# Cobalt Demand: Past, Present, and Future

by

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Submitted to the Department of Materials Science and Engineering in partial fulfillment of the requirements for the degree of Bachelor of Science in Materials Science and Engineering

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## Abstract

Cobalt has become more and more popular in the realms of academia, industry, and media due to its integral role in many of the most commonly-used lithium-ion battery cathodes today. Many issues have been evaluated regarding the controversial labor and volatile sociopolitical environments associated with cobalt mining and concerns over the ability of cobalt supply to continue to meet demand, especially the increasing demand due to the electric vehicle revolution. Cobalt is a critical element in a variety of products outside of the battery industry, including: superalloys, hard-facing metals, cutting tools, magnets, chemical catalysts, and pigments. In this thesis, I assessed the criticality of cobalt demand in non-battery sectors with the intention of assessing whether demand of cobalt in its traditional, inelastic sectors will supply be a limiting factor of technological progress by 2030 and by 2050.

In order to do so, data was collected on the past and present demands of cobalt in its four primary sectors, outside of batteries: superalloys, cutting tools and hard-facing metals, magnets, and chemical catalysts. Future demand projections were made based on the historic data as well as via a bottom-up approach from industry projections for future product demand and cobalt intensity of products. Substitutes for cobalt in these applications were also investigated and are discussed below. The prices at which substitutes become more favorable than cobalt were also evaluated.

Thesis Supervisor: Elsa A. Olivetti
Title: Atlantic Richfield Assistant Professor of Energy Studies

## Acknowledgments

I would first and foremost like to thank my thesis advisor, Professor Elsa Olivetti, for her guidance, patience, kindness, and support throughout the development of this work. Professor Olivetti conceptualized this work and influenced my interest and passion in this topic. She also provided insightful questions and helpful commentary throughout the development, research, and writing of this work. I really appreciated how hands-on she was throughout this past semester and how involved she was with checking in on the progress of the work and helping to improve its quality. Professor Olivetti is an inspiration to all who interact with her due to her hard work, positivity, and the emphasis she places on the "real-world" impacts of her work. Thank you for everything that you have taught me and allowed me to learn for myself!

I also owe many thanks and praise to Xinkai Fu. Xinkai was the primary lead on the supply-side research that is mentioned later on in this work. He was also my main point of contact in the Olivetti Group during the course of my thesis work this semester. Xinkai was always thoughtful enough to send me new articles or direct me towards databases with helpful information and never failed to make time to meet with me regularly to provide feedback on the progress of the work and brainstorm ideas for next steps. Xinkai's work ethic, kindness, and guidance were instrumental in the completion of this work and I will always be grateful to him for that.

I also must add MIT Materials Science and Engineering Department to this list of gratitude. The faculty, staff, and fellow students that have been a part of my Course 3 experience have taught me so much, both inside and outside of the realm of academia. I would not have learned so much, been so passionate about what I've learned, or enjoyed my time at the Institute as much as I have without them. The department has been an incredible source of support and knowledge the past 3 years that I have been a part of it.

And, lastly, I would like to thank my family and friends for their endless support and encouragement.

# Table of Contents

# List of Figures

# List of Tables

# Introduction

## Cobalt Basics:

Cobalt is a hard, lustrous, ferromagnetic metal. Considered rare, even though its concentration on Earth is of medium abundance, cobalt is often only economically viable to acquire as a by-product. In other words, 94% of the time [Petersen, 2016] cobalt is obtained most commonly by the mining and smelting of (and later separation from) other metals; the other metals are most often with copper or nickel. Studies have determined that about 55% of cobalt extraction is a result of nickel mining, 35% comes from copper mining, and the other 10% mostly comes from other platinum group metals; only 2.2% of extracted cobalt was found to come from primary cobalt mining [Sverdrup et. al., 2017].

Cobalt's unique magnetic and metallic properties have resulted in its use in a variety of applications spanning a plethora of industries. These industries include, but are not limited to, aerospace, defense, energy, oil and gas, plastics, art and jewelry, cutting tools, medicine, automobile, and music. Cobalt demand is inflexible in these non-battery sectors due to the critical nature of cobalt in these applications, the difficulty in finding viable alternatives for cobalt (in terms of properties), and the lower price sensitivity of the large industries involved.

## Uses and Sectors:

Cobalt was first used in glasses, glazes, and ceramics for centuries in order to impart blue and purple colors to jewelry, works of art, and functional household items. Differing concentrations of cobalt, varying additional additives, and changing bases (i.e. ceramic versus glass) affect the shade of blue and/or purple observed from cobalt pigments. Cobalt radioisotopes are commonly still used by artists in order to electroplate porcelain elements and improve hardness, oxidation-resistance, and aesthetic properties.

Cobalt's unique magnetic and thermal properties were later discovered and cobalt became a common component in high-performance alloys – ranging from superalloys to medical implant alloys to high-speed steels to permanent magnets. In superalloys, cobalt is used either as an alloying element or as a base. Cobalt-based superalloys consume most of the cobalt produced, outside of lithium-ion batteries [USGS, 2015]. Cobalt is an ideal component of superalloys because it creates superalloys with high-temperature stability and improved corrosion- and wear-resistance. Similarly, cobalt is used in high-speed steels and other cutting tool alloys – for heat- and wear-resistance. And in orthopedic and dental implants, cobalt is used to improve alloy corrosion- and wear-resistance. In permanent magnets, the addition of cobalt improves coercivity and curie temperature values; the most common permanent magnets on the markets are samarium-cobalt and aluminum-nickel-cobalt. Cobalt can also be used as an alloying agent for platinum jewelry, as it helps to make the metal suitable for casting, slightly magnetic, and it is hypoallergenic (unlike nickel).

Cobalt was the first cathode material used for commercial Li-ion batteries and remains a key element to the most common lithium-ion cathodes on the market currently. Lithium-ion batteries containing cobalt tend to have higher charge densities, cycling capacities, and power-to-weight ratios, as well as shorter recharge times than lead-acid and nickel-metal hydride batteries [BMO Capital Markets, 2017]. Cobalt is essential for batteries due to its stabilizing capacity, which maintains battery strength and lifespan; nickel is an extremely energy dense element but is not chemically or structurally stable enough on its own, which is where cobalt comes in. Therefore, cobalt improves the cycle life of lithium-ion batteries. The most common battery cathode compositions are lithium-cobalt oxide (LCO) and nickel-manganese-cobalt (NMC), of varying component compositions. The percentage of cobalt in commercial lithium-ion batteries ranges from 6-60 wt. % [BMO Capital Markets, 2017]. Batteries only accounted for 16% of total cobalt consumption globally in 2000; however, in 2017 they accounted for 55% of the total global cobalt consumption [BMO Capital Markets, 2017].

The last major use of cobalt, both globally and in the United States, is as a catalyst in chemical processes. Cobalt compounds are often used as oxidation catalysts and precursors in the bulk production of polyethylene terephthalate (PET), a common plastic used to make various bottles, protective equipment, and much more. Cobalt carboxylates are used as drying agents in paints, varnishes, resins, and inks – the cobalt compounds are used to induce oxidation of the drying oils. Cobalt carboxylates are also used to improve the adhesion between steel and rubber in applications in which they must be held together; for example, in steel-belted tires or manufacturing applications. Catalysts with cobalt components are used for steam reformation during the production of hydrogen, for the hydrogenation of carbon monoxide into liquid fuels (gas-to-liquid or GTL processes), and for the hydroformation of alkenes. Hydrodesulfurization of petroleum requires the use of a catalyst derived from cobalt (or molybdenum); the majority of cobalt catalyst usage is due to the petroleum industry [Cobalt Institute, 2018].

Cobalt is considered to be highly value additive to superalloys and magnets, moderately value additive to cutting tools and batteries, and of low additional value to chemical catalysis, pigments, resins, and other applications [Sverdrup et. al., 2017]. However, substitution of cobalt with other elements is possible in many cases, with and without changes in performance. In batteries, manganese, nickel, or other rare-earth metals be replace cobalt, but all of these options result in inferior functioning and heavier batteries [Sverdrup et. al., 2017]. The substitution options in the various applications this work focuses on – superalloys, hard metals and cutting tools, magnets, and chemical catalysts – will be discussed in more detail in a later section.

### Social Justice and Supply Concerns:

Two of the primary issues with the use of cobalt in commercial products relate social justice and supply concerns. In regards to social justice, a January 2016 Amnesty International report sparked public concern regarding child labor and unsafe mining conditions in the artisanal mining of cobalt in the DRC [Darton Commodities Limited, 2018]. Further public outrage and social condemnation of companies, including Apple, for using artisanal cobalt from the DRC in their cell phones and laptops was instigated by a Washington Post article tracking cobalt flows from unsuitable environments to consumer products in the U.S. [Frankel, 2016]. Since the DRC supplied 60% of the globally produced cobalt in 2015, corporation movement away from DRC cobalt will significantly affect the available cobalt for commercial applications [USGS, 2015].

Governments have been recently been creating new policies banning the sale of traditional, petroleum-fueled vehicles and setting goals for the number of electric vehicles in their countries. For instance, fossil fuel cars will no longer be sold in Norway by 2025, India by 2030, and Great Britain and France by 2040. Germany, China, and eight other countries have all expressed similar goals, but have not set official target or enforcement dates yet [Petroff, 2017]. Additionally, many automakers, including Tesla, Ford, General Motors, and others have invested large amounts of money in the research and production electric vehicles in order to help countries meet their target goals. Furthermore, as populations become more aware of and accepting of the effects of climate change on the environment, they educate themselves and become more aware of the ways in which they can reduce their carbon footprint. As a result of governments, companies, and individuals, the demand for electric vehicles is rapidly increasing. The growth of the electric vehicle sector directly corresponds to a growing demand for lithium-ion batteries, which in turn directly corresponds to an increasing demand for cobalt. One of the most common lithium-ion battery compositions is that of lithium-cobalt oxide (LCO), which is well-known to be around 60 wt.% cobalt.

To keep up with demand growth, the global supply of refined cobalt has doubled since 2004 [BMO Capital Markets, 2017] and the United States Geological Survey (USGS) estimates the world's cobalt reserves to be around 7,100,000 metric tons [USGS, 2015]. Nevertheless, articles and journals, knowing cobalt's media presence for social justice issues have began promoting the idea that cobalt supply is significantly at risk and will soon run out or will constrain battery production and therefore the electric vehicle sector. For instance, one commodities report contends, "cobalt looks to be the main constraint on battery market growth. Even without a rise in EV demand, we foresee a tight market, while overreliance on the DRC on the supply side cannot be avoided" [BMO Capital Markets, 2017]. These accounts attribute cobalt supply risks to either current extraction capabilities and/or natural reserve levels. Modern technology in a range of industries is heavily dependent upon a single supply country that is geopolitically unstable, produces cobalt as a byproduct of the mining of other metals, and has a complex and controversial supply chain. These reasons, along with large increases in demand for cobalt due to a rapidly-growing battery sector, have fueled fears of cobalt supply shortages.

### Overall concerns and importance of work:

Global cobalt demand has been reported as increasing from approximately 40,000 metric tons in 2000 to almost 104,000 metric tons in 2017; this results in a compound annual growth rate

(CAGR) of about 6%. Such a large annual growth rate indicates that there are reasonable concerns that individuals, companies, and governments have regarding the future supply and demand of cobalt. Consequently, this thesis work aims to assess how demand will change in the four primary non-battery sectors of cobalt consumption and then evaluate whether or not demand will out-pace supply by 2030 and/or by 2050. Furthermore, this work will analyze at what prices viable cobalt substitutes and alternatives will become economically preferential to cobalt and how they will resultantly affect short-term cobalt demand.

# Cobalt Demand Analysis

## Historic and Present Demand

### Historic Demand

The historic cobalt demand was derived from the publicly reported cobalt consumption data from the USGS Minerals Yearbook reports on cobalt, for United States-specific consumption, and from the Cobalt Development Institute's (CDI) Cobalt Facts reports, for global consumption. The total consumption of cobalt at both a national (U.S.) and a global level from 1999-2015 was found to be:

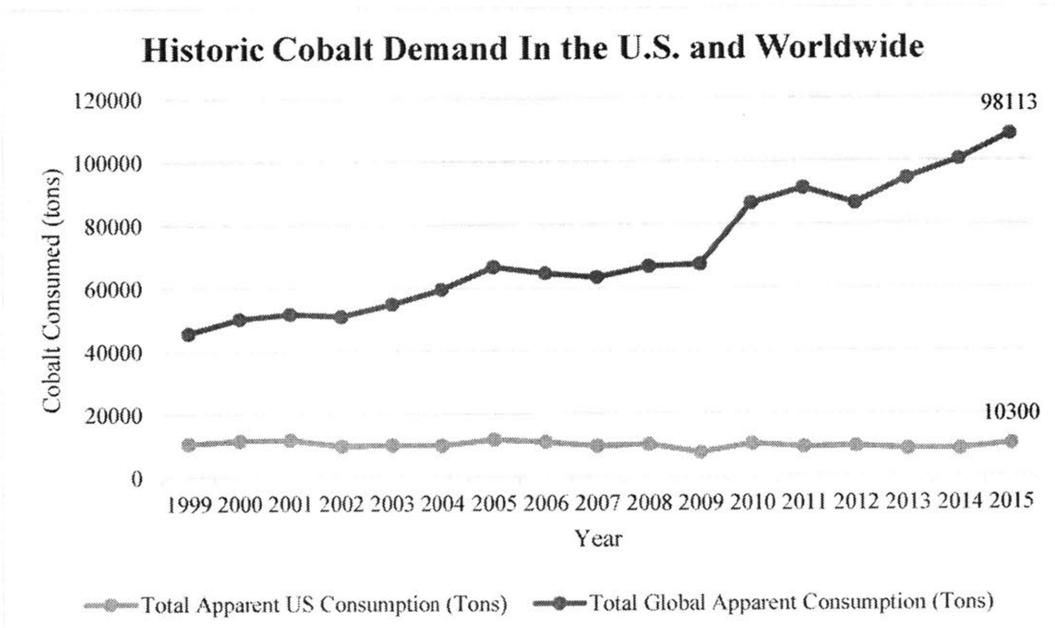


*Figure 1: Graphic representation of the cobalt demand between 1999 and 2015, both in the US and globally, according to data from the USGS and CDI. The graph demonstrates how the trend for cobalt consumption in the U.S. is more stagnant than the trend for cobalt consumption around the world.*

| Year | Total Global Apparent Consumption (Tons) | Total Apparent US Consumption (Tons) |
|---|---|---|
| 1999 | 35,073 | 10,700 |
| 2000 | 38,703 | 11,600 |
| 2001 | 39,971 | 11,800 |
| 2002 | 41,207 | 9,860 |
| 2003 | 44,895 | 10,000 |
| 2004 | 49,636 | 9,950 |
| 2005 | 54,834 | 11,800 |
| 2006 | 53,632 | 11,000 |
| 2007 | 53,657 | 9,630 |
| 2008 | 56,627 | 10,100 |
| 2009 | 59,851 | 7,580 |
| 2010 | 76,363 | 10,300 |
| 2011 | 82,247 | 9,230 |
| 2012 | 77,189 | 9,540 |
| 2013 | 85,904 | 8,650 |
| 2014 | 91,754 | 8,710 |
| 2015 | 98,113 | 10,300 |

*Table 1: Tabulated cobalt demand between 1999 and 2015, both in the US and globally, according to data from the USGS and CDI. The table above corresponds to the data represented in Figure 1.*

The historic breakdown of cobalt consumption by end-use sector in the U.S, based on USGS reported cobalt consumption data is:

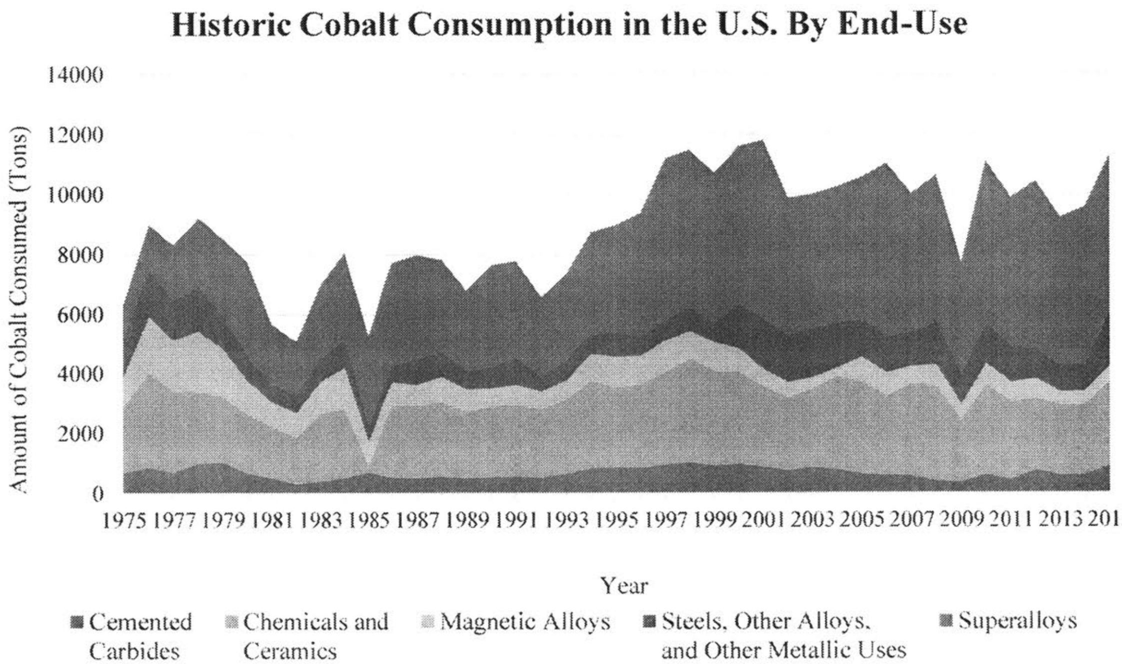


*Figure 2: Cobalt demand between 1975 and 2015 in the U.S. by end-use sector. Data provided by the USGS Minerals Summary reports.*

The historic breakdown of cobalt consumption by end-use sector worldwide, based on CDI reported global cobalt consumption data is:

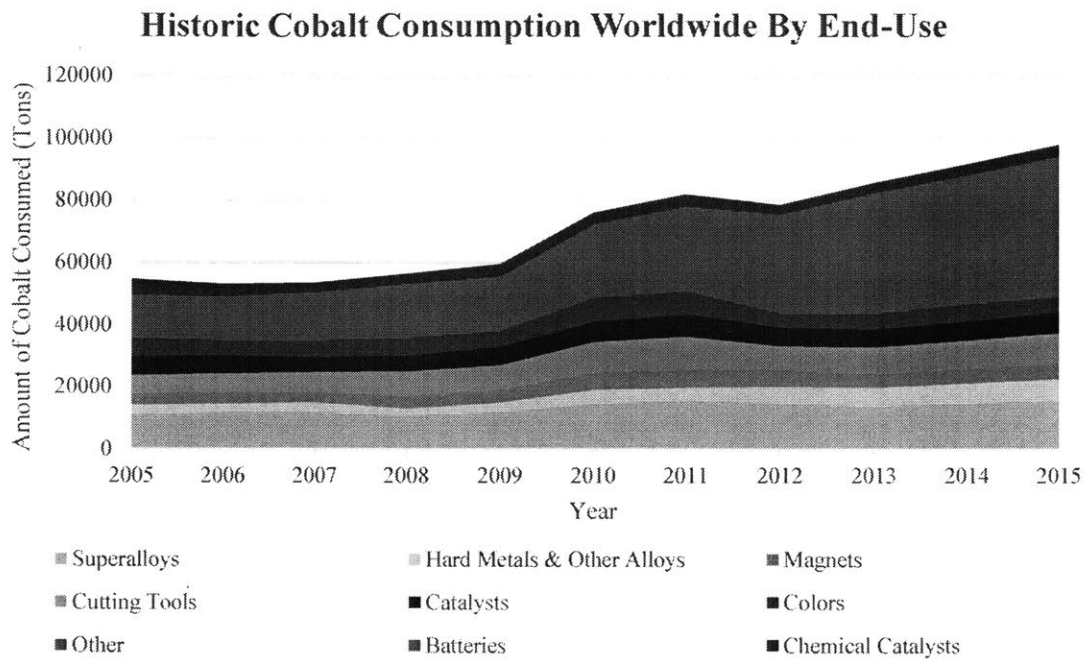


*Figure 3: Global cobalt demand by end-use sector between 2005 and 2015. Data provided by the CDI's Cobalt Facts reports.*

Present Demand

According to the Darton Commodities 2017 Cobalt Market Review, the total refined cobalt consumption globally was 103,900 metric tons; this provided for an 8.1% year-on-year increase from 2016 global consumption [Darton Commodities Limited, 2018]. The 2017 end-use breakdown is illustrated in Figure 4.

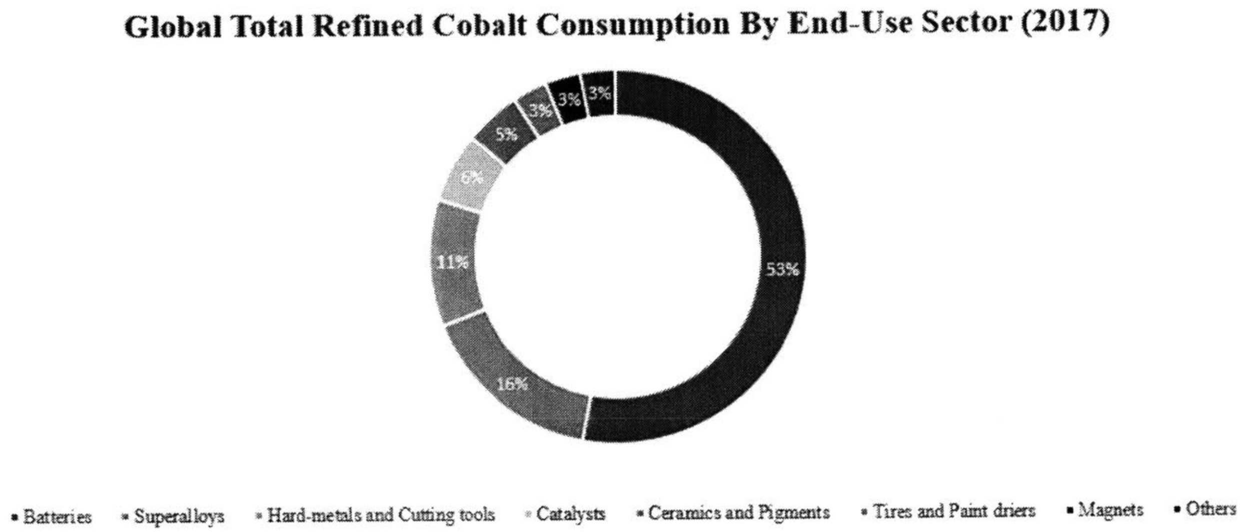


*Figure 4: Global cobalt demand by end-use sector in 2017. Data provided by the Darton Commodities 2017 Cobalt Market Review.*

## Future Demand Projections

Two types of demand projections were made for each end-use sector: (1) history-based projections and (2) bottom-up projections. History-based projections were calculated based on the calculated compound annual growth rate (CAGR) of the available past, reported consumption data. Bottom-up projections were calculated using the industry sales projections of products using cobalt within each industry along with the average cobalt intensity of products. Demand projections were made to both 2030 and 2050. The compound annual growth rate (CAGR) of the two sets of data was calculated using the standard formula:

$$\text{CAGR} = (\text{final value}/\text{initial value})^{(1/\#\ \text{of years})} - 1$$

Future Superalloy Demand

The historic data that was used to calculate the CAGR of the global and U.S. cobalt consumption in superalloys came from the CDI and USGS, respectively.

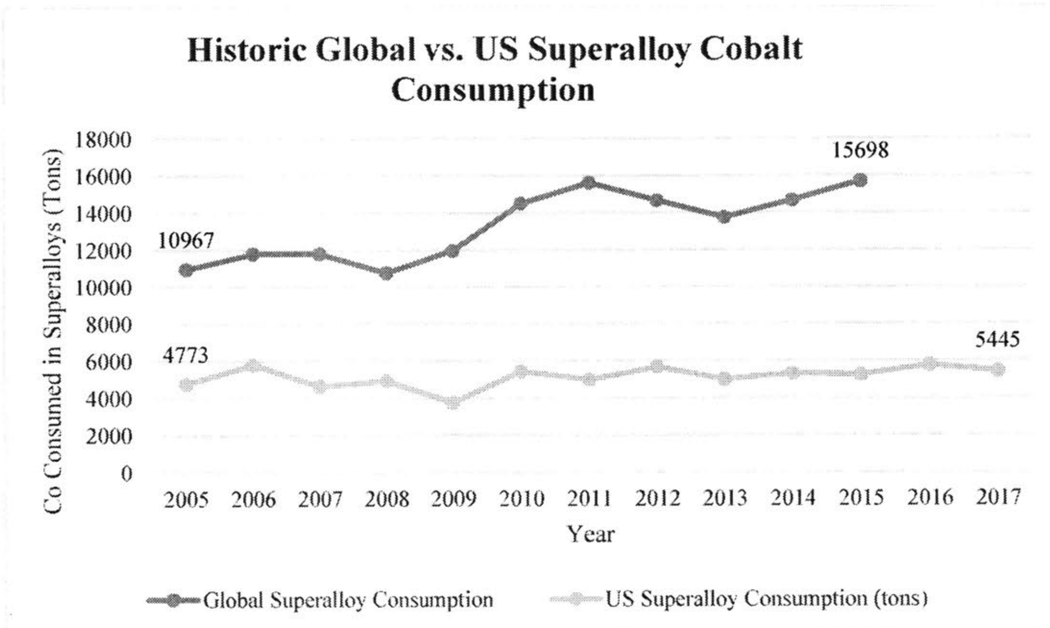


*Figure 5: Historic data for the global and U.S. cobalt consumption in the superalloy sector. Data provided by the CDI and USGS, respectively.*

The global CAGR was found to be 3.65% and the U.S. CAGR was found to be 1.10%. The CAGR values were then used to estimate cobalt demand to the years 2030 and 2050.

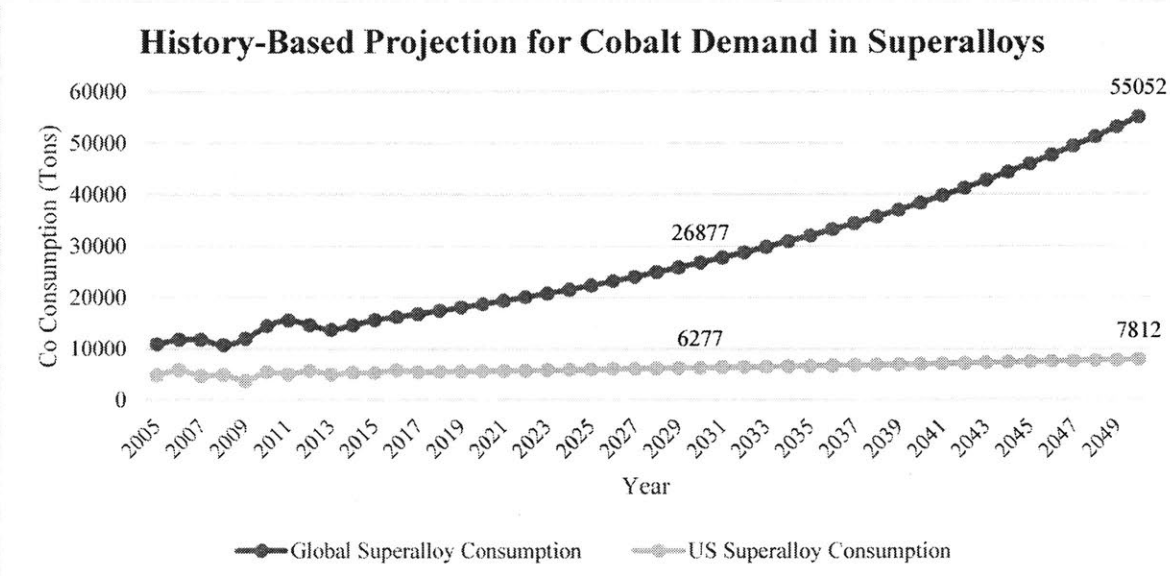


*Figure 6: History-based demand projections for cobalt in the superalloy sector.*

The history-based, or in other words the CAGR-based, projections for cobalt demand from superalloys concluded:

| Year | Predicted Global Superalloy Consumption (Tons) | Predicted US Superalloy Consumption (Tons) |
|---|---|---|
| 2025 | 22,467 | 5,943 |
| 2030 | 26,877 | 6,277 |
| 2050 | 55,052 | 7,812 |

*Table 2: Tabulated cobalt demand projections in the superalloy sector, both in the US and globally, according to data from the USGS and CDI. The table above corresponds to the data represented in Figure 6.*

A second approach was taken to approximate the future U.S. and global demand needs for refined cobalt in the superalloy sector. The projections were made using a bottom-up approach by using future product demand projections combined with materials intensity information. The remaining part of this section will cover the assumptions that this methodology is founded upon and the resulting estimations.

Within the superalloy industry alloys that are cobalt-based or have cobalt additives are used to make turbines and frames for power generation, engines in the aerospace, military, and defense industries, medical implants and imaging devices, and much more. The sectors evaluated and their size in terms of the entire superalloy industry demand are detailed in Table 3.

| **Industry** | **Percentage of Overall Superalloy Demand** |
|---|---|
| Aerospace/Defense | 55 |
| Energy/Power | 30 |
| Medical | 8 |
| Other | 7 |

*Table 3:List of industries included in the bottom-up approach for projecting cobalt demand in superalloys and their respective share of the sector [INSG, 2013].*

For this approach, the superalloy demand was calculated using the primary product in which cobalt is consumed per each of the main industries within the sector. The aerospace and defense industry projected demand was based on jet and aircraft engine demand projections; the energy/power sector demand was estimated using added nuclear and natural gas power projections; the medical and other sectors, as they are small percentages of the superalloy industry and demand information is difficult to track, were estimated using their relative demand in comparison to the other, larger industries.

| Industry | Dominant Product |
| --- | --- |
| Aerospace/Defense | Engines |
| Energy/Power | Turbines |
| Medical | Implants (Orthopedic and Dental) |
| Other | Automobiles |

*Table 4:List of industries included in the bottom-up approach for projecting cobalt demand in superalloys and the product that will represent the industry's cobalt consumption.*

The common alloys and their cobalt intensity for each of these dominant products was determined and is summarized in Table 5.

| Component | Common Alloy Name | Cobalt Intensity of Alloy (wt. %) |
| --- | --- | --- |
| Engine | Inconel 718 | 1 |
| Engine | Astroloy | 17 |
| Engine | Wasaploy | 13.5 |
| Engine | Rene 41 | 11 |
| Turbine | Inconel 718 | 1 |
| Turbine | Inconel 706 | 1 |

*Table 5: List of the dominant products evaluated in the bottom-up approach, the alloy(s) they commonly consist of, and their alloys' cobalt intensity [USGS, 2015].*

From 2012-2031 it is estimated that 149,000 engines will be requested/required by the market globally [INSG, 2013]. Constant demand was assumed per year in order to extrapolate that engine demand will be 180,368 engines from 2012 to 2035 and 298,000 engines from 2012-2050. Engines come in different sizes and so an even-number of small, medium, and large engines was assumed. There are three main companies that produce engines for aerospace and defense applications: Pratt & Whitney, General Electric, and Rolls Royce; in order to account for their different component compositions, each engine size was paired with a different producer. The small engines were considered to be made by Pratt and Whitney, the medium engines by Rolls Royce, and the large engines by General Electric.

| Company | Weight (Tons) | Inconel 718 (wt. %) | Waspaloy (wt. %) | Other (Avg. of Astroloy and Rene 41; wt. %) |
|---|---|---|---|---|
| P&W | 1.95 | 78 | 15 | 7 |
| GE | 8.7 | 65 | 15 | 20 |
| RR | 3.5 | 50 | 11 | 39 |

*Table 6: The main engine-producing companies, the total weight of differently-sized engines for each company, and the percentages of each alloy that the company uses to make its engines [INSG, 2008].*

Engines are approximately composed of 40-50% superalloy [INSG, 2013]. The number of engines, weight per engine, and then the total associated weight of superalloy (for an engine consisting of both 40% and 50% superalloy) was calculated. The material intensity of cobalt per alloy and the amount of each alloy used by the three different companies was then used in order to determine the amount of cobalt needed in order to meet engine demand by both 2035 and 2050, with the above assumptions. Manufacturers must melt ten times the component weight [INSG, 2008] and so the amount of cobalt required for engines was multiplied by ten in order to ultimately obtain the value for the demand for refined cobalt for the aerospace/defense industry.

| Global Projected Refined Cobalt Demand for Aerospace and Defense (Tons) | | |
|---|---|---|
| **Year** | **Upper Demand Estimate** | **Lower Demand Estimate** |
| 2035 | 229,065 | 154,381 |
| 2050 | 402,653 | 322,123 |

*Table 7: Projected demand of cobalt in 2035 and 2050 due to superalloy applications in the aerospace and defense industries.*

From 2008-2035 it is estimated that 312 MW of nuclear power will be installed globally [INSG, 2013]. The global gas-fired power generation capability of OECD countries in 2015 was 2,803 TWh (or 1,279,909 MW) [INSG, 2013]. The number of turbines needed to fill both the nuclear projection to 2035 (and also to 2050; constant demand was assumed per year in order to extrapolate demand out to 2050) and fulfill the natural gas capacity (under the assumption that the capacity remain constant and that one full renewal of capability will occur in the time period to 2035 and once again to 2050). Turbines for nuclear power generation come in different sizes and so an even-number of 15 MW and 30 MW turbines was assumed. Turbines for natural gas power generation come in a variety of sizes; an equal number of 250 MW and 450 MW turbines was assumed. The weights of all turbines are based off of Siemens publicly-available data. All turbines were assumed to consist completely (100%) of superalloys. The material intensity of cobalt per alloy and the amount of each alloy used by the three different companies was then used in order to determine the amount of cobalt needed in order to meet turbine demand up through 2035 and 2050, with the above assumptions. Manufacturers must melt ten times the component weight [INSG, 2008] and so the amount of cobalt required for turbines was multiplied by ten in order to ultimately obtain the value for the demand for refined cobalt for the power/energy industry.

| Turbine Size | Weight (Tons) | Inconel 718 (wt. %) | Inconel 706 (wt. %) |
|---|---|---|---|
| 15 MW | 44.25 | 1 | 1 |
| 30 MW | 88.5 | 1 | 1 |

*Table 8: Table of the two different wind turbine sizes, their corresponding weights, and their alloys' cobalt intensities that are used in the bottom-up demand projections.*

| Global Projected Refined Cobalt Demand for Energy and Power (Tons) | |
|---|---|
| **Year** | **Demand Estimate** |
| 2035 | 133,668 |
| 2050 | 134,819 |

*Table 9: Projected demand of cobalt in 2035 and 2050 due to superalloy applications in the energy industry.*

Research states that the aerospace and defense industries provide 55% of the superalloy sector and the energy and power industries comprise another 30% [INSG, 2013]. This information can be used to check how the projections found above compare. According to the aerospace and defense industry demand projections, the energy and power industry demand should be between 84,208 - 124,944 tons of refined cobalt in 2035 and between 175,703 – 219,629 tons of refined cobalt in 2050. The bottom-up projections for the energy and power industries give similar values, providing confidence in the results of the bottom-up projections.

It was found to be very difficult to collect data on the consumption and demand for superalloys in the medical field. The composition of alloys used was readily available, but the weight of implants varies widely based on patient size and type of implant. Since there was little confidence in an accurate bottom-up approach, projections were made using the aforementioned bottom-up projections and the assumption that the medical industry represents 8% of the superalloy sector [USGS, 2015].

| **Global Projected Refined Cobalt Demand for Medicine (Tons)** | | |
|---|---|---|
| **Year** | **Upper Demand Estimate** | **Lower Demand Estimate** |
| 2035 | 35,645 | 22,455 |
| 2050 | 58,568 | 35,952 |

*Table 10: Projected demand of cobalt in 2035 and 2050 due to superalloy applications in the medical field. Minimum and maximum values determined by the minimum and maximum values derived from engine and turbine demand projections via the bottom-up approach.*

The "other" industries that contribute to the superalloy sector were also found to be widely varying and with a lack of available documentation in order to accurately calculate projected demand via a bottom-up approach. Consequently, projections were made using the aforementioned bottom-up projections and the assumption that the "other" industry represents 7% of the superalloy sector [USGS, 2015].

| Global Projected Refined Cobalt Demand for Other Industries (Tons) | | |
|---|---|---|
| **Year** | **Upper Demand Estimate** | **Lower Demand Estimate** |
| 2035 | 31,189 | 19,648 |
| 2050 | 51,247 | 31,458 |

*Table 11: Projected demand of cobalt in 2035 and 2050 due to superalloy applications in "other" industries. Minimum and maximum values determined by the minimum and maximum values derived from engine and turbine demand projections via the bottom-up approach.*

Overall, the total projected demand for refined cobalt in the superalloy sector is summarized in Table 12.

| Total Global Projected Refined Cobalt Demand for Superalloys (Tons) | | |
|---|---|---|
| **Year** | **Upper Demand Estimate** | **Lower Demand Estimate** |
| 2035 | 494,110 | 324,867 |
| 2050 | 845,134 | 615,245 |
| | | |
| **Total 2012 - 2035** | 494,110 | 324,867 |
| **Total 2012 - 2050** | 1,339,243 | 940,292 |

*Table 12: Bottom-up approach projected demand of cobalt in 2035 and 2050 due to cumulative superalloy applications. Total demand up to both years also listed.*

The bottom-up approach produces significantly higher demand projections than the CAGR-based projections. The CAGR model predicts a global superalloy demand of 526,088 tons total from 2012- 2035, compared to the bottom-up model's total demand to 2035 value of 494,110 tons. Similarly, the CAGR-calculated demand through 2050 is for 1,176,331 tons, while the product-based approach yielded an estimate of 615,245 tons. The two models produce relatively close demand forecasts for the superalloy sector. It follows that a bottom-up approach yields an overestimate, however the difference in order of magnitude in the 2050 projections may be, at least, partially attributed to the fact that not all products made from cobalt-containing superalloys were accounted for in the bottom-up approach.

Future Cutting Tool and Hard Metals Demand

The historic data that was used to calculate the CAGR of the global and U.S. cobalt consumption in cutting tools, which includes cemented carbides and diamond cutting tools, and hard-facing metals, which include high-speed steels and cobalt used for surface-hardening of metals, came from the CDI and USGS, respectively.

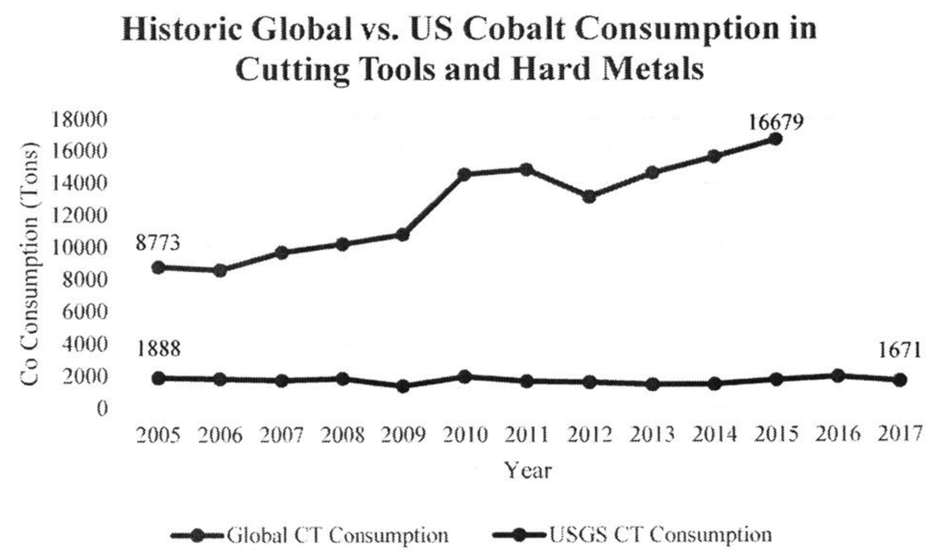


*Figure 7: Historic data for the global and U.S. cobalt consumption in the cutting tools and hard-facing metals sector. Data provided by the CDI and USGS, respectively.*

The global CAGR was found to be 6.64% and the U.S. CAGR was found to be -1.01%. The CAGR values were then used to estimate cobalt demand to the years 2030 and 2050. Due to the large CAGR value difference, the global and U.S. demand projections for this sector were graphed separately.

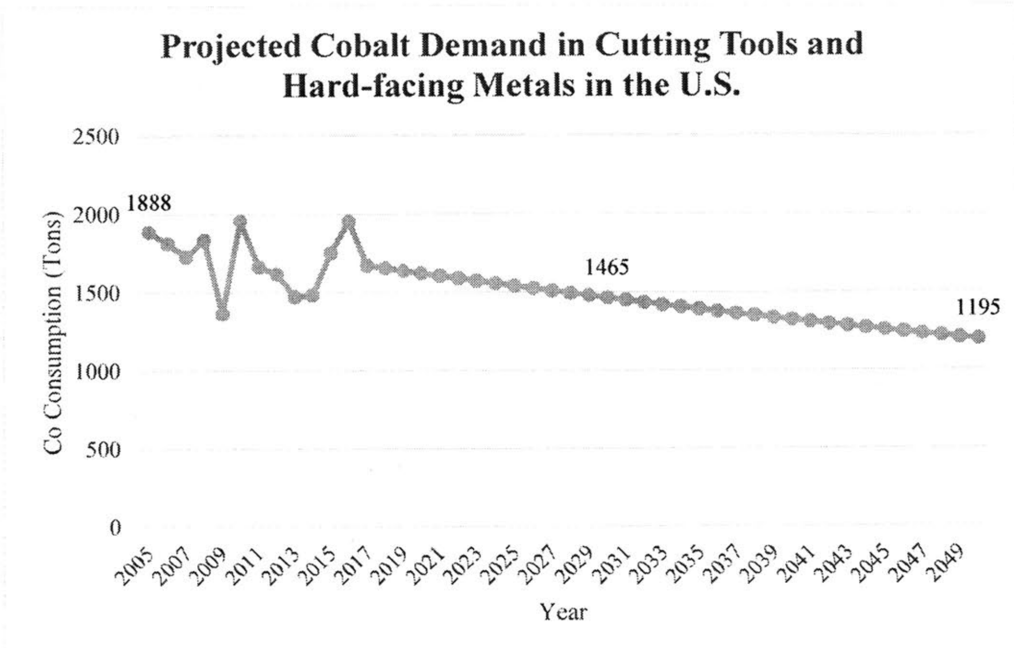


*Figure 8: History-based demand projection for cobalt in the U.S. cutting tool and hard-facing metals sector.*

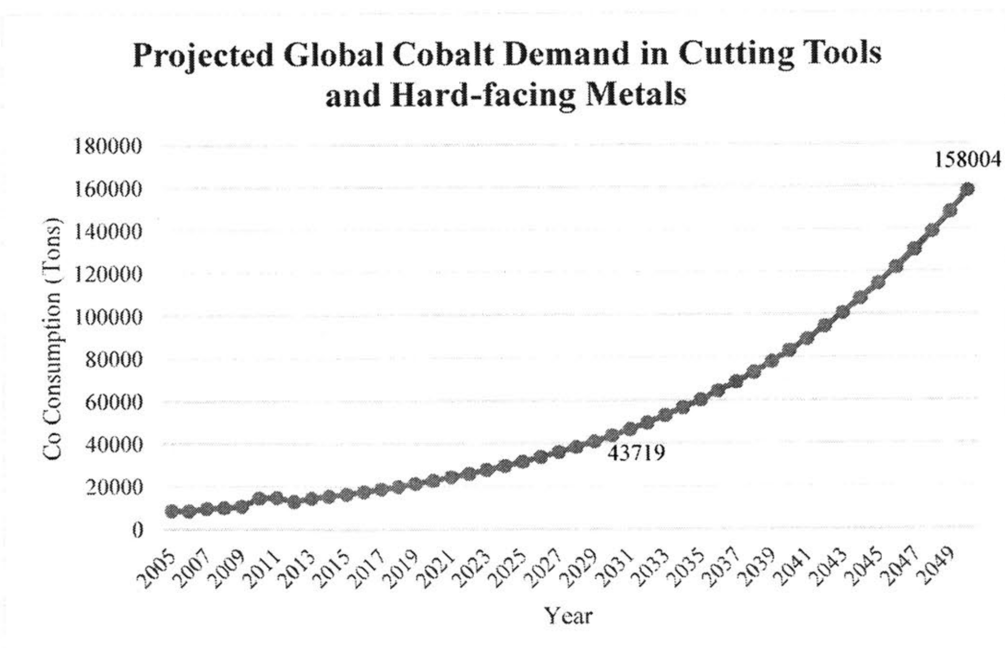


*Figure 9: History-based demand projection for cobalt in the global cutting tool and hard-facing metals sector.*

The history-based, or in other words the CAGR-based, projections for cobalt demand from cutting tools and hard-facing metals concluded:

| Year | Predicted Global Cutting Tools and Hard Metals Consumption (Tons) | Predicted US Cutting Tools and Hard Metals Consumption (Tons) |
|---|---|---|
| 2025 | 31,708 | 1,541 |
| 2030 | 43,719 | 1,465 |
| 2050 | 158,004 | 1,195 |

*Table 13: Projected cobalt demand in the cutting tool and hard-facing metals sector, both in the US and globally, according to data from the USGS and CDI. The table above corresponds to the data represented in Figures 8 and 9.*

The projections made using a bottom-up approach were intended to do so using future product demand projections combined with materials intensity information. No data was able to be found by the author regarding future demand for specific products in this sector; the only available historic and future product demand information was in monetary values. So, the bottom-up approach for this section was performed from two different angles: (1) using cobalt prices and (2) using projected sales revenue and product cost and weight approximations. The remaining part of this section will cover the assumptions that this methodology is founded upon and the resulting estimations.

Within the cutting tool and hard-facing metals industries, alloys that are cobalt-based or have cobalt additives are used in the automotive, aerospace, defense, electronics, construction, ship-building, and other heavy-equipment industries [Grand View Research, 2017]. Cobalt is used to make a variety of products, including but not limited to, bits for lathes and mills, saw blades, turning tools, and high-speed steels. The majority of cobalt-containing cutting tools are cobalt-bound tungsten carbides that are used for cutting tools or as the tips of cutting tools. Cobalt is an ideal binder because it adheres well to the carbide is thought to reduce void percentage and to improve the material's overall toughness, wear-resistance, and strength at high temperatures [Cobalt Institute, 2018].

One of the main producers of cutting tools is a Swedish company, Sandvik. Sandvik provides annual reports, but no specific information regarding cutting tools sales, total part production, specific part production, specific alloys or alloy compositions used, etc. However, the company emphasizes that the demand drivers for cutting tools are global industrial production and primary metals consumption [Sandvik, 2017]. The U.S Cutting Tool Institute (USCTI) and the Association for Manufacturing Technology (AMT) also produce regular (annual and monthly) reports, which proved more helpful to a bottom-up approach to demand projections. Cutting tool sales, in U.S. dollars (USD) , are reported in the USCTI-ATM reports; cutting tool sales represent cutting tool consumption for ~80% of the U.S. cutting tool industry. Monthly cutting tool consumption from January 2014 through January 2018 was collected and summed in order to get total annual consumption for the time period. The reports also contain yearly growth rates, which were used to determine an average growth rate. The average growth rate was found to be 1.72% and was used to predict cutting cool demand out to 2035 and 2050.

Total U.S. cutting tool demand, in USD, was therefore estimated and needed to be converted into a quantity for cobalt demand. This was accomplished by using industrial per-pound prices for tungsten-containing carbide. The minimum price used was $15.21 (USD/lb.) for a 8 wt.% Co steel alloy [Hudson Tool Steep Corporation]. The maximum price used was $73.43 (USD/lb.) for a 15-17 wt.% Co-bound tungsten carbide [Atlantic Equipment Engineers]. Next, the projected annual cutting tool demand values (USD) were divided by both the minimum and maximum prices for cutting tools (USD/ton) in order to obtain minimum and maximum quantities for cutting tools (in tons). Then, the projected minimum and maximum tonnages of cutting tools were converted into refined cobalt demand by multiplying by the minimum and maximum weight-percentages of cobalt assumed in cutting tools – for this analysis it was assumed that the most common industry compositions used fall between 6-10% cobalt.

| **Total Global Projected Refined Cobalt Demand for Cutting Tools (Tons)** | | |
|---|---|---|
| **Year** | **Upper Demand Estimate** | **Lower Demand Estimate** |
| 2035 | 93,196 | 11,583 |
| 2050 | 120,434 | 14,968 |
| | | |
| **Total 2014 - 2035** | 1,714,278 | 213,053 |
| **Total 2014 - 2050** | 3,321,439 | 412,794 |

*Table 14: Price-based projected demand of cobalt in 2035 and 2050 due to cumulative cutting tool and hard-facing metals applications. Total demand up to both years also listed.*

The 2014-2035 total demand projected from the CAGR modelling was found to be 733,006 tons, which falls squarely between the upper and lower demand estimates in this approach. The 2014-2050 total demand was estimated to be 2,303,587 tons, which also lies between the upper and lower approximations of this methodology. However, not all cutting tools and hard-facing metals used in industry use cobalt—there are many applications of ceramics, nitrides, aluminum-based alloys, and non-cobalt-containing carbides and steels. If the cobalt-containing cutting tools and hard-facing materials are instead only assumed to represent 30% of the cutting tool industry, the new demand values projected are closer to, but now lower than, the CAGR projected values.

| Total Global Projected Refined Cobalt Demand for Cutting Tools (Tons) | | |
|---|---|---|
| **Year** | **Upper Demand Estimate** | **Lower Demand Estimate** |
| 2035 | 27,959 | 3,475 |
| 2050 | 36,130 | 4,490 |
| | | |
| **Total 2014 - 2035** | 514,283 | 63,916 |
| **Total 2014 - 2050** | 996,432 | 123,838 |

*Table 15: Price-based projected demand of cobalt in 2035 and 2050 due to cumulative cutting tool and hard-facing metals applications when cobalt-containing materials represent 30% of the sector. Total demand up to both years also listed.*

For the next attempt to a bottoms-up methodology, the cutting tool and hard-facing metals demand was calculated using four of the most common products used in industry in which cobalt is consumed. The cost of each product was found from different industrial retailers and used to covert the total cutting tools demand (USD), from the USCTI-AMT reports, into a number of "units" of each product. The total weight of the product composed of a cobalt-containing alloy (high-strength steel or carbide) was approximated from product specifications (i.e. the turning tool bits total weight for a drill).

| Industrial Products | Cost of Product (USD) | Total Weight of Cobalt Alloy in Product (kg) |
|---|---|---|
| Lathe | $8,000-$30,000 | 5 |
| Mill | $1,400-$9,500 | 8.4 |
| Band Saw (blades) | $100-$755 | 5-14 |
| Drills | $9,000-$2,300 | 5 |

*Table 16: List of dominant industrial products, their cost, and the amount of their mass made of a cobalt-containing alloy. Information used for bottom-up approach. [U.S. Industrial Machinery]*

It was assumed that each product would represent an equal (25%) of the total cutting tool revenue. The same alloy composition range as in the first bottom-up projection approach (6-10 wt. % Co) was assumed in order to calculate total cobalt demand to correspond with product demand

[ASM International]. Manufacturers must melt ten times the component weight [INSG, 2008] and so the amount of cobalt required for tools was multiplied by ten in order to ultimately obtain the value for the demand for refined cobalt for the cutting tool and hard-facing metals industry.

| Total Global Projected Refined Cobalt Demand for Cutting Tools (Tons) | | |
|---|---|---|
| **Year** | **Upper Demand Estimate** | **Lower Demand Estimate** |
| 2035 | 109,493 | 7,154 |
| 2050 | 141,494 | 9,245 |
| | | |
| **Total 2014 - 2035** | 2,014,058 | 131,599 |
| **Total 2014 - 2050** | 3,902,266 | 254,975 |

*Table 17: Bottom-up approach projected demand of cobalt in 2035 and 2050 due to cumulative cutting tool and hard-facing metals applications. Total demand up to both years also listed.*

The demand quantities found through this methodology once again prove that bottom-up approaches are prone to overestimation. In order to mitigate the order-of-magnitude differences in demand projections (compared to the CAGR- and price-based approaches), the cutting tools using cobalt-containing materials were once again assumed to comprise 30% of the entire industry.

| Total Global Projected Refined Cobalt Demand for Cutting Tools (Tons) | | |
|---|---|---|
| **Year** | **Upper Demand Estimate** | **Lower Demand Estimate** |
| 2035 | 32,848 | 2,146 |
| 2050 | 42,448 | 2,774 |
| | | |
| **Total 2014 - 2035** | 604,217 | 39,480 |
| **Total 2014 - 2050** | 1,170,680 | 76,492 |

*Table 18: Bottom-up approach projected demand of cobalt in 2035 and 2050 due to cumulative cutting tool and hard-facing metals applications when cobalt-containing materials represent 30% of the sector. Total demand up to both years also listed.*

The 2014-2035 total demand projected from the CAGR modelling was found to be 733,006 tons, which is now larger than the projected value via this approach. The 2014-2050 total demand was estimated to be 2,303,587 tons, which is also larger than the approximation of this methodology. The discrepancy in projected values should be attributed to the large errors associated with both approach methodologies.

## Future Chemical Catalyst Demand

The historic data that was used to calculate the CAGR of the global and U.S. cobalt consumption in chemical catalysts, which include cobalt compounds used in the hydroformylation of plastics, hydrodesulfurization of petroleum, to catalyze gas-to-liquid fuel processes, and as an oxidizer in various other applications, came from the CDI and USGS, respectively.

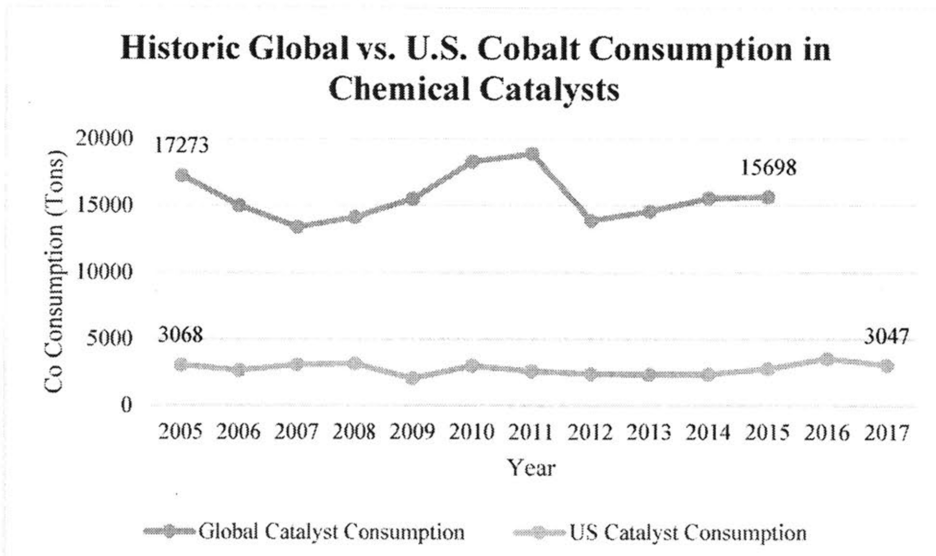


*Figure 10: Historic data for the global and U.S. cobalt consumption in the chemical catalyst sector. Data provided by the CDI and USGS, respectively.*

The global CAGR was found to be -0.95% and the U.S. CAGR was found to be -0.06%. The CAGR values were then used to estimate cobalt demand to the years 2030 and 2050.

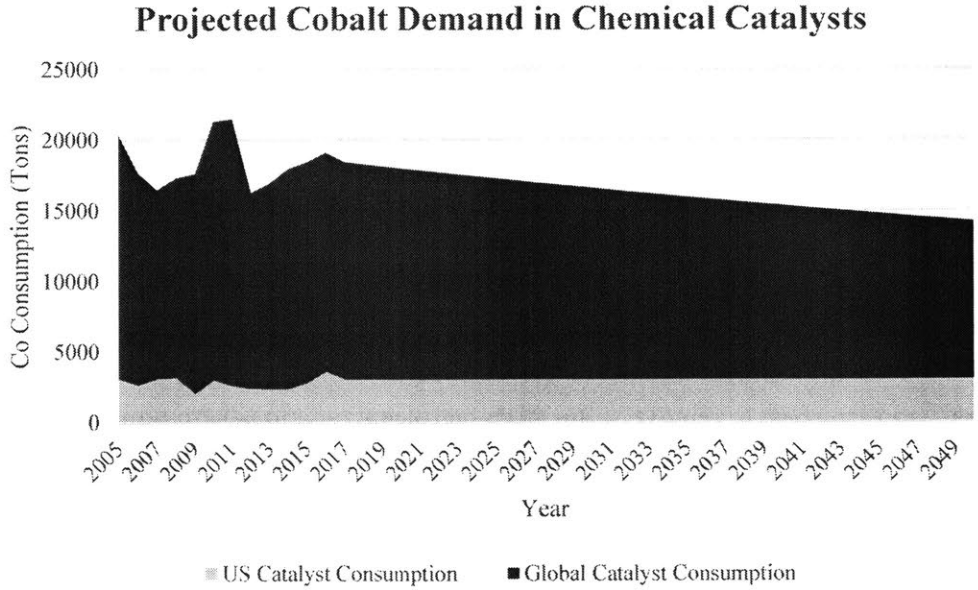


*Figure 11: History-based demand projections for cobalt in the chemical catalyst sector.*

The CAGR-based demand projections from chemical catalysts are shown in Table 19.

| Year | Predicted Global Chemical Catalyst Consumption (Tons) | Predicted US Chemical Catalyst Consumption (Tons) |
|---|---|---|
| 2025 | 14,269 | 3,033 |
| 2030 | 13,604 | 3,024 |
| 2050 | 11,240 | 2,988 |

*Table 19: Tabulated cobalt demand projections in the chemical catalyst sector, both in the US and globally, according to data from the USGS and CDI. The table above corresponds to the data represented in Figure 11.*

A second approach was also taken to approximate the future global demand needs for refined cobalt in chemical catalysts. The projections were made using a bottom-up approach via future product demand projections combined with materials intensity information. The remaining part of this section will cover the assumptions that this methodology is founded upon and the resulting estimations.

Within the chemical catalyst industry, compounds that contain cobalt are used for a range of applications: to synthesize pre-cursors for polyethylene terephthalate (PET), which is the plastic used to make polyester and bottles/containers for a number of applications; in gas-to-liquid (GTL) processes that turn carbon monoxide and hydrogen gases into liquid fuel; as a drying agent in paints, inks, and varnishes; to remove sulfur from petroleum; and to adhere rubbers and metals to each other for manufacturing purposes. The sectors evaluated and accounted for in this bottom-up approach are GTL processing and plastic synthesis.

For this sector, total refined cobalt demand was calculated by first assessing the future demand of the primary products in which cobalt is consumed per each of the main industries within the sector. The GTL industry projected demand was based on production of current facilities and additional installed capacity demand projections. The plastic industry demand was estimated using future global polyester production estimates.

The common alloys and their cobalt intensity for each of these dominant products was determined. Since there are many different cobalt-containing compounds that can be used for both GTL and plastic processes, a range of cobalt intensity determined by academic literature and industry reporting will be used for both applications. The GTL catalysts generally contain 5-20 wt. % cobalt [A Sainna and MK, 2016]. The catalysts used in PET production appear to range from 21-72 wt. % cobalt [Huayou Cobalt]. The minimum and maximum values of these composition ranges will be used in the findings of upper and lower demand projection values.

In 2017, the U.S. Energy Information Administration estimated that 230,000 barrels per day (bpd) of fuel is produced globally via the Fischer-Tropsch GTL process [eia.gov, 2017]. The EIA states that this production will remain constant through 2020; however, from 2021-2024 output of GTL-created fuel will rise to 275,000 bpd [eia.gov, 2017]. From 2025-2035, it is estimated that 405,000 bpd will be produced globally and that by 2040 the production will reach 425,000 bpd [eia.gov, 2017]. A constant demand of 425,000 bpd was assumed from 2040-2050 in order to project demand out to 2050. Annual production was determined and then summed to provide cumulative total production from 2017-2035 and 2017-2050.

According to Shell, one of the companies with GTL facilities worldwide, 1.6 billion cubic feet per day (bcf) of natural gas feed results in 140 kilobarrels/day of GTL fuel [Shell Global, 2012]. This factor was used to determine the total amount of input needed for the calculated projected production. Research was performed to attempt to discern what amount of catalyst is required per reaction, day, kilobarrel of fuel, or any other relevant reaction quantity. Unfortunately, no data was found to be available regarding relative needed amount of catalyst for this process. So, it was assumed that 1-5% of the total input feed will equal the tonnage of catalyst needed. Total demand for refined cobalt from GTL processing was then able to be determined.

| Total Global Projected Refined Cobalt Demand for GTL Cobalt (Tons) | | |
|---|---|---|
| **Year** | **Upper Demand Estimate** | **Lower Demand Estimate** |
| **Total 2017 - 2035** | 2,701 | 135 |
| **Total 2017 - 2050** | 5,538 | 277 |

*Table 20: Bottom-up approach projected demand of cobalt in 2035 and 2050 due to gas-to-liquid industrial activity. Total demand up to both years also listed.*

Next, the cobalt demand from the plastics industry was evaluated. Global polyester production was purported to be approximately 56 million tons in 2010 and was estimated to reach 100 million tons per year by 2020 [NPTEL, 2012]. So, steady and equal growth between 2010-2020 until 100 million tons was reached. 100 million tons was kept constant as the PET demand from 2020-2035; at 2036, it was assumed that the PET demand doubled and then stayed constant at 200 million tons of consumption until 2050. Within the plastics industry, it can be assumed that 60% of PET is used to make textiles (polyester fibers) and 31% is used to make resin for bottles. It was also assumed that 1% of the final amount of PET produced was equivalent to the weight of pre-cursor necessary for processing. Manufacturers must melt ten times the component weight [INSG, 2008] and so the amount of cobalt required for tools was multiplied by ten in order to ultimately obtain the value for the demand for refined cobalt for the cutting tool and hard-facing metals industry.

| **Total Global Projected Refined Cobalt Demand for PET Cobalt (Tons)** | | |
|---|---|---|
| **Year** | **Upper Demand Estimate** | **Lower Demand Estimate** |
| **Total 2017 - 2035** | 2.83E10 | 82,530,000 |
| **Total 2017 - 2050** | 6.43E10 | 187,530,000 |

*Table 21: Bottom-up approach projected demand of cobalt in 2035 and 2050 due to industrial PET production. Total demand up to both years also listed.*

| **Total Global Projected Refined Cobalt Demand for Cobalt in Chemical Catalyts (Tons)** | | |
|---|---|---|
| **Year** | **Upper Demand Estimate** | **Lower Demand Estimate** |
| **Total 2017 - 2035** | 282,96,002,701 | 82,530,135 |
| **Total 2017 - 2050** | 64,296,005,538 | 187,530,277 |

*Table 22: Bottom-up approach projected demand of cobalt in 2035 and 2050 due to cumulative chemical catalyst applications. Total demand up to both years also listed.*

It is apparent that the bottom-up approach for the sector produced a gross overestimate of demand. The overestimation seems to mostly be in the PET-centered calculations. Assumptions in this case may have been too generous; it is hard to know exact values for how much catalyst is required and the material intensity of cobalt in the pre-cursor components used industrially. The 2010-2035 total demand projected from the CAGR modelling was found to be 381,488 tons, which is significantly smaller than the projected value via this approach. The 2010-2050 total demand was estimated to be 561,887 tons, which is also much smaller than the approximation of this methodology. The discrepancy in projected values should be attributed to the large errors associated with the PET bottom-up approach projection. If the amount of catalyst needed per ton of produced PET becomes 0.1%, then the 2010-2035 total demand projected from the bottom-up approach becomes 28,296,000 (upper) to 8,253,000 (lower) tons and the 2010-2050 total demand projection becomes tons. This is still much too high and more research should be done regarding the underlying issues with the methodology in this case, especially including what percentage of PET production is done with cobalt-containing catalysts.

### Future Magnet Demand

The historic data that was used to calculate the CAGR of the global and U.S. cobalt consumption in magnets came from the CDI and USGS, respectively. Two of the four most commonly-used permanent magnets partially consist of cobalt. These types of magnets are used in applications including computer hard drives, wind turbines, speakers, magnetic resonance imaging (MRI) machines, and high-performance servos.

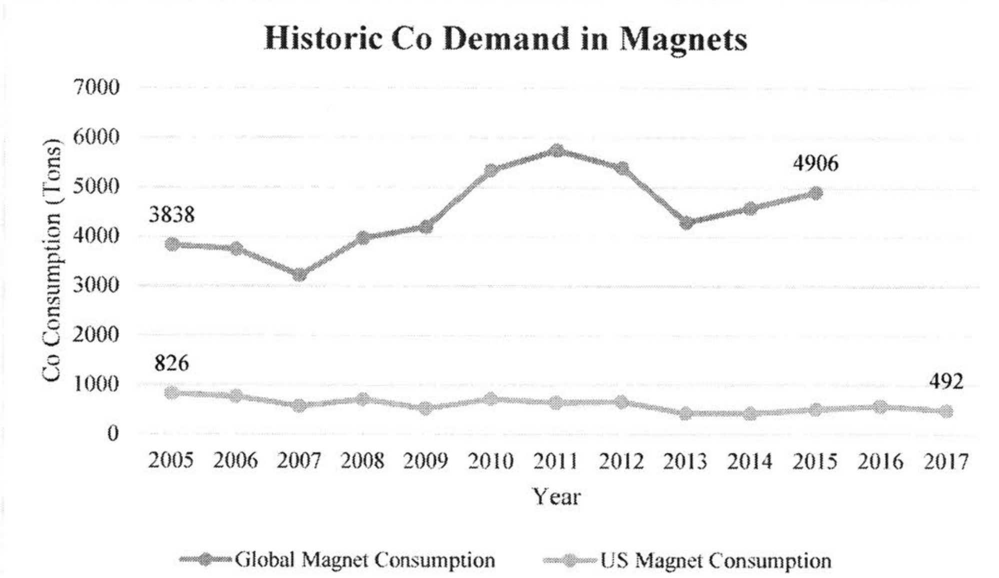


*Figure 12: Historic data for the global and U.S. cobalt consumption in the magnet sector. Data provided by the CDI and USGS, respectively.*

The global CAGR was found to be 2.48% and the U.S. CAGR was found to be -4.23%. The CAGR values were then used to estimate cobalt demand to the years 2030 and 2050. Due to the large CAGR value difference, the global and U.S. demand projections for this sector were graphed separately.

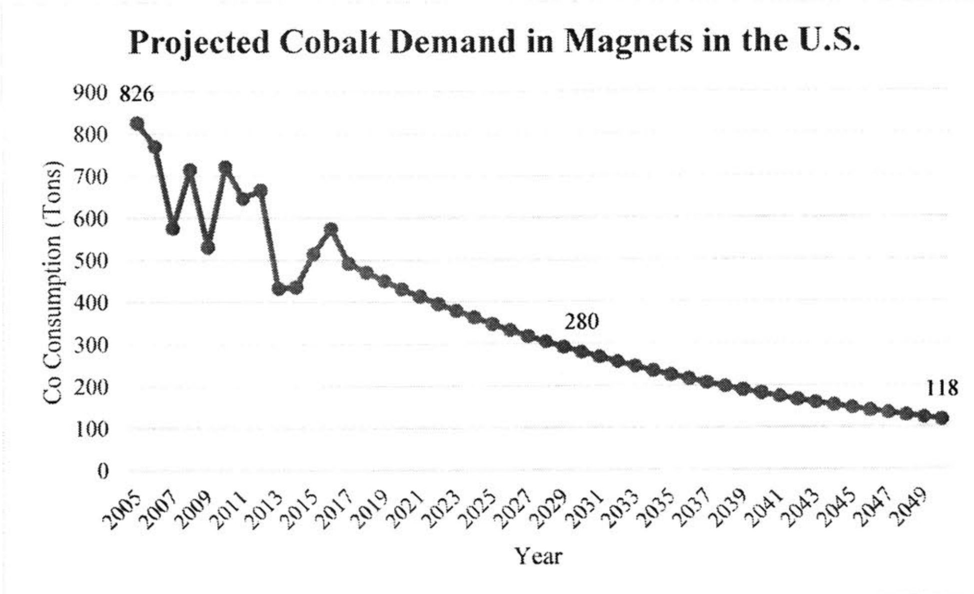


*Figure 13: History-based demand projection for cobalt in the U.S. magnet sector.*

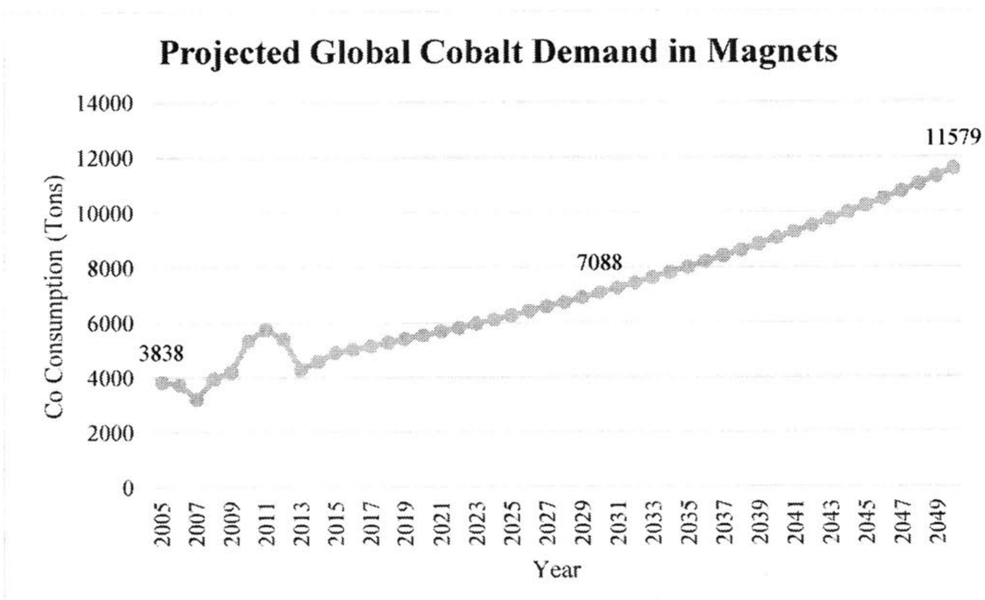


*Figure 14: History-based global demand projection for cobalt magnet sector.*

The history-based, or in other words the CAGR-based, projections for cobalt demand from magnets concluded:

| Year | Predicted Global Magnet Consumption (Tons) | Predicted US Magnet Consumption (Tons) |
|---|---|---|
| 2025 | 6,270 | 348 |
| 2030 | 7,088 | 280 |
| 2050 | 11,579 | 118 |

*Table 23: Tabulated cobalt demand projections in the magnet sector, both in the US and globally, according to data from the USGS and CDI. The table above corresponds to the data represented in Figures 13 and 14.*

An alternate approach was taken to approximate the future global demand for refined cobalt in the magnet sector. The projections were made using a bottom-up approach by using future product demand projections combined with materials intensity information. The remaining part of this section will cover the assumptions that this methodology is founded upon and the resulting estimations.

The permanent magnet industry is comprised primarily by four types of magnet: samarium cobalt (SmCo), ferrite, neodymium-iron-boron (NdFeB), and aluminum-nickel-cobalt (Alnico). SmCo and Alnico magnets are the two types of permanent magnets consisting partially of cobalt, at varying compositions; they are produced at smaller capacities than NdFeB and ferrite magnets. Within the permanent magnet industry alloys that are cobalt-based or have cobalt additives are used mainly for aerospace and defense applications, instrumentation, controls, sensors, and motors in an assortment of industries [Arnold Magnetics, 2018].

For this approach, the permanent magnet demand was calculated using a designated primary product in which cobalt is consumed in each of the main industries within the sector. The aerospace and defense industry projected demand was based on satellite and aircraft demand projections; the automotive sector demand was estimated using projections for the number of new cars to be added into circulation; the cell phone sector's demand for cobalt was based on population projections and the corresponding percentage of the population with a mobile phone. The sectors evaluated in this approach, the specific products in the industry to be analyzed, and the products' projection metrics can be found in Table 24.

| Industry | Product | Projection Metric |
|---|---|---|
| Aerospace/Defense | Satellite Actuators & Sensors | #satellites ordered and predicted to be launched |
| Aerospace/Defense | Aircraft Actuators & Sensors | # new aircraft |
| Automotive | Sensors | # new cars |
| Electronics | Cell Phone Speakers | # mobile phone users |

*Table 24: List of dominant industries, their representative products, and the metric by which the number of 'units' of each product will be determined in the bottom-up approach.*

The common alloys and their cobalt intensity for each of these dominant products was determined and is summarized in Table 25.

| Common Alloy Name | Cobalt Intensity of Alloy (wt. %) |
|---|---|
| $SmCo_5$ | 64 |
| $Sm_2Co_{17}$ | 50 |
| Alnico | 5 - 40 |

*Table 25:List of common magnet alloys containing cobalt and their cobalt compositions.*

From 2012-2031 it is estimated that 149,000 aircraft will be requested/required by the market globally [INSG, 2013]. Constant demand was assumed per year in order to extrapolate that aircraft demand will be 180,368 aircraft from 2012 to 2035 and 298,000 aircraft from 2012-2050.

Aircraft use permanent magnets in a variety of sensors and instrumentation; it was assumed that all aircraft sensors were within the same size range of 0.3 – 2 kg [Cedrat Technologies, 2018]. An assumption of 10 magnetic sensors per aircraft was made [Eclipse Magnetics, 2018]; one-half of magnets were considered to be 100% compositionally $SmCo_5$ and the other half were considered to be 100% compositionally $Sm_2Co_{17}$. Manufacturers must melt ten times the component weight [INSG, 2008] and so the amount of cobalt required for tools was multiplied by ten in order to ultimately obtain the value for the demand for refined cobalt for the cutting tool and hard-facing metals industry.

| Global Projected Refined Cobalt Demand for Magnets in Aircraft (Tons) | | |
|---|---|---|
| **Year** | **Upper Demand Estimate** | **Lower Demand Estimate** |
| 2012 - 2035 | 25,449 | 2,982 |
| 2012 - 2050 | 42,046 | 4,927 |

*Table 26: Bottom-up approach projected demand of cobalt in 2035 and 2050 due to magnetic applications in aircrafts.*

From 2012-2021 it is estimated that 959 satellites will be ordered and 1,080 satellites will be launched [NSR, 2015]. Constant demand was assumed per year in order to extrapolate that demand will be 5,221 satellites from 2012 to 2035 and 3,405 aircraft from 2035-2050. Satellites use permanent magnets in a variety of sensors and instrumentation; it was assumed that all satellite sensors were within the same size range of 0.3 – 2 kg [Cedrat Technologies, 2018]. An assumption of 5 magnetic sensors per aircraft was made [Eclipse Magnetics, 2018]; one-half of magnets were considered to be 100% compositionally $SmCo_5$ and the other half were considered to be 100% compositionally $Sm_2Co_{17}$.

| Global Projected Refined Cobalt Demand for Magnets in Satellites (Tons) | | |
|---|---|---|
| **Year** | **Upper Demand Estimate** | **Lower Demand Estimate** |
| 2012 - 2035 | 368 | 43 |
| 2012 - 2050 | 608 | 71 |

*Table 27: Bottom-up approach projected demand of cobalt in 2035 and 2050 due to magnetic applications in satellites.*

Next, the automotive industry's use of cobalt in magnetic sensors was evaluated. In automobiles, magnetic sensors are primarily used for vibration control and for stop-start break systems. Reports suggest that 0.8 billion new cars are to be added onto roads between 2014 – 2035 [Green Car, 2014]. In all new vehicles magnetic actuators will be used for vibration control and in 45% of new vehicles there will be stop-start break systems [Statista, 2018]. Consequently, 1 magnetic sensor was accounted for 55% of new vehicles and 2 magnetic sensors were accounted for 45% of new vehicles. Constant demand was assumed per year in order to extrapolate demand to 2050. Another assumption made is that the magnets used in automotive actuators (for both applications) all have masses between 60 – 350 g [Cedrat Technologies, 2018]. All of the magnets in this application were considered to be Alnico magnets. Manufacturers must melt ten times the component weight [INSG, 2008] and so the amount of cobalt required for tools was multiplied by ten in order to ultimately obtain the value for the demand for refined cobalt for the cutting tool and hard-facing metals industry.

| Global Projected Refined Cobalt Demand for Magnets in Automobiles (Tons) | | |
|---|---|---|
| Year | Upper Demand Estimate | Lower Demand Estimate |
| 2014 - 2035 | 1,790,154 | 38,360 |
| 2014 - 2050 | 1,161,935,154 | 65,764 |

*Table 28: Bottom-up approach projected demand of cobalt in 2035 and 2050 due to magnetic applications in automobiles.*

And, finally, the electronics industry's use of cobalt in speakers was analyzed. Cell phones were the chosen product for this sector due to their large projected growth, market dominance, and data availability. Cobalt is used in many types of speakers, including cell phone speakers, via Alnico magnets [Arnold Magnetics, 2018]. The World Bank estimates that there will be one billion more people worldwide in 15 years (compared to the 2018 population of 7.3 billion) and that by 2050 there will be 9.7 billion people globally. McKinsey, an internationally renowned consulting group, predicts that by 2030 75% of the global population will own a mobile device. The percentage of the population with a mobile device (75%) was held constant in the projections to both 2035 and 2050. Another assumption made is that the magnets used in automotive actuators (for both applications) all have masses between 1 - 5 g; this is an estimate made without a basis in industry practice, due to an inability to find such data. All of the magnets in this application were considered to be Alnico magnets. Manufacturers must melt ten times the component weight [INSG, 2008] and so the amount of cobalt required for tools was multiplied by ten in order to ultimately obtain the value for the demand for refined cobalt for the cutting tool and hard-facing metals industry.

| Global Projected Refined Cobalt Demand for Magnets in Cell Phones (Tons) | | |
|---|---|---|
| Year | Upper Demand Estimate | Lower Demand Estimate |
| 2018 - 2035 | 291,010 | 18,188 |
| 2018 - 2050 | 611,783 | 38,236 |

*Table 29: Bottom-up approach projected demand of cobalt in 2035 and 2050 due to magnetic applications in cell phones.*

The resulting total refined cobalt demand projected to be required by the permanent magnet sector can be found in Table 30.

| Global Projected Refined Cobalt Demand for Magnets (Tons) | | |
|---|---|---|
| **Year** | **Upper Demand Estimate** | **Lower Demand Estimate** |
| 2018 - 2035 | 2,106,981 | 59,573 |
| 2018 - 2050 | 1,162,589,591 | 108,998 |

*Table 30: Bottom-up approach projected cumulative demand of cobalt in 2035 and 2050 due to industrial magnetic applications.*

The projected cobalt demand that is concluded from the bottom-up approach in this sector appears to be an extreme over-estimate. This is partially due to the large growth expectations in the automotive and electronics industries; and NdFeB magnets are also often used in electronics and automotive applications, which would lower the demand projections. Additionally, the underlying assumptions of this approach are rather generous to cobalt. The CAGR-method predicts that the 2018-2035 demand should sum to 118,039 tons and the 2018-2050 demand to cumulatively be 265,134 tons; both values are significantly less than the bottom-up demand projection suggests.

## Supply Projections vs. Demand Projections

The CAGR-projected demand values for each sector were added together to provide a total, cumulative projected demand value, as can be seen in Figure 15 and Table 31. The bottom-up approach-projected demand values were also summed in order to obtain a cumulative demand value, as demonstrated in Table 32. The bottom-up approach projections were not graphed because due to the large differences in order of magnitudes of the projected values in the different sectors, graphing does not provide any additional information.

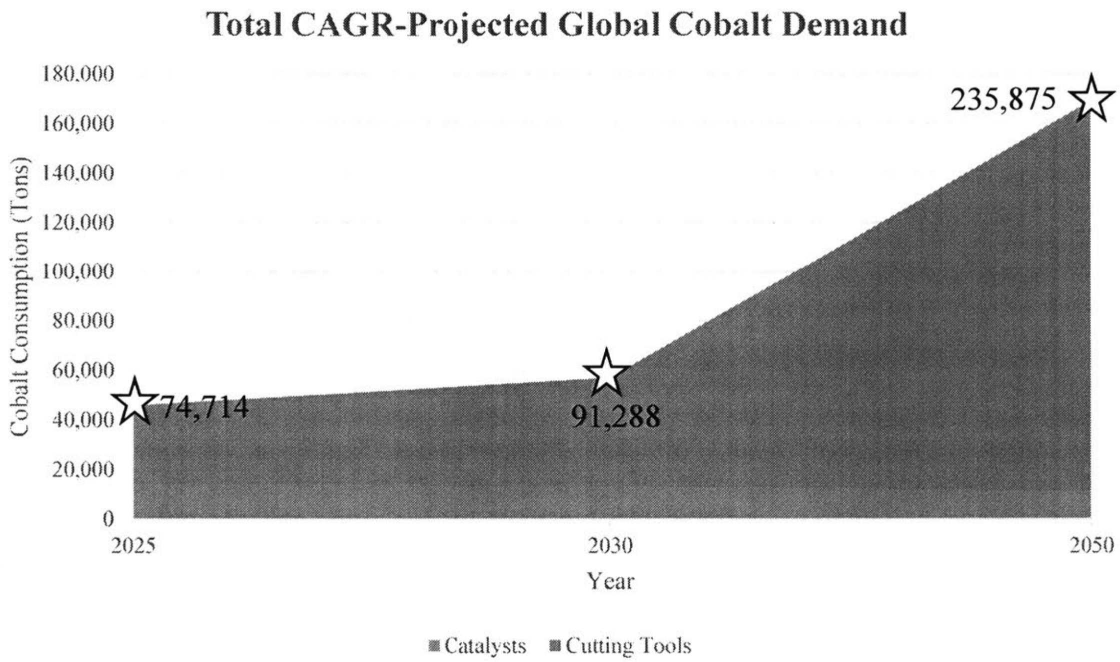


*Figure 15: Cumulative projected cobalt demand for 2025, 2030, and 2050 from CAGR-based predictions.*

| Global CGAR- Projected Total Refined Cobalt Demand (Tons) | | | | | |
|---|---|---|---|---|---|
| **Year** | **Superalloys** | **Cutting Tools** | **Catalysts** | **Magnets** | **Total** |
| 2025 | 22467 | 31,708 | 14,269 | 6,270 | 74,714 |
| 2030 | 26,877 | 43,719 | 13,604 | 7,088 | 91,288 |
| 2050 | 55,052 | 158,004 | 11,240 | 11,579 | 235,875 |

*Table 31: CAGR- projected total demand of cobalt in 2025, 2030, and 2050; total and sector-breakdown demand projections shown.*

| Global Bottom-Up- Projected Total Refined Cobalt Demand (Tons) | | | | | |
|---|---|---|---|---|---|
| Year | Superalloys | Cutting Tools | Catalysts | Magnets | Total |
| 2035 | 324,867 - 494,110 | 2,146 - 32,848 | 82,530,135 – 28,296,002,701 | 59,573 - 2,106,981 | 82,916,721 - 28,298,636,640 |
| 2050 | 615,245 - 845,134 | 2,774 - 42,448 | 187-530,277 - 64,296,005,538 | 108,998 - 1,162,589,591 | 188,257,294 - 65,459,482,711 |

*Table 32: Bottom-up- projected total demand of refined cobalt in 2035 and 2050; total and sector-breakdown demand projections shown.*

Now that the total demand has been calculated, the supply projections can be discussed and compared to the demand values. Research on cobalt supply has been done at the same time as this work in MIT's Olivetti Group. The supply-side calculations by the group, and similar calculations done by a private commodities firm, can be found in Table 33. The "refined cobalt" term used in the table below is better described as a measure of the current refined amount with the addition of mining production possibilities (the refining losses have not been taken into account completely).

| Projected Total Global Refined Cobalt Supply (Tons) | | |
|---|---|---|
| Year | Olivetti Group Supply Estimates | Darton Commodities Supply Estimates |
| 2017 | 149,000 | 132,000 |
| 2023 | 160,000 | 158,000 |

*Table 33: Tabulated values for total global cobalt supply in 2017 and 2023 by the Olivetti Group and Darton Commodities.*

If all of the above information in combined into one table for an easier comparison (Table 34), we can see that in the short-term, in 2025, if we assume that the supply projection for 2023 remains constant to 2025, there is no cobalt shortage. In fact, there is actually an 85,286 ton surplus of cobalt that may be used for other industries, such as batteries. The Olivetti Group has also forecasted cobalt demand due to growth in the battery sector, mostly due to electric vehicle demand growth. Their research suggests that in 2025 predicted battery demand will be between 136,000 – 330,000 tons of refined cobalt [Olivetti et. al., 2017]. If this is the case, there will be a shortage in cobalt available for the battery sector, which is much more elastic than the sectors discussed in this work (superalloy, cutting tool, catalyst, and magnet).

| **Total CAGR-Projected Global Refined Cobalt Demand vs. Total Projected Global Supply (Tons)** | | | | |
|---|---|---|---|---|
| **Year** | **CAGR-Demand** | **Bottom-Up Demand** | **CAGR-Demand + Battery Demand** | **Supply Projections** |
| 2025 | 74,714 | - | 136,000-330,000 | ~160,000 |
| 2030 | 91,288 | ~82,916,721 | - | - |
| 2050 | 235,875 | ~188,257,294 | - | - |

*Table 34: Total demand projections from the two approaches taken to project demand in this paper. The lower demand estimates are provided in the bottom-up column. The total non-battery and battery demand projection and the supply projection for the overlapping year of projections are also shown.*

# Cobalt Alternatives

There are many reasons that partial and complete substitutions for cobalt in existing materials technology and new alternative materials without cobalt have been a major focus of the academic and industry communities for decades. Cobalt's volatile pricing and the geopolitical instability in the DRC, the producer of more than half of the world's raw cobalt supply, and the toxicity of the element have prompted researchers since the 1980's to look for alternatives to cobalt in a variety of applications to reduce import dependency. Technological innovation and improvement, materials conservation, and maintenance of industrial competitiveness are additional reasons for both academics and industry leaders alike to focus on cobalt alternatives. This section will review the current knowledge of the scientific community and cobalt-dependent industries regarding viable cobalt substitutes. Then, an analysis of the price points at which, upon the achievement of acceptable performance, alternative materials will be preferential to cobalt. The scale of the effects of substituting out cobalt on the demand projections from earlier in this work will conclude the section.

## Viable Substitutions

Most research supports the claim that most cobalt substitutions are only viable at high costs – due to increased cost of replacement/additional materials or increased manufacturing and processing measures – or with a loss in overall performance [Cobalt Institute, 2018]. Cobalt substitutes will be discussed in this work for superalloys, cemented carbides, magnets, driers and paints, and catalysts for petroleum and plastics processing.

## Superalloys

The superalloys using cobalt range in compositions from 0-65 wt. % cobalt. The low-cobalt range is when cobalt is used as an alloying element to improve toughness, corrosion-resistance, and/or wear-resistance. Larger cobalt composition alloys are based in cobalt for similar reasons, but are often used for higher temperature applications, where cobalt's unique properties maintain proper functioning at higher temperatures. In engines and turbines, where cobalt is used in a variety of components, nickel- and iron-based alloys, ceramics, composites (ceramic-ceramic, carbon-carbon, and fiber-reinforced metal matrix composites), titanium aluminides, and Niobium replacement (of cobalt) have all been studied thoroughly.

The use of iron- and nickel-based superalloys have generally been found to significantly lose performance abilities at high temperatures. One study found that it may be possible to half the amount of cobalt in nickel-based superalloys with little to no effect [NASA, 1987]. Heat treatment was found to allow a lower cobalt content and produce a significantly higher yield strength, yet also result in a lowered rupture life [NASA, 1987]; further research and heat testing could help to remedy the performance effects. Other research found that using tantalum as a cobalt substitute in MAR-M 247, a superalloy with a 10% cobalt content [Strategic Materials] used for cast rotors, resulted in an alloy with increased tensile and creep strength [Strategic Materials]. Furthermore, niobium has been investigated as an alternative to cobalt as an alloying element in Inconel superalloys; niobium is an ideal substitute because it is largely imported from Brazil, a more geopolitically stable country than the DRC, it is cheaper than cobalt, and it is easy to manufacture [NASA, 1987].

However, the main contender for substituting out cobalt are ceramic matrix composites. Ceramic and composites can withstand higher temperatures than cobalt-containing superalloys;

however, ceramics are incredibly brittle, which limits their usability, and composites are currently are expensive, difficult to manufacture, and highly variable in properties in different directions. Silicon carbide-reinforced alloys have been evaluated recently as viable alternatives for cobalt-containing superalloys. These alloys are iron-based and contain no cobalt or other strategic metals. They are a popular focus of study due to their potential to significantly reduce component weight or to extend service life of products, while diminishing dependence on strategic materials. There is still work to be done before these ceramic-metal composites have been proven to meet the safety requirements of the aerospace and defense sector and before their cost is competitive.

In the medical industry, titanium alloys comprise the majority of medical implants and would be the most viable alternative to cobalt-containing alloys in use. Cobalt is generally used because nickel can cause allergic reactions in some; therefore, titanium aluminides and other titanium-based alloys not containing nickel or cobalt would be the implemented substitutes [CRM_InnoNet].

There are available substitutes, however, substitution for cobalt in jet engines will probably not occur in the short-term, due to the safety requirements of the aerospace and defense sector. Therefore, cobalt substitution in superalloys can only be considered to possibly impact superalloys in turbines and medical implants.

### Cutting Tools and Hard-facing Metals

The alloys used in this sector of cobalt demand range in compositions from 5-30 vol. % cobalt. In diamond and metal cutting tools and hard-facing metals, cobalt is added in order to increase material toughness as well as corrosion- and wear-resistance. Generally, substituting cobalt out of its applications in this sector or using an alternate material completely have resulted in losses of performance, but research and developments in this field are extremely active.

In the cutting tool industry, 75% of components consist of cemented carbide. One of the most commonly used cemented carbides used in industry is tungsten carbide (WC); cobalt is regularly used as a binder to toughen tungsten carbide. Cobalt is used because it is an effective binder, but it has a relatively low melting temperature and limited hardness at high temperatures. Also, cobalt can be toxic and, as previously mentioned, is subject to large fluctuations in price and market availability due to the political environments in the majority- cobalt producing country.

Alternatives to cobalt-toughened WC tools that have been studied include alternative binders, partial supplementation of cobalt binders, and completely different carbide base materials. Some proposed solutions are: tantalum carbide, cobalt-iron-copper alloys, iron-copper alloys, ceramics (silicon carbide, silicon nitride, aluminum silicates), nickel-based superalloys, and rhenium-toughened silicon carbide [CRM_InnoNet].

Variable cermets have been researched as options for reducing the amount of cobalt used in the cutting tools and hard materials sector. Titanium carbide (TiC) and titanium nitride (TiN) have been investigated; both cermets wet better with nickel, molybdenum, or chromium binders, rather than a cobalt binder [NASA, 1987]. As a result, both TiC and TiN are used for machining ferrous metals due to their better wear-resistance, hardness, usability at higher speeds, and chemical stability than WC-Co alloys; however, they are more brittle, less tough, and often have shorter lifetimes and thermal conductivity [NASA, 1987]. The disadvantages have prevented higher cermet market penetration [NASA, 1987].

Different binders for WC have been investigated thoroughly, producing both partial and complete substitutes for cobalt with varying degrees of commercial viability. WC-Fe alloys have been produced via hot isostatic pressure (HIP) processing and iron was determined to be an outstanding substitute for cobalt [Kulin et. al., 1981]. Cobalt-iron-copper and iron-copper alloys were also both found to be generally acceptable substitutes for WC-Co alloy applications and as a way to reduce cobalt demand in the sector [Kulin et. al., 1981]. Iron-nickel and iron-manganese have also been alternate WC binders studied; iron-manganese bound WC showed slightly higher toughness and slightly lower toughness than cobalt-bound WC [Kulin et. al., 1981]. Iron-nickel bonded WC was produced with a similar hardness as WC-Co and minimally increased toughness through additional heat treatments [Kulin et. al., 1981]. Many patents describe the use of combined iron, nickel, and cobalt binder compositions and resulting increased toughness and corrosion-resistance, compared to just cobalt as a single binder. Additionally, WC-Fe alloys have been produced via hot isostatic pressure (HIP) processing and iron was determined to be an outstanding substitute for cobalt [Kulin et. al., 1981]. Cobalt-iron-copper and iron-copper alloys were also both found to be generally acceptable substitutes for WC-Co alloy applications and as a way to reduce cobalt demand in the sector. Additionally, rhenium was shown to have a positive effect on component performance [Waldorf, 2008]. Research suggests that WC-Re and WC-Co-Re (cobalt- and rhenium-bonded WC; composition of ~20 wt. % Re) have superior hardness, although lowered toughness, than WC-Co [Waldorf, 2008]. However, the WC-Co-Re cutting tools were found to be "two times more durable" than commercial WC-Co tools in machining various hard and heat-resistant alloys. The production costs and complexity have made WC-Co-Re manufacturing not suitable for commercialization and therefore not economically competitive. Overall, research has found that tools made with alternative binders show significantly less wear compared to solely cobalt-bound cemented carbides [Waldorf, 2008]. The improved performance of alternative binder tools was shown to allow an increase of 18% cutting speed without tool life trade-offs [Waldorf, 2008].

For wear-resistant metal alloys, which generally contain 5 wt. % cobalt, ceramics are also the primary replacement material under consideration. Ceramic cutting tools have become more common for higher-speed and lower feed applications. Silicon and aluminum-based ceramics provide increased productivity, wear-resistance, lifetime, and corrosion-resistance to metallic alloys. The ceramic materials specifically being used/studied to replace cobalt-containing alloys include: $Al_2O_3$-TiC, $Si_3N_4$, $Si_3N_4$-$Al_2O_3$ (sialon), $SiC_w$-$Al_2O_3$, CBN (cubic boron nitride), and PCD (polycrystalline diamond) [Strategic Materials]. Additionally, the market cost of ceramics and tungsten carbide are not significantly different; approximately two-thirds of ceramic tool sales are alumina-based [Strategic Materials]. However, ceramics are only usable under conditions that promote cracking and chipping [Strategic Materials]. The main issue with the switching to ceramic components is that most machine tools cannot accept ceramic components (no part standardization and no interest in industry to change all machines to have such a capability) [Strategic Materials].

### Magnets

The primary cobalt-containing magnets are aluminum-nickel-cobalt (AlNiCo) and samarium-cobalt (SmCo) permanent magnets. These types of magnets are used in electric motors, microphones, various sensors, speakers, computers, turbines for wind power generation, and MRI's. The main permanent magnet types commercially available made of either ferrite (combined with either Sr, Ba, or CoO), one of the two cobalt-containing magnets aforementioned, or neodymium-iron-boron (NdFeB). NdFeB magnets are the most powerful and is the most commercially important magnets of the four most common types. Neodymium is an expensive element that makes up almost one-third of NdFeB magnets [Arnold Magnetics, 2018]. However, ferrite magnets, nickel-iron magnets, or ceramic magnets may also be used if neodymium prices make NdFeB magnets economically un-viable for applications. However, only magnets with cobalt retain their magnetic properties at high temperatures, due to cobalt's high curie temperature.

### Chemical Catalysts

Cobalt is a popular catalyst for chemical reactions in the plastic, paint, and energy industries. It is instrumental in the commercial production of materials that are used by most Americans every day, like water bottles, petroleum, and paints. A discussion on the substitution options for cobalt in batteries will not be included in this section, although there has been and continues to be a great deal of research on the topic.

Cobalt is used by paint manufacturers as an oxidizing (and a drying) agent. Alternatives that have been researched are cerium, iron, lead, manganese, and vanadium [USGS, 2017]. According to industry producers, manganese driers are the current main substitute for cobalt because of their high drying power, which is almost as powerful as cobalt's, and their improved film hardness [USGS, 2017]. The main disadvantages to manganese substitution in paints is that they commonly discolor and darken white and light-colored paints, they require longer drying times, and their substitution capacity is situationally-dependent [SubsPort, 2018]. Cobalt salts used as driers can also be substituted for iron compounds; however, manganese compounds are preferred by industry.

The hydroformylation step of plastic production depends on cobalt-containing compounds. Rhodium, acetate, and manganese-sodium-boron compounds are considered by the academic community to be viable replacements for PTA production [CRM_InnoNet]. Copper-iron-manganese compounds are under investigation for their viability in substituting cobalt in polyester resin production [CRM_InnoNet].

The energy industry depends on cobalt as a catalyst for the hydrodesulfurization of petroleum; this is a difficult step of the refining process, since catalysts used must be sulfur-resistant in order to minimize the creation of unsafe by-products. Ruthenium, molybdenum, nickel, tungsten are known, acceptable substitutes for cobalt in this case, however, their viability is feed-dependent [CRM_InnoNet].

## Summary

There is a range of viability regarding the substitutes and alternatives to cobalt discussed above. Full development of solutions and commercial-scale implementation of solutions will require more time, energy, and capital in all cases. Although there is a strong growth demand forecasted for cobalt – a CAGR value of 5.3% from 2016-2025 – the issues of price volatility, increase prices, and concentrated supply in controversial and unstable environments have required governments and companies to consider viable material alternatives. This will become more and more essential as cobalt demand continues to rise.

A summary table of the viable materials alternatives, per sector, is provided below (Table 35). Price comparisons were made between the current market prices of cobalt $88,750 (USD/ton) and the substituting element/material for short-term substitutes to determine economic viability *[LME or InfoMine, 2018]*. Long-term substitutes and alternatives must be economically competitive with future cobalt prices; an estimated long-term price estimate for cobalt is $22.50 (USD/lb.) [BMO Capital Markets, 2017].

| Substituting/Alternate Material | Short-term or Long-term Implementation Viability | Partial or Complete Replacement | Economic Viability |
|---|---|---|---|
| **Superalloys** | | | |
| Tantalum (alloying agent) | Long-term | Complete | Lower |
| Heat-treated Nickel Superalloy | Long-term | Complete | Lower |
| Niobium (alloying agent) | Long-term | Complete | Higher |
| Ceramic Matrix Composites | Long-term | Complete | Lower (but greater manufacturing costs) |
| | | | |
| **Cutting Tools and Hard-facing Metals** | | | |
| Titanium Cermets (Ni, Mb, or Cr- alloyed TiC and TiN) | Long-term | Complete | Lower |
| WC-Fe | Long-term | Complete | Lower |
| WC-Co-Fe-Cu | Short-term | Partial | Lower |
| Heat-treated Fe-Ni-WC | Long-term | Complete | Lower |
| WC-Co-Re, WC-Re | Long-term | Partial, Complete | Higher |
| Ceramics | Long-term | Complete | Lower (but greater manufacturing costs) |
| **Magnets** | | | |
| NdFeB | Short-term | Complete | Lower |
| Ferrites | Short-term | Complete | Lower |
| **Chemical Catalysts** | | | |
| Manganese | Short-term | Complete | Higher |
| Rhodium | Short-term | Complete | Higher |
| Ruthenium | Short-term | Complete | Lower |
| Nickel | Short-term | Complete | Lower |
| Molybdenum | Short-term | Complete | Lower |
| Tungsten | Short-term | Complete | Higher |

*Table 35: Summary table of the most viable discussed alternatives to/substitutes for cobalt in this section. Implementation time, degree of substitution, and costs of candidates included to help visualize and consider the viability of the options.*

As the table demonstrates, the most likely sectors of partial or complete cobalt replacement are in the magnet and catalyst sectors. Since the magnet and catalyst sectors had such large bottom-up demand projections, substitution of cobalt in these sectors would greatly reduce projected cobalt demand. In other words, it can easily be concluded that with viable theoretical and practical substitutions of cobalt in the traditional, inelastic sectors above, demand of cobalt from these sectors will decrease and allow for more cobalt to be available to more elastic sectors on the market, such as the battery industry.

# Conclusion

The popularity, interest, and dialogue around the element cobalt has exponentially grown due to its unique ability to stabilize lithium-ion battery cathode materials. The increased discussion around the metal has illuminated the precarious labor and geopolitical environments surrounding the world's major source of raw cobalt, as well as the high dependency of cobalt supply on copper and nickel demand, due to the by-product nature of cobalt extraction. The increased demand for cobalt and the lack of stability in supply sources has created worries regarding the ability of cobalt supply to meet demand not just in new, elastic sectors dominated by battery demand, but also in traditional, inelastic sectors of cobalt consumption. Four major inelastic sectors of cobalt consumption are: superalloys, cutting tools and hard-facing metals, chemical catalysis, and permanent magnets.

This thesis assessed the future demand for the four aforementioned inelastic sectors for cobalt demand in order to determine if a supply shortage in these critical sectors is to be expected in the short-term (to 2025-2035). Long-term demand projections (to 2050) were also made with the intent of opening the discussion past the short-term supply-demand discussion and into possible long-term shortage concerns to evaluate if and when cobalt supply may hinder technological progress.

Historic data was used to predict future demand through CAGR predictions. Alternative methodology was used to attempt bottom-up demand predictions through predicted product demand and material intensity. Overall, this work concludes that demand shortage in the cumulative inelastic sectors of cobalt demand is not likely in the short-term, since demand projections totaled approximately 85,000 tons of refined cobalt below calculated supply for 2025.

However, if the projected battery sector demand is included in the supply-demand comparison, then there is a shortage of cobalt of between 51,000 – 245,000 tons, depending on battery sector growth assumptions. Long-term demand predictions show large increases in cobalt demand even within the inelastic sectors. Therefore, it is recommended that long-term supply predictions be estimated in order to determine if, and if so, how large, supply shortages may be in the future. Most likely, due to the large increase in demand from 2035 – 2050, a long-term cobalt supply shortage will occur. The bottom-up approaches covered in this work were done with the best information the author was able to gather. Higher quality data following cobalt flows more accurately, more accurate data regarding the material intensity of cobalt in products, more in-depth evaluations of specific industries (rather than high-level, single or double component representatives of an entire industry), more easily available data regarding the number of different products companies sell/produce, and more publicly-available information would all improve bottom-up projections for future cobalt demand.

In the case of perceived supply shortages, substitutes for cobalt and alternative materials to cobalt-containing materials become especially important to research and understand. This thesis provides a preliminary review of common substitutes and alternatives to cobalt/cobalt-containing materials. A chart with the economic and technical feasibility for many partial and complete cobalt replacements was included to help to focus where further research could be the most impactful. A quantitative evaluation of the most viable substitutes/alternatives and their effect on future cobalt demand projections would be especially significant. Recycling and other processes to help keep current cobalt flowing throughout materials systems and the incurring effects on new cobalt demand would also be important for further consideration.

# Resources


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