 000**	**10 000**	**10 000**	**10 000**
Mining mass (tonnes/yr)	260	260	620	2 600	2 600	6 200	26 000	26 000	62 000	62 000
Annual Pt production (tonnes)	**0.00031**	**0.00031**	**0.02**	**0.00**	**0.00**	**0.22**	**0.03**	**0.03**	**2.17**	**2.17**
Yrs to depletion	5.2	5.2	5.2	4.2	4.2	4.2	6.5	6.5	6.5	6.5
Year		**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**	
Total production that year (tonne)		-	-	-	**0.0003**	**0.02**	**0.2**	**4.4**	**4.4**	

TABLE 14: FORECASTED ASTEROID PLATINUM SUPPLY (tonnes) - continued

MODEST UP-SCALE SCENARIO

Parameter	**Asteroid #1**	**Asteroid #2**	**Asteroid #3**	**Asteroid #4**	**Asteroid #5**	**Asteroid #6**	**Asteroid #7**	**Asteroid #8**	**Asteroid #9**	**Asteroid #10**
Type	**C-type**	**C-type**	**M-type**	**C-type**	**C-type**	**M-type**	**C-type**	**C-type**	**M-type**	**M-type**
1st year of production	**2030**	**2035**	**2035**	**2040**	**2040**	**2040**	**2045**	**2045**	**2045**	**2045**
Diameter (m)	**10**	**20**	**20**	**50**	**50**	**50**	**100**	**100**	**100**	**100**
Volume	524	4 189	4 189	65 450	65 450	65 450	523 599	523 599	523 599	523 599
Density (g/cm^3)	2.6	2.6	6.2	2.6	2.6	6.2	2.6	2.6	6.2	6.2
Mass (tonnes)	1 361	10 891	25 970	170 170	170 170	405 789	1 361 357	1 361 357	3 246 312	3 246 312
Pt concentration (ppm)	1.2	1.2	35.0	1.2	1.2	35.0	1.2	1.2	35.0	35.0
Pt reserves (tonne)	**0.002**	**0.013**	**0.91**	**0.20**	**0.20**	**14.2**	**1.6**	**1.6**	**113.6**	**113.6**
Mining volume (m^3/yr)	**100**	**100**	**1 000**	**10 000**	**10 000**	**10 000**	**100 000**	**100 000**	**100 000**	**100 000**
Mining mass (tonnes/yr)	260	260	6 200	26 000	26 000	62 000	260 000	260 000	620 000	620 000
Annual Pt production (tonnes)	**0.00031**	**0.00031**	**0.22**	**0.03**	**0.03**	**2.17**	**0.31**	**0.31**	**21.7**	**21.7**
Yrs to depletion	5.2	41.9	4.2	6.5	6.5	6.5	5.2	5.2	5.2	5.2
Year		**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**	
Total production that year (tonne)		**-**	**-**	**-**	**0.0003**	**0.2**	**2.2**	**46.3**	**10.4**	

TABLE 14: FORECASTED ASTEROID PLATINUM SUPPLY (tonnes) - continued

FAST UP-SCALE SCENARIO

Parameter	Asteroid #1	Asteroid #2	Asteroid #3	Asteroid #4	Asteroid #5	Asteroid #6	Asteroid #7	Asteroid #8	Asteroid #9	Asteroid #10
Type	C-type	C-type	M-type	C-type	C-type	M-type	C-type	C-type	M-type	M-type
1st year of production	**2030**	**2035**	**2035**	**2040**	**2040**	**2040**	**2045**	**2045**	**2045**	**2045**
Diameter (m)	**20**	**50**	**50**	**100**	**100**	**100**	**1000**	**1000**	**1000**	**1000**
Volume	4 189	65 450	65 450	523 599	523 599	523 599	523 598 776	523 598 776	523 598 776	523 598 776
Density (g/cm^3)	2.6	2.6	6.2	2.6	2.6	6.2	2.6	2.6	6.2	6.2
Mass (tonnes)	10 891	170 170	405 789	1 361 357	1 361 357	3 246 312	1 361 356 817	1 361 356 817	3 246 312 409	3 246 312 409
Pt concentration (ppm)	1.2	1.2	35.0	1.2	1.2	35.0	1.2	1.2	35.0	35.0
Pt reserves (tonne)	**0.013**	**0.204**	**14.20**	**1.63**	**1.63**	**114**	**1 634**	**1 634**	**113 621**	**113 621**
Mining volume (m^3/yr)	**1 000**	**10 000**	**10 000**	**100 000**	**100 000**	**100 000**	**10 000 000**	**10 000 000**	**10 000 000**	**10 000 000**
Mining mass (tonnes/yr)	2 600	26 000	62 000	260 000	260 000	620 000	26 000 000	26 000 000	62 000 000	62 000 000
Annual Pt production (tonnes)	**0.00312**	**0.03120**	**2.17**	**0.31**	**0.31**	**21.70**	**31.20**	**31.20**	**2170**	**2170**
Yrs to depletion	4.2	6.5	6.5	5.2	5.2	5.2	52.4	52.4	52.4	52.4
Year		**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**	
Total production that year (tonne)		-	-	-	**0.0031**	**2.2**	**24.5**	**4 408**	**4 402**	

6. Potential impact of asteroid supplied platinum

6.1. Introduction: Ground control to Major Tom

Precious metals are likely to be only a small by-product in early asteroid mining operations. At these early development stages of space mining, the amount of platinum extracted is likely to be insignificant compared to the amount mined on earth. However, if space mining develops to such an extent that much larger asteroids can be mined, and the number of asteroids being mined increases, there is the potential for space-mined platinum to significantly impact on the terrestrial platinum market.

This section compares the forecasted asteroid platinum supply under the 3 scenarios to forecasted terrestrial supply. The section then concludes with a discussion of the potential impact of asteroid platinum supply on terrestrial production and the potential uses for space-mined platinum.

6.2. Comparison of asteroid to terrestrial supply

Table 15: Comparison of Forecasted and Asteroid Platinum Supply below, compares the potential asteroid platinum supply under each of the 3 scenarios to the forecast terrestrial supply (assuming a 2% growth rate in terrestrial supply in all 3 cases).

TABLE 15: COMPARISON OF FORECASTED ASTEROID AND TERRESTRIAL PLATINUM SUPPLY										
	2030		2035		2040		2045		2050	
	Tonnes	% of total supply	Tonnes	% of total supply	Tonnes	% of total supply	Tonnes	% of total supply	Tonnes	% of total supply
SLOW UP-SCALE SCENARIO										
Asteroid supply	**0.00031**	0%	**0.02**	0%	**0.23**	0%	**4.4**	1%	**4.4**	1%
Mine production	186	69%	205	69%	226	69%	250	68%	276	68%
Recycled supply	83	31%	92	31%	101	31%	112	31%	123	31%
Total terrestrial supply @ 2%	**268**		**296**		**327**		**361**		**399**	
Total supply	**268**		**296**		**328**		**366**		**403**	
Asteroid % of terrestrial	**0.0001%**		**0.007%**		**0.07%**		**1.2%**		**1.1%**	
MODEST UP-SCALE SCENARIO										
Asteroid supply	**0.00031**	0%	**0.22**	0%	**2.2**	1%	**46.3**	11%	**10.4**	3%
Mine production	186	69%	205	69%	226	69%	250	61%	276	67%
Recycled supply	83	31%	92	31%	101	31%	112	27%	123	30%
Total terrestrial supply @ 2%	**268**		**296**		**327**		**361**		**399**	
Total supply	**268**		**297**		**330**		**408**		**409**	
Asteroid % of terrestrial	**0.0001%**		**0.07%**		**0.7%**		**13%**		**3%**	
FAST UP-SCALE SCENARIO										
Asteroid supply	**0.0031**	0%	**2.2**	1%	**24.5**	7%	**4 408**	92%	**4 402**	92%
Mine production	186	69%	205	69%	226	64%	250	5%	276	6%
Recycled supply	83	31%	92	31%	101	29%	112	2%	123	3%
Total terrestrial supply @ 2%	**268**		**296**		**327**		**361**		**399**	
Total supply	**268**		**299**		**352**		**4 769**		**4 801**	
Asteroid % of terrestrial	**0.001%**		**0.7%**		**7%**		**1220%**		**1103%**	

Source: own calculations based on parameters outlined in thesis.

Note from the table that asteroid supply as a percentage of terrestrial supply in 2050 is less than in 2045 in the *Modest* and *Fast upscale* scenarios; this is due to lower supply towards the end of the forecast period as asteroids mined from earlier in the period become depleted at a much faster rate.

It is clear that under a *slow up-scale scenario*, asteroid supply will represent at most 1% of terrestrial supply in any given year. However, asteroid supply has the potential to significantly impact on terrestrial supply under the *Fast up-scale* scenario and less so under the *Modest up-scale scenario,* but in both cases only from about 2040.

Because of the very small amount of platinum available in asteroids 100m diameter or less, under the *Slow- and Modest up-scale scenarios*, the forecast for asteroid supply is not very sensitive to the number of asteroids mined or rate of mining through-put. However, if the size of asteroids scales up as fast as assumed under the *Fast up-scale scenario*, an increase in the number of asteroids could significantly amplify the impact.

6.3. Potential impact of asteroid platinum supply

The analysis in this thesis shows that platinum from asteroids would only become viable as a primary product for Earth-based markets at a scale that implies a very large in-space mining operation, but in these circumstances it would have a profound impact on the earth's supply.

The production decisions of earth-based platinum producers depend on the quantity of platinum supplied by the asteroid miner into the global market (Hein2 et al, Oct 2018). The theory presented in *Section 4.2: The economics of exhaustible resources* suggests that mining on earth continues up to the point where prices are high enough to justify a switch of technique to asteroid mining; miners would maximise their discounted profits by ensuring that they deplete their resources along a path such that the last ton of ore is mined on earth at the exact time that the "back-stop" asteroid alternative becomes economical.

Under the *Slow- and Modest up-scale scenarios*, asteroid platinum supply until 2050 will represent only a small percentage of terrestrial supply in any particular year. While asteroid supply is these scenarios could perhaps be used to tide over short-term deficits on Earth, given the effort of shipping material down to Earth, the platinum would be, at best, used as an industrial metal in space or, at worst, be left unprocessed. In this case, terrestrial miners would not have to adjust their production schedules to take into account the impact of asteroid mined supply.

The amount of platinum potentially available under the *Fast scale-up scenario* however warrants further consideration. Calculations in *Table 17: Comparison of Forecasted and Asteroid Platinum Supply* show that asteroid supply, in the *Fast up-scale scenario* could represent more than a 1000% of projected terrestrial demand.

In the worst-case scenario that we are unable to expand current known economic terrestrial PGM reserves, asteroids will offer a ready-to-exploit "perfect substitute" to compensate for depleted terrestrial resources. As terrestrial reserves deplete, platinum prices would increase to such a degree that asteroid mining eventually becomes the more viable alternative.

But even in the absence of the risk of depleted resources, the potentially enormous “back-stop” source of platinum should factor into terrestrial platinum miners’ long-term planning.

If large-scale asteroid platinum supply was to become a reality by 2050, platinum producers would therefore have to drastically accelerate their rate of production to ensure that terrestrial resources are depleted by such time. Such rapid production would most likely exceed demand over this period and tend to suppress the price of platinum.

Such low prices would undermine the profitability of platinum producers and they may be forced to plan for “economic” rather than “physical’ depletion. In such a case, production would be retarded to ensure that prices increase slowly to reach the “choke” price at which asteroid supply becomes economical. Unexploited resources would then be left in the ground.

Because PGM production is concentrated in so few areas, and controlled by a limited number of producers, the industry can be considered as oligopolistic. In line with the economic theory, these producers should have sufficient control over the pace of production to ensure that an optimal extraction path is followed.

However, due to the power of compound interest, and the rate of technological change (which can render the best of plans redundant almost overnight) few planners are looking much more than 30 or 40 years into the future, when asteroid supply could become a reality. Asteroid-mined platinum might begin to be viable by then, but by then the true imponderable is likely to be demand: will new technologies be PGM hungry, or not? The diesel engine may be redundant by then, but other technologies may demand PGM catalysts.

The magnitude of platinum supply that could become available under the *fast up-scale* scenario therefore holds intriguing potential. Potential uses for such large-scale asteroid supply include as feedstock for technologies for which the metal’s price makes its use prohibitive, such as fuel-cells. There is potentially enough platinum supply in asteroids to migrate a large proportion of the global economy to fuel-cells. Such scale could not be achieved by terrestrial supply. Asteroid miners can provide large quantities of platinum directly to fuel-cell producers at preferential prices, allowing them to withdraw from the terrestrial supply market and thereby not undercutting terrestrial prices.

Also, even where there is not a potential shortage of reserves in the ground, the environmental cost of mining may compel terrestrial miners to relocate their operations into space, with Earth-resources left undeveloped. These large quantities of platinum would also be mined in space and not on Earth, providing further fodder for the “ultimate” environmentally friendly energy solution.

7. Conclusion

This thesis investigates the potential existence of a high-volume asteroid-derived platinum supply from an economic perspective to assess the possible impact on long-term platinum supply. The thesis finds that, depending on the speed at which the size of an asteroid practical to mine up-scales, space-mined platinum has the potential to drastically impact on the terrestrial platinum market.

Asteroid supply has the potential to significantly impact on terrestrial supply under the *Fast up-scale* scenario and less so under the *Modest up-scale scenario,* but in both cases only from about 2040. Under a *slow up-scale scenario*, asteroid supply will present no more than 1% of terrestrial supply in any given year.

The quantum of "back-stop" platinum potentially available under the *Fast up-scale* scenario may force terrestrial miners to accelerate their rate of production significantly to ensure that they extract the maximum amount of revenues before such supply becomes available. Terrestrial resources may even have to be left unexploited.

Potential uses for asteroid mined platinum supply include as an emergency reserve if terrestrial platinum resources come under pressure later in the 21st century and as potential enabler to move the planet towards a zero-emission hydrogen economy. Asteroid mining may also offer an alternative to polluting Earth-based operations.

The calculation of asteroid mineral supply is however sensitive to 3 major assumptions that require further investigation:

- The size of asteroid that it will be practical to mine over the next few decades.
- The mineral throughput that space-based machinery can achieve.
- That the size of space-based resource demand is sufficient to absorb all asteroid mined material.

The start of the impact of asteroid platinum supply is most likely beyond the normal mine-planner's time-horizon. Terrestrial PGM producers should nevertheless heed developments in the asteroid mining industry as the potential impact is too large to ignore.

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