7 COBALT

7.1 Overview

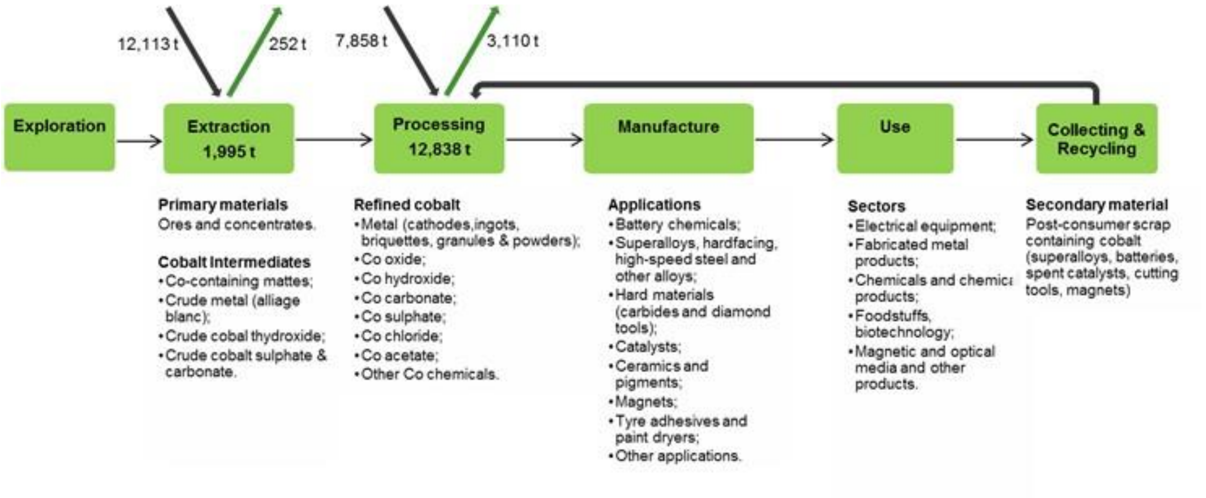


Figure 85: Simplified value chain for cobalt

Cobalt (chemical symbol Co) is a transition metal appearing in the periodic table between iron and nickel. Cobalt is a shiny, silver-grey metal with many diverse applications due to its unique properties. It is a hard metal retaining its strength at high temperatures, has a high melting point, is ferromagnetic keeping its magnetic properties at the highest temperature of any other metal, is multivalent, produces intense blue colours, is able to form alloys with other metals imparting high-temperature strength and increased wear-resistance, is vital as a trace element in living organisms.

For this assessment, both cobalt extraction and processing are analysed. At mine stage, cobalt is assessed in the form of cobalt ores and concentrates, and at the processing stage in the form of refined cobalt. The intermediate cobalt products were considered as part of the cobalt ores and concentrates imports.

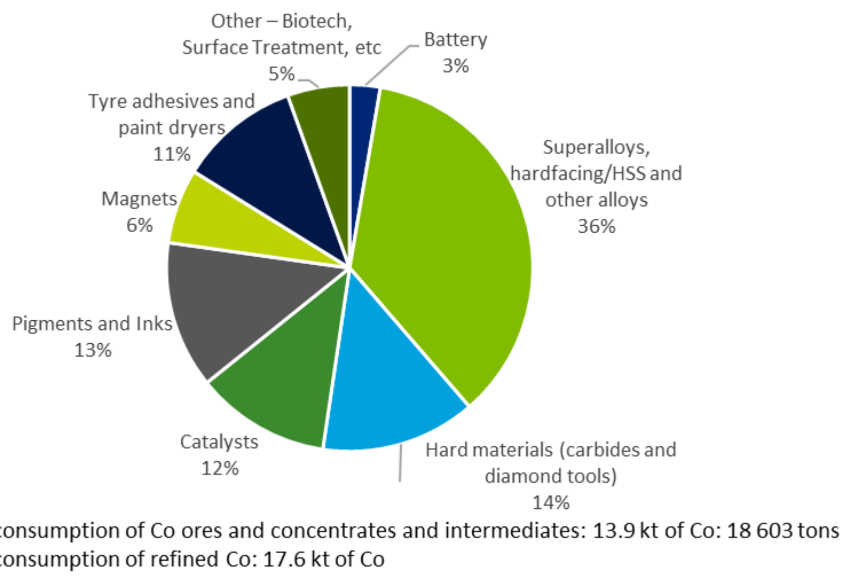


Figure 86: End uses of cobalt in the EU, in Co content, in 2015. (Cobalt Institute 2019e)(Cobalt Institute 2019d)

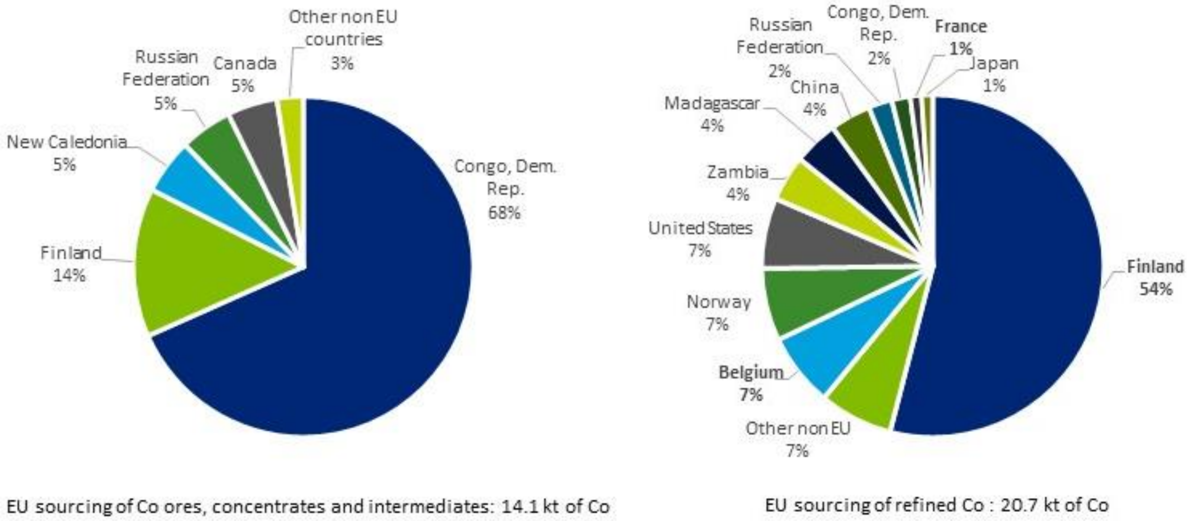


Figure 87: EU sourcing of cobalt ores, concentrates and intermediates (left) and refined cobalt (right), between 2012 and 2016.

The trade codes used in this assessment and the relevant assumptions are the following:

• *For cobalt ores and concentrates*: CN 26050000 "Cobalt ores and concentrates" considering a 10% of Co content;
• *For cobalt intermediates*:
CN 81052000 "Cobalt mattes and other intermediate products of cobalt metallurgy; unwrought cobalt; cobalt powders" assuming 17% of Co content if trade value is below 10 EUR/kg, and 60% if trade value is 10-20 EUR/kg,
CN 75011000 "Nickel mattes" assuming a specific Co content for each producer in the exporting country to the EU based on background information from (Roskill 2014);
• *For refined Co*:
CN 28220000 "Cobalt oxides and hydroxides" assuming 70% of Co content,
CN 28273930 "Cobalt chlorides", considering 25% of Co content,
CN 81052000 "Cobalt mattes and other intermediate products of cobalt metallurgy; unwrought cobalt; cobalt powders" assuming 100% of Co content if trade value is higher than 20 EUR/kg,
CN 28332930 "Sulphates of cobalt and of titanium" assuming that cobalt products represent half of the flows, with a Co content of 20%.

Quantities are expressed in Co content, and all figures are averaged over the five years 2012–2016 data unless otherwise mentioned.

Global mine and refined production of Co has grown considerably over the last two decades at an annual rate of over 7%, underpinned by strong demand for cobalt in rechargeable batteries. Cobalt is mainly produced as a by-product from nickel and copper production. The extraction of cobalt is dependent on the extraction of copper and nickel. In 2018, cobalt production as a by-product of copper mines represented the 56% of the world total. 37% of the global cobalt supply was obtained as a by-product of nickel production. Only 7% was sourced from mining operations in which cobalt is the main commodity. The cobalt produced by these copper/nickel companies is traded internationally in the form of cobalt ores and concentrates, intermediate cobalt products and refined cobalt metal and chemicals. The Democratic Republic of the Congo (DRC) is the world's dominant producer and exporter of cobalt ores and concentrates with a share of 97% of global exports in terms of value in 2017. Likewise, it is also the largest exporter of cobalt intermediates and refined cobalt globally by a significant share (58%) of total exports by value in 2017. Since the time period under review, the predominant exported products from the Democratic Republic of the Congo are intermediates containing cobalt, and only a relatively small amount of cobalt contained in ores and concentrates is exported. China is the world's largest importer of both cobalt ores and concentrates (61% of total imports by value), and cobalt intermediates and refined cobalt (39% of total imports by value). Export taxes are applied by the Democratic Republic of the Congo to various cobalt raw materials.

The expansion of the electric vehicle market globally and in the EU should increase the demand for cobalt exponentially in the next decade, at an annual growth rate ranging from 7% to 13%. A market deficit is projected from 2025 onwards.At the same time supply disruptions are possible due to overconcentration of supply in the Democratic Republic of the Congo for mined cobalt and China for refined cobalt, slow development of new mining capacity, impact of copper and nickel demand, and unethical practices in artisanal mining in the Democratic Republic of the Congo.

Cobalt prices have been considerably volatile in the past, strongly affected by concerns over the supply and demand balance, but also by the prevailing political situation of the principal producer, the Democratic Republic of the Congo. While in March 2016 cobalt price was close to EUR 20,000 per tonne, it rose sharply to EUR 76,700 per tonne (+273%) within two years in March 2018 but returned to previous levels of about EUR 25,800 (-66%) per tonne in June 2019. The recent price rise was a consequence of market excitement regarding a possible cobalt shortfall resulting from the electrification of the automotive sector. However, this anticipation was obviously premature as the market is now (2019) in surplus.

The EU consumption of cobalt ores, concentrates and intermediates is 13,856 tonnes of contained cobalt (2,358 tonnes in ores and concentrates and 11,498 tonnes in Co intermediates and nickel mattes), the majority of which are sourced through imports from the DRC (68% of EU sourcing) and domestic production in Finland (14% of EU sourcing). The import reliance for cobalt ores, concentrates and intermediates is 86%.

The EU consumption of refined cobalt is 17,585 tonnes of cobalt content, which mainly originates from domestic production in Finland (54% of EU sourcing) and Belgium (7% of EU sourcing). The import reliance for refined cobalt is 27%.

Superalloys, which are used to make parts for gas turbine engines, are the major application for cobalt in the EU. They account for 36% of the cobalt consumed in the EU for manufacturing of finished products. Other applications for which cobalt is an essential raw material include carbides and diamond tools (14%), pigments and inks (13%), catalysts (12%), and tyre adhesives and paint dryers (11%). In the global context, the rechargeable battery market represents the largest and fastest-growing demand for cobalt; in 2016, rechargeable batteries consumed half of cobalt worldwide. Superalloys represent the second largest application for cobalt globally with a share of 18% of total global demand.

Substitution possibilities for cobalt are limited in many of its applications because of its remarkable properties. Substitution can be achieved in battery chemicals through other chemistries without cobalt based on nickel and manganese, or through content reduction in configurations with less cobalt loading. Due to loss of performance, functional cobalt substitution is severely restricted for superalloys and hard materials.

Cobalt is a crucial raw material for the implementation of the EU long-term strategy for the climate-neutral economy by 2050 as it is employed in the manufacture of rechargeable batteries for electric vehicles and energy storage systems.

Global resources of cobalt are estimated at approximately 25 million tonnes. The world's most important cobalt resources are located in the copper-cobalt deposits in the area commonly known as the central African Copper belt which spans across the Democratic Republic of the Congo and Zambia. In addition, vast resources of cobalt are identified in manganese nodules and cobalt-rich crusts on the oceans' seafloor. World land-based reserves of cobalt are estimated at 6.9 million tonnes, with the majority situated in the Democratic Republic of Congo (49 %), Australia (17%) and Cuba (7%). Within Europe, resources of cobalt are known to exist in Finland, Sweden, Spain, Greece and Poland. Finland is the sole country with reported cobalt reserves complying with an international reporting system.

World mine production was nearly 134 kt as an average over 2012-2016. The Democratic Republic of Congo dominated global mine supply with 59% of the worldwide total. China (7%) was the second mine producer. In the EU, cobalt is mined as a by-product of nickel and copper mining in Finland. The annual domestic production amounted to almost 2 kt, but this represents approximately 1% of the yearly worldwide total.

World production of refined cobalt averaged to nearly 93 kt over 2012-2016. In contrast to mine output, China is the world's top producer of refined cobalt with almost half of the world total (49%), followed by Finland (12%) and Canada (6%). Domestic production in the EU is around 13 kt, with 87% of the total output produced in Finland. Cobalt is also produced in Belgium (11%) and France (2%). The total EU production of refined cobalt accounts for about 14% of the world total.

End-of-life products such as cobalt-bearing alloys, batteries and spent catalysts can be collected and recycled. The end-of-life recycling input rate in the EU was 19% in 2016 (Draft Co MSA 2019). The future potential for increased recycling of cobalt from EV batteries is particularly high. However, due to the lifespans of electric vehicle batteries, significant amounts of secondary cobalt will only become available for recycling in the near future (from 2025 onwards). The EU already holds sufficient relevant recycling infrastructure to treat the future end-of-life EV batteries.

Regarding socio-economic issues, these are mainly related to the situation in the Democratic Republic of Congo: poor governance, political instability, trade restrictions. Additionally, a varying amount of global cobalt supply originates from arti-sanal and small-scale mining (up to 20% of the global mine supply) raising concerns on human rights abuse.These are considered particular risks for the future security of supply.

Five cobalt salts (cobalt diacetate, cobalt dinitrate, cobalt carbonate, cobalt sulfate and cobalt carbonate) have been identified as substances of very high concern under the Regulation (EC) 2006/1997 and have been placed on the candidate list for authorisation. In December 2018, the European Chemicals Agency proposed restriction measures on the manufacture and use of these salts.

7.2 Market analysis, trade and prices

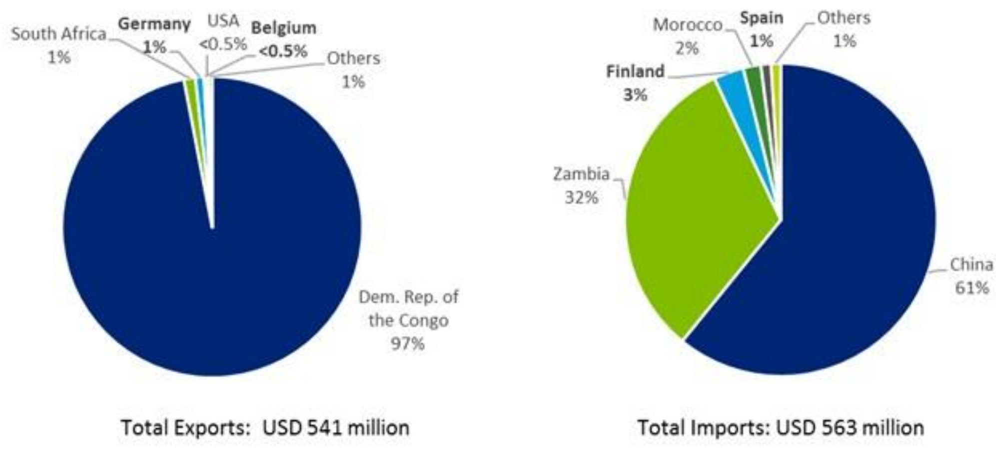
7.2.1 Global market

Cobalt demand is growing steadily in the last two decades, reflecting the increased use in superalloys and catalysts. Recently a huge rise in demand is observedfor rechargeable Li-ion batteries. Initially, used in consumer electronics and ICT applications, and lately for electric vehicles and energy storage applications (Alves Dias *et al.*, 2018) (Roberts and Gunn 2014)(Roskill 2014).

Since 1998, cobalt production is growing rapidly. The world mine production increased from around 32 kt in 1998 to more than 135 kt in 2017 at a compound annual rate of 7.6%.At the same time world production of refined cobalt increased from about 27 kt in 1998 to nearly 120 kt in 2017 at a compound annual rate of 7.8% (background data from (BGS 2019) and (WMD 2019). The increase in global mine production has been supplied mostly by DRC, which increased its share from 16%(1998) to 61%(2017) of the worldwide production. In 2010 it even reached 69%. As concerns the refined output, the increase was driven mainly by China which enlarged its share from 5% in 1998 to more than 58% in 2017 (background data from (BGS 2019a)). The market value of the world production of refined cobalt in 2018 was estimated at EUR 7.7 billion[53].

Cobalt is traded in numerous forms such as cathodes, powders, salts and chemicals and qualities (Al Barazi 2018). This variety reflects the numerous stages of the cobalt production chain and the fact that cobalt is mainly extracted as a by-product in nickel and copper mines which may have no capacity for refining produced cobalt. It is difficult to quantify the international trade in cobalt content, as it’s considerable amounts are contained within nickel and copper ores and concentrates, mattes etc. of variant compositions (Roskill 2014). Moreover, aggregated HS codes of several cobalt commodities make it challenging to track global trade in terms of cobalt content, i.e. HS 810520 ‘Cobalt mattes and other intermediate products of cobalt metallurgy; unwrought cobalt; cobalt powders’.

Prior to refining, cobalt ores and concentrates are typically processed to intermediate products domestically to lower the high costs of shipping bulky ores/concentrates of lower value. Trade of ores and concentrates can take place due to corporate integration of mine operations and intermediate processing plants, or lack of domestic processing facilities (Roskill 2014). In 2017, the DRC was the dominant supplier of cobalt ores and concentrates with about 161 kt of exports in gross weight (HS 260500), accounting for 97% of the value of world exports. However, since 2012, only a relatively small amount of cobalt contained in ores and concentrates is exported. The DRC government is aiming at increasing domestic refining of copper and cobalt products and decreasing exports of ores and concentrates. Therefore, the predominant exported product is hydrometallurgical intermediate containing cobalt such as hydroxide. In addition, refinery producers have increasingly preferred to import partially processed intermediate products, as opposed to unprocessed concentrates (Roskill 2014). In 2017 China was the major destination country for world exports of cobalt ores and concentrates with a 61% share of the value of world imports, followed by Zambia (32%) and Finland (3%) (UN Comtrade 2019). Chinese companies have many life-of-mine contracts with African producers to supply their smelters, and much of the cobalt they refine is used domestically (Hannis and Bide 2009). Figure 88 shows the top world importers and exporters of cobalt ores and concentrates based on trade data for code HS 260500 ‘Cobalt ores and concentrates’.



[53] Estimation based on an average price of cobalt in 2018 of EUR 61,555 per tonne (LME cobalt cash) and the refined cobalt world production in 2018 of 124,344 tonnes (Cobalt Institute, 2019b)

Figure 88: Top-5 cobalt exporting (left) and importing (right) countries in 2017 for cobalt ores and concentrates[54] by value. Background data from (UN Comtrade 2019)

The international market of refined cobalt can be roughly split into metal products (e.g. cathodes, briquettes, ingots, granules, powder), and chemical products (e.g. cobalt chloride, oxide, hydroxide, and salts). For cobalt intermediates and refined cobalt, the DRC is the most significant exporter (58%) in terms of value, followed by China (12%) and Canada (9%). China is again the largest importer of refined cobalt (39%), followed by Zambia (12%), Japan (10%), US (10%) and South Korea (8%).

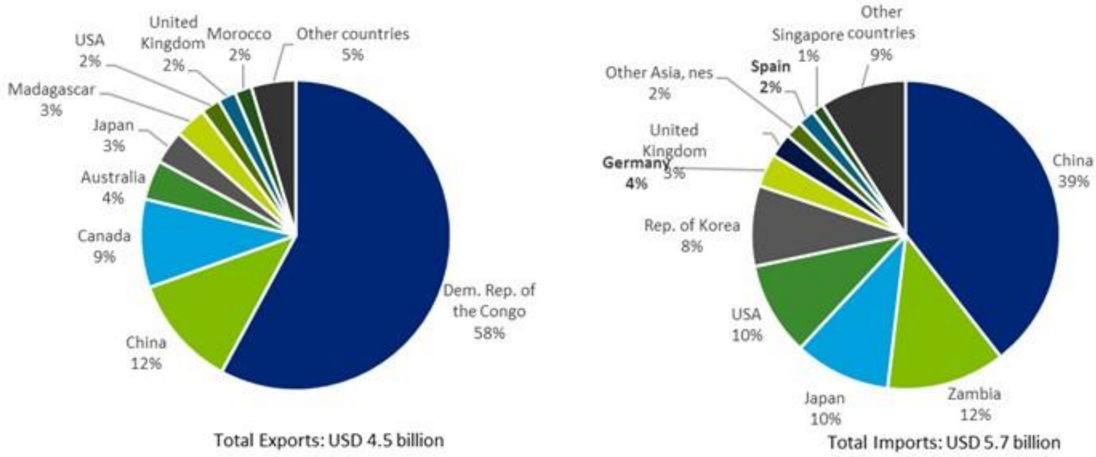


Figure 89 presents the top world importers and exporters of cobalt intermediates and refined Co by aggregating trade data for trade codes HS 282200 'Cobalt oxides and hydroxides', and HS 810520 'Cobalt mattes and other intermediate products of cobalt metallurgy; unwrought cobalt; cobalt powders'.

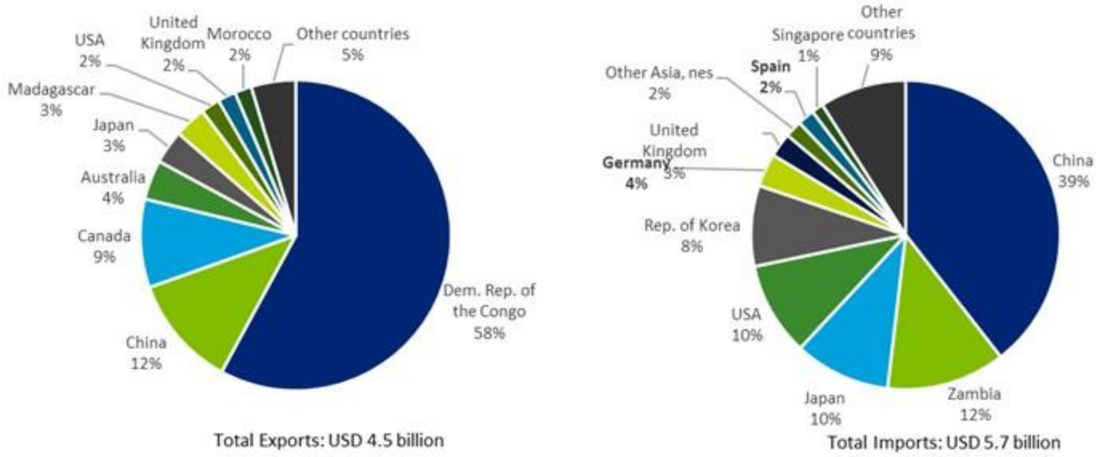


Figure 89: Top-10 cobalt exporting (left) and importing (right) countries in 2017 for cobalt intermediates and refined cobalt[55] by value. Background data from (UN Comtrade 2019)

[54] World trade of nickel or copper ores and concentrates containing cobalt may not be covered. In addition, as the DRC does not report exports of cobalt raw materials, the DRC export figures have been inferred from import statistics.

[55] World trade of nickel or copper intermediates containing cobalt may not be covered. In addition, as the DRC does not report exports of cobalt raw materials, export figures have been inferred from import statistics

Regarding export restrictions, the DRC, the world's top producer of cobalt, in 2017 applied export taxes (0.5% export tax and 1% export surtax) on *ad valorem* basis to cobalt ores and concentrates, cobalt oxides and hydroxides, cobalt mattes and other intermediate products of cobalt metallurgy, unwrought cobalt, and cobalt powders (OECD 2019). Also, in 2017 DRC introduced an export prohibition for copper and cobalt concentrates; however, a moratorium up to the final resolution of the country's energy deficit has been granted, as it is stated in the relevant legal act (R.D. Congo 2017). Among other restriction measures in the trade of cobalt raw materials in place in 2017 as reported by (OECD 2019), China imposes an *ad valorem* export tax to cobalt ores and concentrates and cobalt oxides and hydroxides of 15% and 10% respectively, and Zambia an 10% *ad valorem* export tax to cobalt ores and concentrates.

7.2.2 Outlook for supply and demand

Various studies have estimated the perspective of future cobalt demand. They are based on different scenarios on the global deployment of electric vehicles, the vehicle types comprising the fleet (e.g. plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs)), the associated timing of market penetration, the mix of battery chemistries, and demand for batteries for domestic storage systems, and portable electronic devices

A recent JRC report (Patrícia Alves Dias et al. 2018) analysed the demand and supply of cobalt in the transition to electric mobility. It concluded that cobalt demand might experience a 3.7-fold increase between 2017 and 2030, driven by the expansion of the electric vehicles market and energy storage systems. The usage in Li-ion batteries will boost cobalt consumption, in particular in Nickel-Manganese-Cobalt (NMC) and Nickel-Cobalt-Aluminium (NCA) chemistries, both of which use cobalt as a cathode material (Patrícia Alves Dias et al. 2018).

The latest (May 2019) outlook report published by the International Energy Agency (IEA) verifies the rapid increase of the global electric car fleet (in 2018 exceeded 5.1 million, up 2 million from 2017) (Bunsen et al. 2019). According to IEA's estimates, the annual cobalt demand for the batteries of EVs sold in 2018 was about 17 kt. In a scenario based on the announced policy ambitions[56] and assuming a mix of battery chemistries of 10% NCA, 40% NMC 622 and 50% NMC 811 for 2030, the study forecasts that the annual demand for cobalt for battery manufacturing will increase to around 170 kt in 2030, whereas in a scenario with higher EV uptake[57] the annual demand for cobalt in 2030 for EVs batteries will be more than twice as high, i.e. exceeding 350 kt per year.

On the supply side, the market is currently experiencing a surplus due to several expansions in mining capacity that have occurred in the last few years, mainly in the DRC. The JRC report projects that the global mining capacity of approximately 160 kt tonnes of cobalt in 2017, will reach between 193 and 237 kt tonnes in 2030 (Patrícia Alves Dias et al. 2018). However, while new mining projects, substitution and recycling can improve the stability of cobalt supply until 2030, worldwide demand is expected to consistently exceed supply from 2025 onwards (see Figure 90). The JRC report highlights various barriers and risks in relation to the structure of the cobalt supply which is highly prone to disruptions, e.g. overconcentration of supply in DRC for mined cobalt and China for refined cobalt, slow speed of developing new mining capacity from exploration to production, dependence on copper and nickel demand as cobalt is a by-product, and sourcing concerns due to unethical practices in artisanal mining in the DRC.

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[56] Global EV sales reach 23 million and the stock exceeds 130 million vehicles in 2030.

[57] Scenario under the assumption that EVs will reach a 30% market share for all modes except two-wheelers by 2030. EV sales and stock nearly double by 2030 reaching 43 million and more than 250 million respectively.

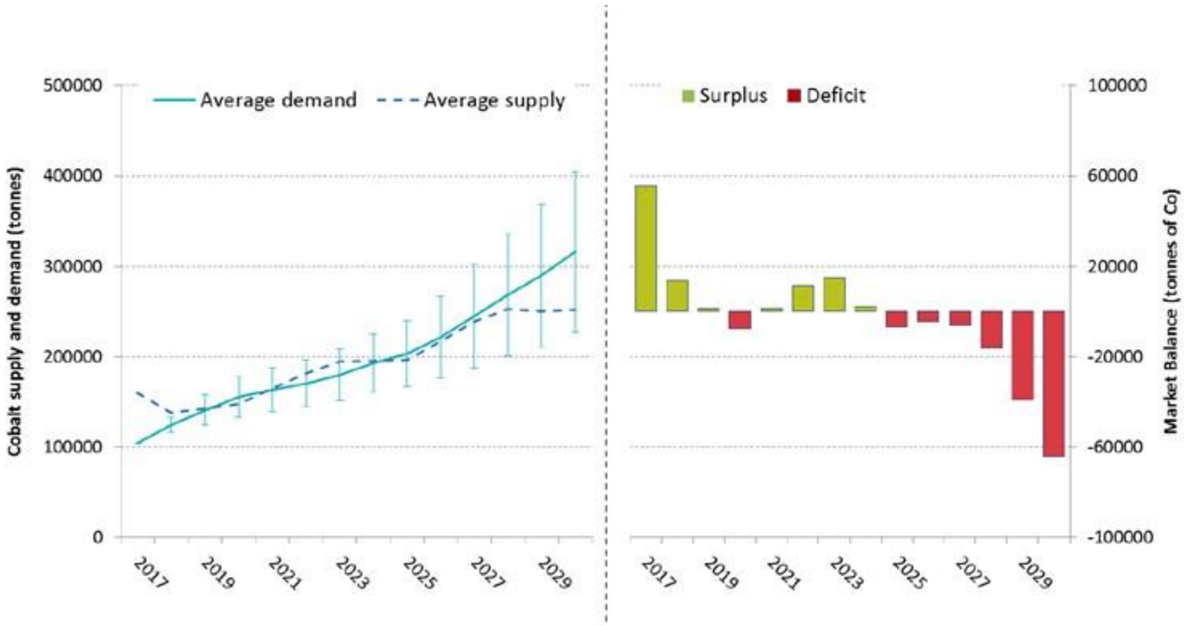

Figure 90: Average global supply-demand balances between 2017 and 2030 (Patrícia Alves Dias et al. 2018)

According to (Ait Abderrahim and Monnet 2018), the EU cobalt demand for jet engines and batteries for EVs, for domestic use, smartphones and laptops will increase from 2 kt in 2015 to about 32 kt in 2035. 32 kt is higher by 2.5 times in comparison to the total EU cobalt consumption in 2012 for all applications. Electric vehicles and domestic energy storage will drive the growth of cobalt demand in the EU with expected use of 25.5 kt and 4 kt respectively by 2035.

The market forecast for world cobalt supply and demand is presented in Table 37.

Table 37: Qualitative forecast of supply and demand of cobalt

Material	Criticality of the material in 2020		Demand forecast			Supply forecast		
	Yes	No	5 years	10 years	20 years	5 years	10 years	20 years
Cobalt	x		+	+	+	+	+	?

7.2.3 EU trade

The average annual EU import in 2012-2016 was 12,113 tonnes of cobalt contained in ores and concentrates and cobalt intermediates. Imports of ores, concentrates and intermediates come mostly from the DRC (80%). Other countries of origin for EU imports are New Caledonia (6%), Russia (6%) and Canada (5%). On the other hand, EU imports of refined cobalt are less concentrated and have a wider distribution of sourcing countries (see Figure 93). In particular, the EU imported about 7,858 tonnes of refined cobalt, with Norway and the US the leading exporters (each 18%). Zambia (11%), Madagascar (11%) and China (10%) are included in the top EU suppliers for refined cobalt.

Figure 91 and Figure 92 illustrate the import and export flows of these materials to and from the EU collectively and demonstrate that the EU is a net importer of cobalt-bearing materials. The EU reliance on imports of cobalt ores, concentrates and intermediates is estimated at 86%, while the import reliance for refined cobalt amounts to 27%. Figure 93 shows the origin countries for the EU imports of cobalt.

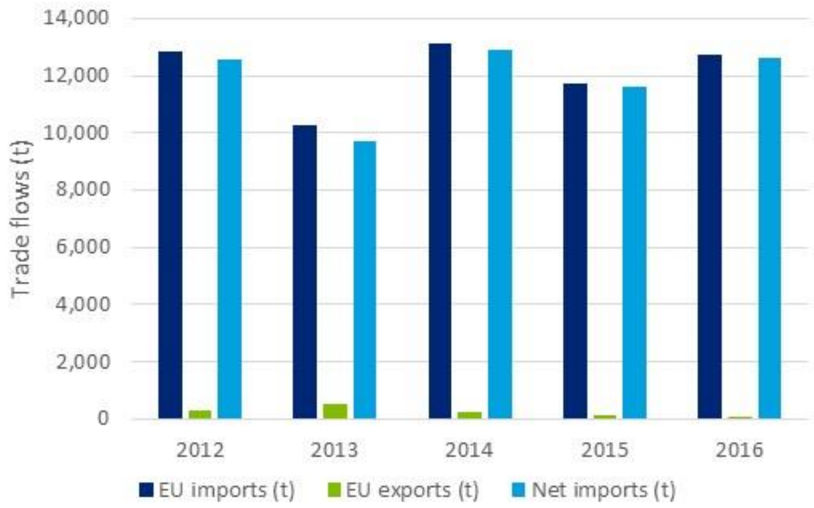

Figure 91: EU trade flows for cobalt ores, concentrates and intermediates (ESTAT Comext 2019)

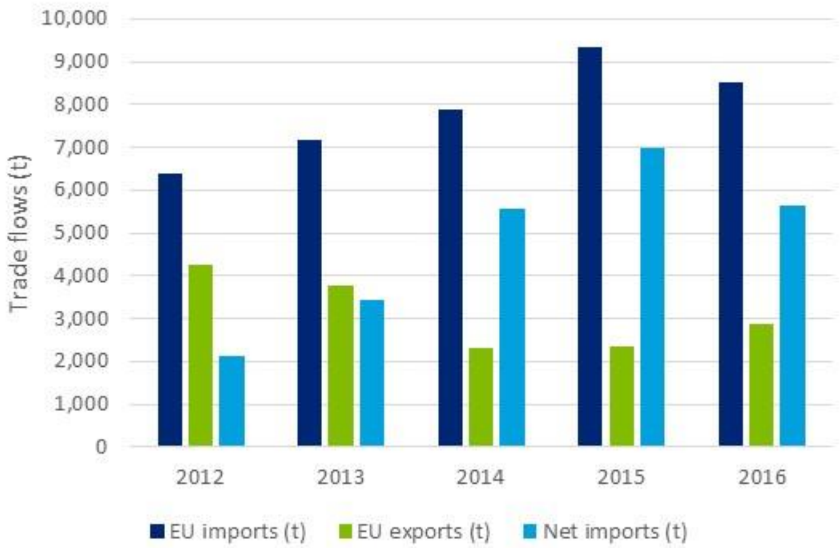

Figure 92: EU trade flows for refined cobalt (ESTAT Comext 2019)

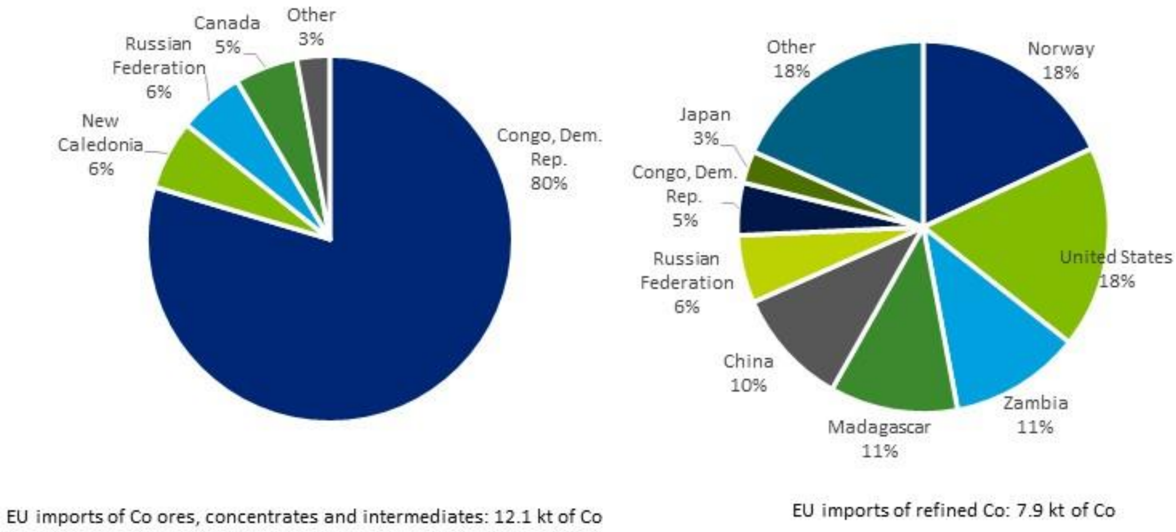

Figure 93: Countries of origin for EU imports of cobalt ores, concentrates and intermediates (left) and refined cobalt (right). Average 2012-2016. Background data from (ESTAT Comext 2019) (ULJAS 2019)

As regards export restrictions applied by the leading EU suppliers, the DRC applies an export tax and export duty to cobalt ores and concentrates, as well as to refined cobalt products as it is described in Section 7.2.1 (OECD 2019).

Regarding trade agreements there is a EU-Canada Comprehensive Economic and Trade Agreement.

7.2.4 Prices and price volatility

Cobalt is mainly traded in the forms of cathode (cut and broken), metal powder, salts and chemicals. The price of many cobalt compounds is negotiated individually between producers, distributors and end users, depending on the product quality and the specifications required (Al Barazi 2018). Benchmark prices are assessed by price reporting agencies. Cobalt is also exchange-traded e.g. at the London Metal Exchange (LME).

For many years, cobalt prices were only available from the Metal Bulletin free-market quotation, and this is still commonly used as a benchmark by the industry (European Commission 2017)(Fastmarkets 2019b). Cobalt spot prices reported by price reporting agencies refer to a variety of products and specifications. For example, prices provided by Fastmarkets MB include the free-market cobalt standard-grade (min 99.8% Co), cobalt sulphate (min 20.5% Co, China ex-works), the cobalt hydroxide index (min 30% Co, CIF China), cobalt tetroxide (min 72.6% Co, China delivered) etc. (Fastmarkets 2019a).

The LME began trading cobalt in 2010 in cash and futures contracts (Roberts and Gunn 2014). Until that time, cobalt was traded only on the free market (Hannis and Bide 2009)(Al Barazi 2018). The LME cobalt contract, which is physically settled, includes coarse-grained metal powder, briquettes, broken or cut cathodes, ingots, and rounds (LME 2019b). Cobalt traded on the LME in 2015 represented only 20% of global refined cobalt metal production and 9.5% of refined world production of cobalt metal and chemicals. This reveals that the LME cobalt contract is still in the early stage of acceptance as a primary pricing mechanism (USGS 2017). In January 2018, the minimum purity required for cobalt metal delivery under the LME cobalt contract changed from 99.3% (low-grade) to 99.8%, or high-grade (Kusigerski 2018). In March 2019, the London Metal Exchange's introduced a new cash-settled cobalt contract, which is settled against Fastmarkets' MB benchmark standard-grade cobalt price (LME 2019b).

For historical perspective, cobalt prices became considerably volatile since the late 1970s (Al Barazi 2018). Various events which influenced cobalt prices may be noted in Figure 94, ranging from de-stocking, geopolitical unrest, recession and concerns over future supply (Patrícia Alves Dias et al. 2018). Since 2000, cobalt demand has risen gradually, driven from strong demand for rechargeable batteries used in portable electronic equipment (Patrícia Alves Dias et al. 2018). A significant price increase was seen over the 2002-2004 and 2006-2008 periods. This was due to a supply decrease, uncertainty over sufficient future supply andlinked to a high level of global economic growth supported by strong Chinese demand (Al Barazi 2018). In 2002, the price of high-grade cobalt averaged just under USD 15,400 per tonne but increased to an average of over USD 86,000 per tonne by 2008 (see Figure 94). The rise in cobalt metal prices interrupted by the global economic crisis, causing prices to decreased dramatically between 2008 and 2009 as supply exceeded demand (Roskill 2014).

In 2017, a sharp increase of cobalt prices took place due to market expectations driven by an increase of demand for battery raw materials for EVs (DERA 2017)(DERA 2018).The price of cobalt in March 2016 was close to EUR 20,000 per tonne, and incresad almost four times within two years to around EUR 76,700 per tonne in March 2018. (S&P Global Market Intelligence 2019b). Since then, cobalt prices dropped to around EUR 25,800 per tonne in June 2019 (S&P Global Market Intelligence 2019b). This was due to an oversupply of cobalt hydroxide from the DRC, limited stockpiling and consumer preference to cobalt hydroxide and cobalt salts rather than metal. (Fastmarkets 2019d) (Fastmarkets 2019c)(Roskill 2019a)(Reuters 2019);

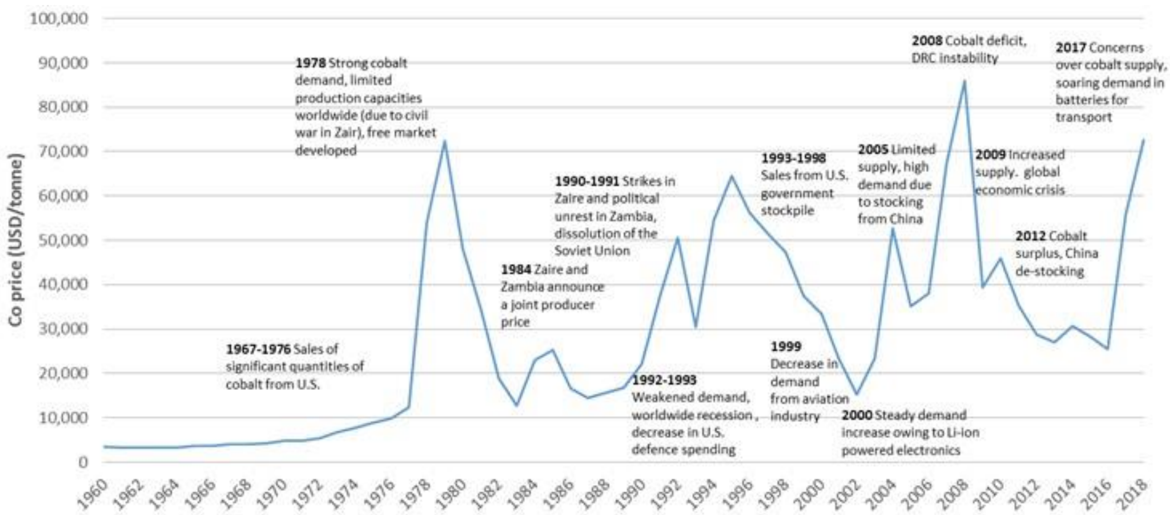

Figure 94. Annual average prices[58] of cobalt from 1960 to 2018 and significant events affecting cobalt prices. Background data from (USGS 2013) (USGS 2017a) (USGS 2018b) (DERA 2017a) (DERA 2018c) (Patrícia Alves Dias et al. 2018) (Roskill 2014) (European Commission 2014b)(Roberts and Gunn 2014)

[58] Nominal prices not adjusted for inflation

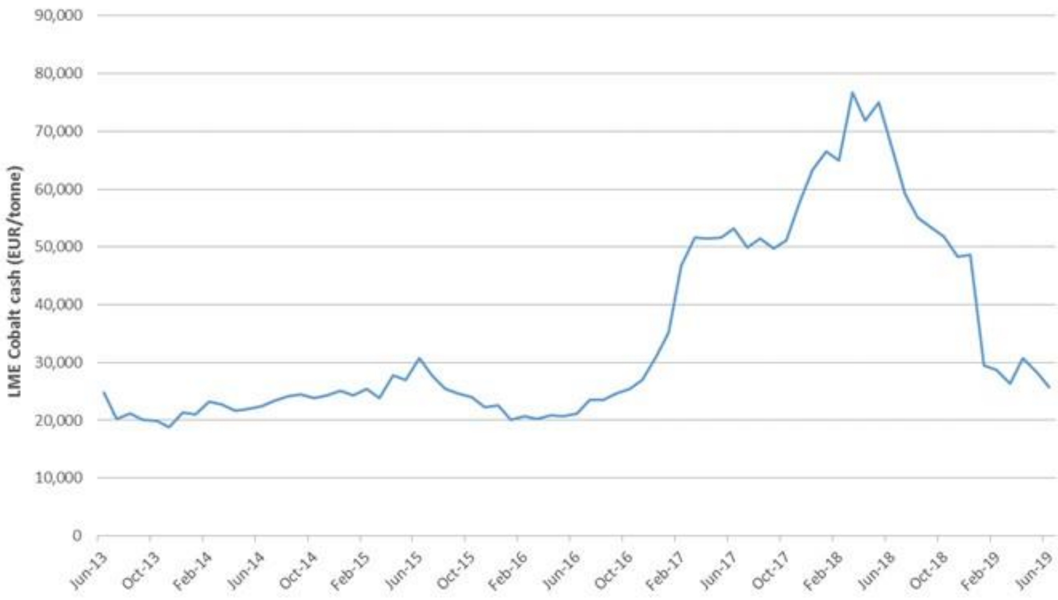

Figure 95. LME-cobalt cash from June 2013 to June 2019, monthly average (EUR/tonne). Data from (S&P Global Market Intelligence 2019b)

Cobalt prices generally follow similar trends to those of nickel, except the period 2017-mid 2018 when cobalt prices surged. The constrains to the mineral supply of copper and nickel affect global cobalt output, such as the cobalt production decrease in 2016, mainly owing to lower production from nickel operations (Patrícia Alves Dias et al. 2018). Raise in cobalt prices, such as the one observed in 2017, can be expected when increasing cobalt demand is not associated with a growing demand for copper and nickel. (Al Barazi et al. 2018).

7.3 EU demand

7.3.1 EU consumption

For cobalt ores, concentrates and intermediates the EU consumption is 13,856 tonnes per year in cobalt content, on average over the 2012–2016 period. Of this only 1,743 tonnes per year (averaged over 2012–2016) came from the EU (calculated as EU production – exports to non-EU countries). The remaining 12,113 tonnes were imported. The EU consumption consists of 2,358 tonnes of cobalt contained in ores and concentrates and 11,498 tonnes of cobalt contained in cobalt intermediates and nickel mattes. The net import reliance as a percentage of apparent consumption is 86% for cobalt ores, concentrates and intermediates.

The apparent consumption of refined cobalt in the EU amounts to 17,585 tonnes of cobalt content per year on average during 2012–2016. The amount of EU consumption covered by domestic production was 9,728 tonnes per year (again averaged over 2012–2016 and calculated as EU production – exports to non-EU countries). The remaining 7,857 tonnes were imported, resulting in net import reliance of 27% for refined cobalt.

7.3.2 Uses and end-uses of cobalt in the EU

On a global scale cobalt is primarilyused in manufacturing of battery chemicals (Ni-Cd, Ni-metal hydride and Li-ion rechargeable batteries used in portable electronic devices, energy storage systems and electric vehicles). In 2016 this was half of the worldwide consumption of cobalt. Other significant uses include superalloys mainly used in turbine engine components (18% of world consumption), and hard materials used in carbides for cutting tools (8%). Pigments used in colouring glass and ceramics and in paints (6%), catalysts for petroleum refining and plastics manufacturing (5%), magnets used in electric motors and loudspeakers (3%), tyre adhesives and paint dryers (3%), and a number of other minor end uses including foodstuffs, biotechnology, medicine, electroplating, electronics etc. make up the remaining one quarter of global consumption.

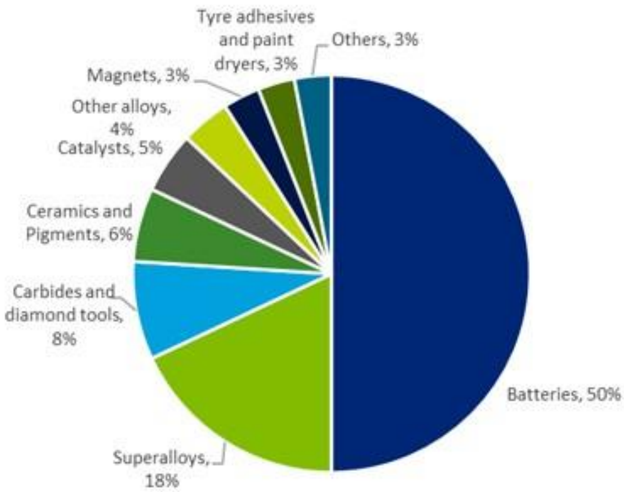

Figure 96: Global end uses of cobalt in 2016. (Darton Commodities in (BRGM 2017))

In the EU, the manufacturing of superalloys consumes 36% of the total demand for cobalt. Other applications for which cobalt is an essential raw material for the EU downstream industry are hard metals (cemented carbides and diamond tools) for metal tooling (14% of total demand), inks and pigments (13%), catalysts (12%), tyre adhesives and paint dryers (11%), magnet alloys (6%), battery chemicals (3%), and other uses (5%)(Cobalt Institute, 2019e)(Cobalt Institute, 2019d).

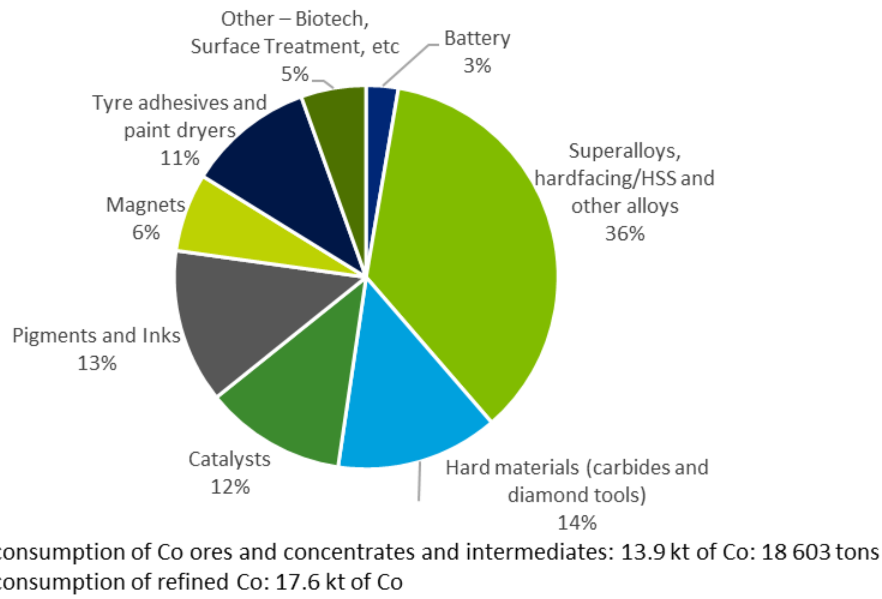

Figure 97: EU end uses of cobalt[59] in 2016 (Cobalt Institute 2019e)(Cobalt Institute 2019d).

The diverse uses of cobalt can be divided into two broad categories: metallurgical and chemical.

7.3.2.1 Metallurgical applications

Cobalt metal is required for the production of superalloys, hardfacing alloys and high-speed steels, magnet alloys, hard materials and special alloys.

Superalloys are alloys that have been developed specifically for high-temperature service, where a combination of high strength and resistance to surface degradation is required. Superalloys are employed in several critical applications such as jet engines, gas turbines, space vehicles, rockets, nuclear reactors, and power plants. Cobalt is used as the matrix or as an alloying element in superalloys because of the high melting point and superior corrosion resistance at high temperatures. Three alloy types can be distinguished under the definition of "superalloys": cobalt, nickel, or iron-based alloys. Cobalt is mainly present in cobalt-based and nickel-based alloys, which account for 6% and 80% respectively of the superalloy production. Cobalt-based wrought alloys contain around 30% of cobalt, and cobalt-based casting alloys may contain up to 65% cobalt. Cobalt-based superalloys provide higher melting points than nickel (or iron) alloys, superior hot corrosion resistance to gas turbine atmospheres, and excellent thermal fatigue resistance and weldability over nickel superalloys. However, as the rupture strength of cobalt-based superalloys is lower at the interval of 815 °C to 1,100 °C temperatures than nickel-based alloys, they tend to be used for static (i.e. not rotating) applications. A high proportion of nickel-based superalloys, which have the majority share of the market, contain cobalt up to 20% by weight. Cobalt is not normally present in iron-based superalloys (Roskill 2014) (Cobalt Institute 2019c).
The term 'hardfacing' refers to hard alloys' deposition by a welding process on a base of softer metal to protect it from wear. Cobalt-based hardfacing alloys are selected for their excellent resistance to the broadest combination of wear types. Hardfacing alloys mainly contain cobalt, chromium, molybdenum and nickel in various compositions. The most frequently used hardfacing cobalt alloys typically contain 40% to 60% cobalt (i.e. Stellite alloys) (Roskill 2014).

[59] Cobalt demand for products manufactured in the EU

Cobalt is also an alloying element of high-speed steels (HSS) for the manufacture of cutting tools when high strength at elevated temperature is required. Cobalt is used in both traditional tool grades as well as in powder metallurgy grades at typical compositions ranging from 8% to 13% Cobalt (Roskill 2014).

The category 'hard materials' includes cemented carbide materials and diamond tools. Cobalt powder is employed as the binding material in the manufacture of cemented carbides to increase resistance to wear, hardness and toughness, essential qualities for cutting tools and wear-resistant components used by the metalworking, mining, oil drilling, and construction industries. The carbide is mainly produced from tungsten (Cobalt Institute 2019c). Similar to cemented carbides, cobalt is also used together with synthetic diamond in the manufacture of diamond tools such as grinding wheels and diamond saws, as the matrix that binds the wear-resistant particles together (Roskill 2014).

Since cobalt is ferromagnetic, it is used as an alloying metal in magnetic alloys for permanent magnets used in electrical equipment. Cobalt has the highest known Curie point of 1,121°C than any other metal, i.e. the temperature at which magnetic properties are lost. Cobalt is used either in the high-strength samarium-cobalt permanent magnets for electric motors or the lower-powered aluminium-nickel-cobalt magnets. Magnets containing cobalt are used in electric motors, generators, magnetic resonance imaging (MRI), microphones, loudspeakers, sensors, computer hard disk drives and many other applications (Hannis and Bide 2009) (Cobalt Institute 2019c). Furthermore, Co-bearing coatings may be applied to neodymium-iron-boron magnets for improved thermal stability and corrosion resistance (Cobalt Institute 2019c).

Other uses of cobalt in alloys include special alloys used for prosthetic limbs in orthopaedics due to excellent biocompatibility, wear-resistance and strength. Co-Cr and Co-Cr-Mo implants are mainly used, mostly in knee and hip operations and fracture repair (Cobalt Institute 2019c) (Roskill 2014).

7.3.2.2 Chemical applications

In chemical applications, cobalt is used in the manufacture of various chemical compounds for a wide range of end-uses.

Cobalt is utilised mostly in rechargeable batteries. Cobalt substances used as chemical precursors for cathode materials are cobalt sulphate, dichloride and dinitrate (Cobalt Institute 2019d). Cobalt compounds for manufacturing active cathode materials are cobalt oxide, cobalt hydroxide, cobalt sulphate and cobalt metal of high purity. Cobalt is an essential constituent of lithium-ion batteries which compared to other battery types offer superior energy and power density as well as cycling ability. The lithium cobalt oxide (LCO) type, which has a cathode composed of $LiCoO_2$ containing 60% of Co which accounts for 50% of the weight of the cathode, is used in portable electronic devices such as cell phones, tablets and laptops. Lithium-nickel-manganese-cobalt oxide (NMC) type, which has a cathode that contains 10-20 % cobalt, is used in electric vehicles and energy storage units (e.g. in renewable energy farms). Lithium-nickel-cobalt-aluminium oxide (NCA) batteries are used in EV applications as well as in industry and medical devices (Cobalt Institute 2019c). In recent years, Li-ion chemistries have shifted towards lower cobalt compositions (Mathieux et al. 2017) due to the high cobalt price. However, some cobalt is still necessary to maintain high performance, stability and safety (Cobalt Institute 2019d). Cobalt is also used in both anode and cathode of Ni-metal hydride batteries (NiMH batteries contain on average 4% of Cobalt) with applications in power tools and in hybrid electric vehicles, as well as in the cathode of Ni-Cd batteries (electrode contains on average 1 % of Co) (Cobalt Institute 2019c). The significant increase in the numbers of portable electronic devices, most of which contain lithium-ion batteries, has driven considerable growth in demand for cobalt in recent years. In 2005, battery chemicals represented just 25% of global end uses of cobalt (Mathieux et al. 2017), while in 2016 battery chemicals for rechargeable accounted for 50% of total cobalt consumption. In 2020, a projected share of 60% is expected (Patrícia Alves Dias et al. 2018).

As cobalt is multivalent, it enhances the catalytic action; therefore, cobalt salts are used as precursors for industrial catalysts in the petrochemical and plastic industries. In particular, cobalt oxides are used in desulphurisation reactions in oil refining, in combination with molybdenum trioxide and aluminium oxide, which represents the highest tonnage of cobalt used in catalyst applications. Moreover, cobalt acetate is mixed with manganese bromide to be used as a catalyst in the synthesis of organic compounds, i.e. terepthalic acid (TPA) and di-methylterephthalate (DMT), which are precursors for the manufacture of PET. Cobalt is also used in hydroformylation reactions for the synthesis of alcohols for detergents, and aldehydes for the manufacture of plastics. Catalysts containing cobalt are also used in the production of synthetic diesel from natural gas. Cobalt compounds used in catalysts are cobalt metal, cobalt oxide, cobalt acetate, cobalt sulphate, cobalt chloride, cobalt hydroxide, cobalt carboxylates (Cobalt Institute 2019c)(Roberts and Gunn 2014).

One of the earliest known uses for cobalt is in pigments to produce an intense blue colour in glass, porcelain, ceramics, paints, inks and enamels. A variety of cobalt compounds, including cobalt oxides and other complex forms, can be used as colourants for a variety of blue-based tints. Cobalt can also be used as a decolouriser to suppress yellowish tint glass that originates from iron contamination. (Cobalt Institute 2019c)

Cobalt carboxylates are used in the production of adhesives that promote the bonding of the rubber to the steel bracing in steel-belted radial tyres (Roskill 2014). Cobalt carboxylates are also the principal cobalt compound used by the paint and ink industry to accelerate drying in inks, varnishes and oil-based paints (Cobalt Institute 2019c). The typical concentration of cobalt in ambient cure alkyd paint is around 0.06% (Roskill 2014).

Cobalt is a bio-essential trace element for bacteria, plants, animals and humans. It forms part of vitamin B12, which is of vital importance in the physiology of the human body, e.g. in red blood cell formation and neurological health. Humans have to obtain vitamin B12 from animal-derived foods. Only ruminant animals are able to synthesise vitamin B12 from elemental cobalt. As well as being essential for humans in the form of vitamin B12, cobalt is important for nitrogen fixation by free-living bacteria, blue-green algae and symbiotic systems. Cobalt underpins the biotechnology industry as it as an indispensable trace element for growth medium in fermentation processes which produce important biomolecules (e.g. therapeutic peptides, antigens, antibodies, single-cell proteins, vitamins, enzymes and antibiotics) utilised in many medical and pharmaceutical applications such as active pharmaceutical ingredients, diagnostic tools for analysis, production of antigens and antibodies etc. Finally, cobalt is also used in animal feeds as it is an essential nutrient for animals. Cobalt is added in trace quantities (typically between 1 and 5 ppm), mainly in the form of cobalt carbonate and cobalt sulphate, as a dietary supplement to animal feeds for ruminants (Cobalt Institute 2019c)(Roskill 2014).

A smaller market for cobalt chemicals, principally cobalt sulphate and dichloride, is electro and electroless-plating of cobalt and cobalt-alloy coatings to provide wear and corrosion resistance to the substrate (Roskill 2014). Other smaller applications include integrated circuits (contacts, metals leads and packages), semiconductors, magnetic recording media, and medical uses of cobalt isotopes (^{60}Co, ^{58}Co, ^{57}Co, ^{55}Co) such as radiotherapy treatments, equipment sterilisation, brain imaging etc. (Cobalt Institute 2019c) (Roskill 2014).

Relevant industry sectors are described using the NACE sector codes in Table 38.

Table 38: Cobalt applications, 2-digit and examples of associated 4-digit NACE sectors, and value-added per sector, Value-added average 2012-2016 (Eurostat 2019a)

Applications	2-digit NACE sector	Value-added of NACE2 sector (M€)	Examples of 4-digit NACE sector(s)
Battery chemicals	C27 – Manufacture of electrical equipment	80,745	C2720 – Manufacture of batteries and accumulators
Superalloys, hardfacing, HSS, other alloys	C25 – Manufacture of fabricated metal products	148,351	C2511 – Manufacture of metal structures and parts of structures; C2550 Forging, pressing, stamping and roll-forming of metal, powder metallurgy; C2561 – Treatment and coating of metals; C2573 – Manufacture of tools; also possibly C3030 – Manufacture of air and spacecraft and related machinery
Hard materials (carbides, diamond tools)	C25 – Manufacture of fabricated metal products	148,351	C2573 – Manufacture of tools
Catalysts	C20 – Manufacture of chemicals and chemical products	105,514	C2013 – Manufacture of other inorganic basic chemicals; C2059 – Manufacture of other chemical products n.e.c.
Pigments and inks	C20 – Manufacture of chemicals and chemical products	105,514	C2012 – Manufacture of dyes and pigments
Magnets	C27 – Manufacture of electrical equipment	80,745	C2711 – Manufacture of electric motors, generators and transformers; C2790 – Manufacture of other electrical equipment; also possibly C2620 – Manufacture of computers and peripheral equipment; C2680 – Manufacture of magnetic and optical media
Tyre adhesives and paint dryers	C20 – Manufacture of chemicals and chemical products	105,514	C2030 – Manufacture of paints, varnishes and similar coatings, printing ink and mastics; C2052 – Manufacture of glues

7.3.3 Substitution

Substitutes for cobalt are continuously being researched mainly due to high price volatility, geopolitics of supply, cost and environmental benefits (Roberts and Gunn 2014). While in the majority of applications, the substitution of cobalt would result in lower product performance, there are a few examples where cobalt can be replaced in the production process. Nickel is the main substitute for cobalt in most applications (Patrícia Alves Dias et al. 2018). Substitution in the criticality assessment has been considered as follows:

<u>Batteries</u>: Substitution of cobalt in Li-ion cells is possible by nickel and manganese with adequate to good performance (Patrícia Alves Dias et al. 2018)(Tercero et al. 2018a), but with a potential compromise on thermal stability and safety (Cobalt Institute 2019d). In the criticality assessment, substitution in Li-ion batteries has been assessed through other chemistries, as well as through Co content reduction. There is a wide range of different

battery technologies available which could be considered as potential substitutes for the battery chemistries that contain cobalt. For example, the chemistries of $LiFePO_4$ (LFP) and $LiMn_2O4$ (LMO) without cobalt can be used instead of $LiCoO_2$ (LCO), $LiNiMnCoO_2$ (NMC) and $LiNiCoAlO_2$ (NCA) in Li-ion batteries. Also, amongst cobalt-bearing cathodes, several configurations with different cobalt contents are available (Patrícia Alves Dias et al. 2018).

The following battery chemistries have been examined in detail in the assessment: Lithium-nickel-manganese-cobalt-oxide (NMC) with reduction of Co content, Lithium-manganese-oxide (LMO), Lithium-iron-phosphate (LFP), Lithium-nickel-cobalt-aluminium-oxide (NCA) with a decrease of Co content, and NiCd/NiMH. In LMO and NiCd/NiMH potential substitutes, the performance is considered to be lower than for the battery chemistries that contain cobalt, whereas for NMC, LFP and NCA the performance is deemed to be similar. For all potential substitutes, the cost is assessed equal or lower relative to cobalt-based chemistries (Battery Universtity 2018).

The cobalt contents of Li-ion batteries are expected to be reduced rather than eliminated in the future (USGS 2019) (Roskill 2019b). According to the latest report prepared by the Joint Research Centre, cobalt use in EV batteries can be reduced by 17% until 2025 and between 2025 and 2030 by another 12%, driven by substitution efforts towards more widespread use of NMC 622 and NMC 811 cathodes. Also, alternative, cobalt-free technologies are foreseen in the future (Patrícia Alves Dias et al. 2018).

<u>Superalloys, Hardfacing, HSS and other alloys</u>: Potential substitutes include composites (e.g. fibre-reinforced metal matrix composites, carbon-carbon and ceramic-ceramic composites), titanium-aluminides, nickel-based alloys, and iron-based superalloys. In some cases cobalt can be also substituted by niobium, rhenium, and PGMst in superalloys. All the above alternatives may replace to some extent cobalt-containing alloys used in applications such as jet aircraft engines, turbine blades for gas turbines, space vehicles or chemical equipment but with reduced overall performance e.g. loss of performance at high temperatures in some cases (Tercero et al. 2018)(Cobalt Institute 2018) (Harald Ulrik Sverdrup, Ragnarsdottir, and Koca 2017). Substitution of cobalt in turbine engine components by nickel has been evaluated from poor (Tercero et al. 2018) to adequate (Patrícia Alves Dias et al. 2018).

<u>Hard materials</u>: Materials such as nickel, nickel-aluminium, iron and iron-copper are potential substitutes for cobalt used as a metallic binder in cemented carbides for cutting tools, metal rollers and engine components. All of these possible substitutes result in a loss of product performance in the essential properties such as resistance to wear, hardness and toughness (Tercero et al. 2018).

Substitutes for other application categories were not considered in detail during the criticality assessment because their application shares were less than 10% of the total cobalt used. However, potential substitutes in other applications include:

<u>Magnets</u>: There is potential for substitution of cobalt-alloyed magnets by nickel-iron alloys, or, primarily, by neodymium-iron-boron alloys (Patrícia Alves Dias et al. 2018). Nd-Fe-B magnets have the highest energy density compared to other permanent magnets, making it the material of choice in high-performance applications where the size and weight are key requirements (Pavel et al. 2016). However, weaknesses are still present in high-temperature applications, which have been addressed by coating techniques with the addition of cobalt (Cobalt Institute 2019c). Other potential substitutes include barium or strontium ferrites (Patrícia Alves Dias et al. 2018) (USGS 2019).

<u>Pigments</u>: Substitution of cobalt in pigments is straightforward and alternatives with very good performance are available. Cerium, acetate, iron, lead, manganese, or vanadium can all be used as substitutes (Patrícia Alves Dias et al. 2018) (USGS 2019) (Harald Ulrik Sverdrup, Ragnarsdottir, and Koca 2017). However, in the automobile industry, issues of performance are reported in the use of cobalt-based pigments. Cobalt complex dyes have a high light-fastness which cannot be achieved by using alternative dyes resulting in colour fading. (European Commission 2017)

Catalysts: Cobalt may be substituted to some extent without significant performance loss. Ruthenium, molybdenum, nickel and tungsten can be used instead of cobalt, for instance in hydro-desulphurisation. An alternative ultrasonic process can also dispense with the use of cobalt, and rhodium can serve as a substitute for hydro-formylation catalysts (Patrícia Alves Dias et al. 2018). For chemical catalysts, platinum and palladium are also reported as potential substitutes for some of the used cobalt (Harald Ulrik Sverdrup, Ragnarsdottir, and Koca 2017). Ruthenium and iron are available substitutes for biodiesel production (Fischer–Tropsch process). Although cobalt catalysts provide the highest yield and longest life-time and they are preferred when the feedstock material is natural gas (R. L. Moss et al. 2011).

Other Uses: Copper-iron-manganese for curing unsaturated polyester resins and titanium-based alloys may be used as substitutes in prosthetics. (USGS 2019) Oxidised Zirconium is also considered a substitute for prosthetic hip implants. (Roskill 2014) There is no substitute for cobalt in biotechnology industry (European Commission 2017).

A study carried out by (Graedel et al. 2015) assessed cobalt's substitutes performance as 54 on a scale from 0 to 100[60].

7.4 Supply

7.4.1 EU supply chain

Despite domestic production of cobalt ores and refined cobalt, the EU remains dependent on imports, with an import reliance of 86% for cobalt ores, concentrates and intermediates, and 27% for refined cobalt.

The cobalt flows through the EU economy are demonstrated in the following Figure 98.

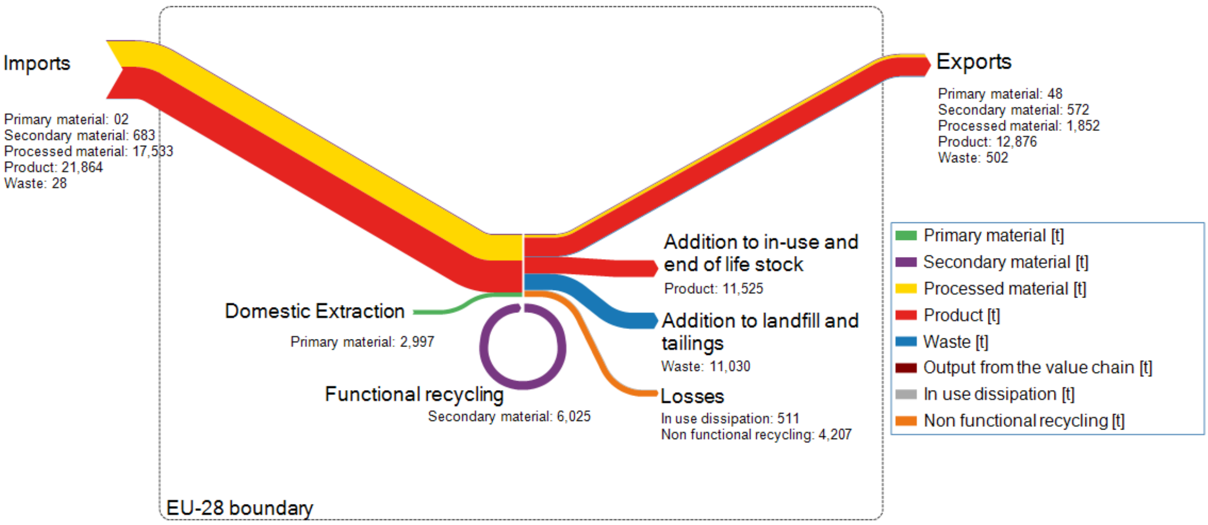

Figure 98: Simplified MSA of cobalt flows in the EU, 2016. (Draft MSA of Cobalt 2019)

7.4.1.1 Cobalt mine supply

[60] On this scale, zero indicates that exemplary substitutes exist for all major uses and 100 indicates that no substitute with even adequate performance exists for any of the major uses.

Cobalt is currently mineed only in Finland in three mines as a by-product of nickel or copper (FODD 2017)(Gautneb et al. 2019). In particular:

• The open-pit Sotkamo (Talvivaara) mine operated by Terrafame. It is a large, low-grade black-shale hosted Zn-Ni-Cu-Co mine which produces cobalt as by-product to nickel and zinc. The mined nickel-rich polymetallic ore is processed in heaps by bioleaching under ambient pressure and temperature. Cobalt and other metals are precipitated as sulphide and marketed as intermediate nickel-cobalt sulphide. At full scale, cobalt production capacity is estimated at 1,800 tonnes per year (Patricia Alves Dias et al. 2018). Terrafame is constructing a new battery chemicals plant on-site that will change the current production target from 30 kt Ni-Co-sulphide to 170 kt of Ni-sulphate and 7,400 t of Co-sulphate. Commercial production is announced to commence at the start of 2021, and the end-use market of products will be manufacturing of batteries for electric vehicles (Terrafame Oy 2018) (TerraFame 2018a);
• The underground Kylylahti copper-zinc mine operated by Boliden Mining. The Kylylahti mine extracts from a small-sized Cu-Zn-Ni-Co deposit. Production started in 2012. The average annual production between 2012 and 2016 has been 1,000 tonnes of cobalt (GTK 2019b). In 2018, the mine produced 278 tonnes of Cobalt (Gautneb et al. 2019);
• The open-pit Kevitsa nickel-copper mine also operated by Boliden Mining. The Kevitsa mine exploits a large low-grade Ni-Cu-PGE deposit. Production started in 2012, and averaged to 370 tonnes of cobalt per year over the 2012-2016 period (GTK 2019a). In 2018, the mine produced 591 tonnes of cobalt (Gautneb et al. 2019).

The Hitura mine in Finland producing cobalt in nickel-copper concentrates suspended production in 2013 (FODD 2017), and the Aguablanca mine in Spain producing Ni-Cu concentrates containing cobalt closed in 2016 (USGS 2017). In Greece and Poland, cobalt is extracted in operating mines of lateritic nickel and copper ores, respectively, but it is not recovered as a by-product (Lauri et al. 2018). The H2020 project METGROW+ (2016-2020) is currently studying the extraction of cobalt from Polish and Greek low-grade Ni-bearing laterites by innovative metallurgical technologies (Mäkinen et al. 2018).

On a global scale, EU mine production is small (nearly 2,000 tonnes per year) representing a share of only 1.5% of the total. New Caledonia (French overseas territory) produces circa 4,000 tonnes annually, covering 4% of the world total mine production.

Figure 99 presents the EU sourcing (domestic production and imports) for cobalt ores and concentrates and cobalt intermediates based on averages over the period 2012–2016. The amount of imported cobalt contained within ores and concentrates is about 400 tonnes and 11,700 tonnes for intermediates.

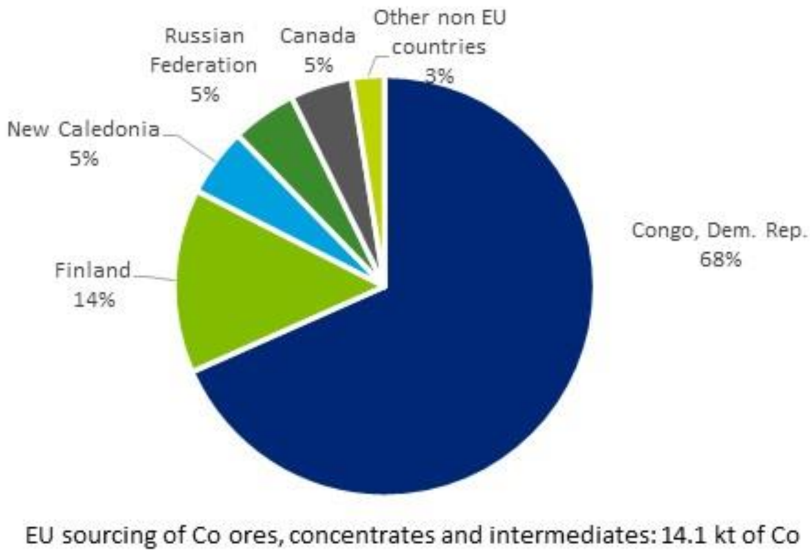

Figure 99: EU sourcing of cobalt ores, concentrates and intermediates. Average 2012-2016 (Eurostat 2019), (ULJAS, 2019), (WMD, 2019).

7.4.1.2 Intermediates and refined Co supply

The EU is an important producer of refined cobalt accounting for almost 14% of the world's production. Intermediates and refined cobalt are currently produced in:

•The Kokkola cobalt refinery in Finland, operated by Freeport Cobalt. It produces metal powders and a wide range of cobalt chemicals (i.e. acetate, carbonate, hydroxide, oxide, sulphate) for chemical, pigment, and powder metallurgy applications.It also produces battery-grade cobalt compounds used as precursors for cobalt-based cathode materials. According to production data published by the Cobalt Institute, the average annual production has been about 10,300 tonnes over 2012-2016, while in 20018 production reached 12,874 tonnes (Cobalt Institute 2019b). The yearly capacity is reported to be 15,000 tonnes of cobalt (USGS 2018). The refinery mainly processed intermediate hydroxide and alliage blanc imported from the Democratic Republic of the Congo, as well as intermediates from Harjavalta plant in Finland (Roskill 2014) (USGS 2017). According to the company, more than 50% of the total feed is secondary material from residues and by-products (Freeport Cobalt 2019);
• The Harjavalta nickel refinery in Finland, operated by Norilsk Nickel, produces cobalt intermediates in the form of cobalt sulphate and cobalt solutions. The refinery processes various nickel-bearing materials sourced from Norilsk's operations in Russia and third parties, e.g. Ni-Co mattes and nickel concentrates (Roskill 2014) (Nornnickel 2018). According to Roskill, the capacity is 380 tonnes of cobalt in the form of cobalt sulphate (Roskill 2014);
• Umicore operates the Olen refinery in Belgium which produces refined cobalt in various forms such as metal powder, cobalt salts (cobalt carbonate, cobalt sulphate, cobalt chloride, etc.) and cobalt oxide. Various cobalt materials, such as cobalt residues and other cobalt-containing materials, are processed into a wide range of refined cobalt products (USGS 2018) (Roskill 2014). Refined cobalt capacity is reported as 1,500 tonnes per year (USGS 2018);
•In France, Eramet produces cobalt chloride at the Sandouville nickel refinery, as a by-product of refining nickel matte imported from New Caledonia. From mid-2017 the refinery is supplied with nickel matte by a new European source. (Eramet 2019) Capacity is reported to be 500 tonnes of cobalt (USGS 2018).

Figure 100 presents the EU sourcing (domestic production and imports) for intermediate and refined cobalt as an average over the period 2012–2016. EU production of refined Co was nearly 13 kt per year, and imports were approximately 7 900 tonnes per year of cobalt oxides and hydroxides, cobalt sulphates, and cobalt chlorides.

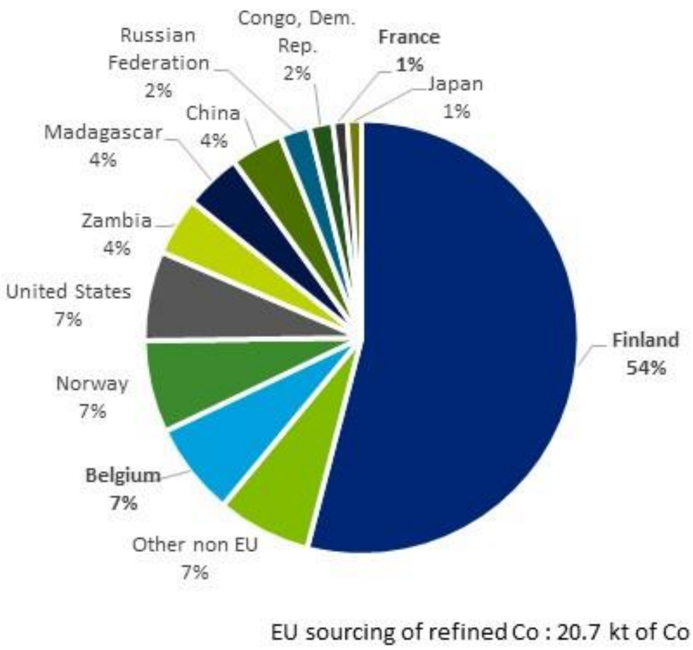

Figure 100: EU sourcing of refined cobalt. Average 2012-2016 (Eurostat 2019), (ULJAS, 2019), (WMD, 2019).

7.4.1.3 Supply of recycled cobalt

In the Freeport Cobalt refinery in Kokkola in Finland, more than 50% of the total feed is material from secondary sources (e.g. cobalt contained in residues and by-products) according to company's statement (Freeport Cobalt 2019). The plant applies hydrometallurgical processes, which can extract and purify cobalt to obtain high-quality chemicals (Sundqvist Ökvist et al. 2018).

Hydrometal in Engis, Belgium, processes cobalt-containing wastes from by-products of zinc metallurgy. The input material consists of cement coming from zinc electrolysis, which typically contains 5-7% cobalt, and by adequate processing, cobalt concentrates are obtained with a Co content of over 65%, which are sold to cobalt refineries (Sundqvist Ökvist et al. 2018).

Nickelhütte Aue GmbH in Germany processes secondary materials such as electroplating sludges and residues from non-ferrous metal processing. Currently, around 50 tonnes of cobalt is recovered annually in the form of cobalt chemicals (Al Barazi 2018).

Cobalt is also recovered from batteries by several recyclers and through different processes (Mathieux et al. 2017). Data on the quantities recovered from batteries are not available. Cobalt is recovered in the following operating battery recycling plants in the EU:

- In *Umicore's* plant in Belgium (Hoboken), a patented process is applied that combines a pyro-metallurgical treatment and a hydro-metallurgical process to recycle spent rechargeable batteries. Previously separated NiMH and Li-ion batteries are smelted with an ultra-high temperature plasma torch. The obtained alloy containing cobalt and nickel is further refined by a downstream hydrometallurgical process to produce $CoCl_2$. The plant has a combined capacity of 7,000 tonnes of treating Li-ion and NiMH batteries (Patrícia Alves Dias et al. 2018)(Sundqvist Ökvist et al. 2018);
- *Akkuser* in Finland (Nivala) recovers cobalt from Li-ion batteries (Roskill 2019b). The company treats annually 1,000 tonnes of Li-ion batteries (Lebedeva, Di Persio, and Boon-Brett 2017);

- *Accurec* in Germany (Krefeld) recycles annually 1,500-2,000 tonnes of Li-ion batteries. Cobalt is recovered by a combination of pyrolysis and hydrometallurgical treatment of the slag (Lebedeva, Di Persio, and Boon-Brett 2017) (Kushnir 2015);
- In *Recupyl's* plant in France (Grenoble), cobalt is reported to be recovered from spent Li-ion batteries by hydrometallurgical treatment (Kushnir 2015). Capacity is 110 tonnes of Li-ion batteries per year (Lebedeva, Di Persio, and Boon-Brett 2017);
- *SNAM* in France recovers cobalt by a combination of pyro-, mechanical and hydrometallurgical treatment. Total capacity is 300 tonnes of various types of batteries (Lebedeva, Di Persio, and Boon-Brett 2017).

According to (Patrícia Alves Dias et al. 2018), the current recycling infrastructure in the EU should enable the recycling of around 160,000 units of used batteries from EVs. This is well above the forecasted amount of batteries available for recycling in the EU until 2025. Estimates show that around 500 tonnes of recycled cobalt from EV batteries deployed in the EU should be available in 2025, and may amount, to.5,500 tonnes of recycled cobalt in 2030, accounting for around 10% of European cobalt consumption in the EVs sector. The existing large recycling capacity in the EU is likely to expand in the future and attract significant volumes from abroad (Patrícia Alves Dias et al. 2018).

7.4.2 Supply from primary materials

7.4.2.1 Geology, resources and reserves of cobalt

Geological occurrence: Cobalt has a relatively low abundance in the Earth's crust. Estimates of the crustal abundance vary between 15 and 30 parts per million (Roberts and Gunn 2014). For example, (Al Barazi 2018) reports the average cobalt content in the earth's crust as 25 ppm and (Rudnick and Gao 2014) about 27 ppm. According to (Rudnick and Gao 2014) the abundance of cobalt in the upper crust is around 17 ppm. Cobalt is not found as a pure metal in nature but in conjunction with other elements (mainly Fe, Ni, Cu and S), which are usually predominant. Among common cobalt-bearing minerals are sulphides and sulpharsenides such as cobaltite (CoAsS), carrollite ($Cu(Co,Ni)_2S_4$), erythrite ($Co_3(AsO_4)_2 \cdot 8H_2O$) and skutterudite ($(Co,Ni)As_{3-x}$).

Cobalt is a minor constituent in a number of ore types in various geological settings. The main ore types in which cobalt minerals can be found in economic concentrations are the following (Slack, Kimball, and Shedd 2017) (Roberts and Gunn 2014) (Hannis and Bide 2009):

- *Stratiform sediment-hosted deposits of Cu-Co sulphides and oxides*, typically exploited for copper. The most significant deposits are situated in the Central African Copperbelt which extends for 500 kilometres across north-western Zambia and south-eastern parts of the Democratic Republic of Congo. Typical grades of the cobalt sulphide minerals are between 0.1 and 0.4% Co, which are the highest among the different geological settings in which cobalt is occurring;
- *Magmatic deposits of Ni-Cu (-Co-PGE) sulphides*, primarily worked for nickel, copper and platinum group metals (PGMs). Significant deposits of this type include the Norilsk deposit in Russia, the Sudbury deposit in Canada, and the Kambalda deposit in Western Australia, all of which are primarily worked for nickel. Ore grade averages to 0.1% Co;
- *Lateritic Ni-Co deposits* mainly worked for nickel. Significant examples are found in New Caledonia and Cuba. Typical ore grades in these deposits range from 0.05% to 0.15% Co;
- *Hydrothermal and volcanogenic deposits*. Cobalt is a by- or co-product of mining polymetallic ores. Such deposits occur in Finland, Sweden, Norway, USA, Canada and Australia. The Bou Azzer deposit in Morocco, where cobalt is currently extracted as the main product, also falls within this category. A typical ore grade is 0.1% Co.

Significant potential resources of cobalt occur on the seafloor within polymetallic nodules (or 'ferromanganese nodules') and cobalt-rich polymetallic crusts (or 'ferromanganese crusts'). Both settings are enriched in many rare and critical metals with significant concentrations. The Fe-Mn nodules lie mainly on abyssal plains at water depths of 3,500-6,500 m (Slack, Kimball, and Shedd 2017). The highest concentrations occur in the Pacific Ocean, in the Clarion-Clipperton Zone, which extends from off the west coast of Mexico to as far west as Hawaii where the quantity of Fe-Mn nodules is estimated at 21.1 billion tonnes and the mean content of cobalt in the nodules at 0.2% by weight (Ecorys 2014). Co-rich ferromanganese crusts occur at relatively shallow depths of 800 to 3,000 m (Slack, Kimball, and Shedd 2017). A rough estimate of the quantity of crusts in the central Pacific region is about 7.5 billion tonnes. In Co-rich crusts, cobalt commonly shows values greater than 0.5% by weight (Ecorys 2014). Legal, economic, and technological barriers have prevented so far exploitation, but advances in technology may allow the production of these resources to be economically viable (Slack, Kimball, and Shedd 2017) (Roberts and Gunn 2014). Additional investigation and exploration would be necessary to estimate these marine resources, given that the interest in seabed exploration fluctuates depending on market conditions (i.e. metal price hikes) (European Commission 2019b). According to (Harald Ulrik Sverdrup, Ragnarsdottir, and Koca 2017), ocean mining contribution to global cobalt supply is not foreseen before 2050.

In Europe, most of the known cobalt-bearing deposits and occurrences are clustered in the Nordic countries (Finland, Sweden and Norway). Deposits are more scattered throughout South and Central Europe (Gautneb et al. 2019). The GeoERA project MINDeSEA has identified that most of the cobalt occurrences and deposits in ferromanganese crusts and polymetallic nodules in the seabed are concentrated in Spanish and Portuguese waters (European Commission 2019b).

Global resources and reserves[61]: The United States Geological Survey estimates cobalt global resources to be approximately 25 million tonnes. The largest are located in the sediment-hosted copper-cobalt deposits in the Democratic Republic of the Congo and Zambia. Significant cobalt resources also exist in nickel-bearing laterite deposits in Australia, nearby island countries and Cuba. Magmatic nickel-copper sulphide deposits are located in Australia, Canada, Russia and the US. Cobalt resources occurring in manganese nodules and cobalt-rich crusts on the seafloor are estimated to be more than 120 million tonnes (USGS 2019).

World reserves of cobalt are estimated at around 6.9 million tonnes of contained cobalt (USGS 2019). The Democratic Republic of the Congo has the largest global cobalt reserves (49%), followed by Australia (17%) and Cuba (7%). Global reserves of cobalt are shown in Table 39.

[61] There is no single source of comprehensive evaluations for resources and reserves that apply the same criteria to deposits of cobalt in different geographic areas of the EU or globally. The USGS collects information about the quantity and quality of mineral resources but does not directly measure reserves, and companies or governments do not directly report reserves to the USGS. Individual companies may publish regular mineral resource and reserve reports, but reporting is done using a variety of systems of reporting depending on the location of their operation, their corporate identity and stock market requirements. Translations between national reporting codes are possible by application of the CRIRSCO template, which is also consistent with the United Nations Framework Classification (UNFC) system. However, reserve and resource data are changing continuously as exploration and mining proceed and are thus influenced by market conditions and should be followed continuously.

Table 39: Global reserves of cobalt in 2018. Data from (USGS 2019)

Country	Estimated cobalt reserves (kt of Co content)	Percentage of the total (%)
Democratic Republic of the Congo	3,400	49%
Australia[62]	1,200	17%
Cuba	500	7%
Philippines	280	4%
Russian Federation	250	4%
Canada	250	4%
Madagascar	140	2%
China	80	1%
Papua New Guinea	56	<1%
United States of America	38	<1%
South Africa	24	<1%
Morocco	17	<1%
Other countries (unspecified)	640	9%
World total (rounded)	6,900	

S&P (S&P Global Market Intelligence 2019a) estimates that nearly three-quarters (72%) of the cobalt resources and 59% of the cobalt reserves are held by primary copper producers. Nickel is the primary product in operating mines controlling 25% of resources and 38% of reserves of cobalt currently exploited. Only 3% of resources and 3% of reserves are owned by companies for which cobalt is their primary product.

EU resources and reserves*:* The largest cobalt resource in Europe is located at the Sotkamo (Talvivaara) polymetallic Ni-Cu-Zn-Co sulphide deposit in Finland. Other significant deposits in Finland, by tonnes of contained cobalt, include the Kevitsa Ni-Cu-PGE, the Kylylahti Cu-Zn, the Sakatti Ni-Cu-PGE, the Hautalampi Ni-Cu-Co and the Juomasuo Au-Co deposits. In Greece, reserves reported for the lateritic nickel deposits include almost 50,000 tonnes of cobalt and mineral resources comprise additional 79,000 tonnes of cobalt. Ore reserves listed for Poland contain 75,000 tonnes of cobalt and additional 7,300 tonnes of resources but are poorly documented, whereas, in Sweden, total resources amount to about 20,000 tonnes of cobalt. Resources of cobalt are also known to exist in Spain (Lauri et al. 2018) (FODD 2017) (S&P Global Market Intelligence 2019a). Table 40 and Table 41 present cobalt resources and reserves data respectively, sourced from the Fennoscandian Mineral Deposits database and corporate reports.

Table 40: Cobalt resources data in the EU

Country	Classification	Quantity (Mt of ore)	Grade (% Co)	Reporting code	Reporting date	Source
Finland	Total resource	78.7	0.003	JORC	12/2017	(FODD 2017)[63]
	Total resource	46.8	0.006	NI43-101	12/2017	
	Historic resource estimate	35.6	0.010	None	12/2017	
	Total resource	1,525	0.017	JORC	06/2018	(FODD 2017)

[62] Joint Ore Reserves Committee (JORC)-compliant reserves were about 390,000 tonnes
[63] The compilation refers to medium and large deposits only

						(Terrafame 2018b) [64]
	Measured	26.1	0.022	PERC	12/2018	(Boliden 2019b) (Boliden 2019c)[65]
	Indicated	118.6	0.013		12/2018	
	Inferred	19.9	0.011		12/2018	
Sweden	Total resource	366.4	0.003	NI43-101	12/2017	(FODD 2017)
	Historic resource estimate	52	0.015	None	12/2017	(FODD 2017)

Table 41: **Cobalt reserves data in the EU**

Country	Classification	Quantity (Mt of ore)	Grade (%Co)	Co content (t)	Reporting code	Reporting date	Source
Finland	Proven	63.3	0.012	7,850	PERC	12/2018	(Boliden 2019b) (Boliden 2019c)[66]
	Probable	66.6	0.011	7,250			

7.4.2.2 Exploration and new mine development projects in the EU

Exploration projects targeting cobalt among other metals in polymetallic deposits were (2019) ongoing across the EU, mainly in Finland and Sweden, but also in Slovakia, Germany, Spain, Cyprus, Austria, Poland, and Czechia(S&P Global Market Intelligence 2019a). The more advanced projects are situated in Sweden, in which, cobalt is a companion metal of the main commodities, e.g. the Haggan vanadium project, and the Ronnbacken nickel project at prefeasibility/scoping stage.

7.4.2.3 Cobalt mining

Cobalt is mostly extracted as a by-product of copper and nickel mining. Data[67] from 2017 shows that 56% of world cobalt primary supply comes from copper mines and 37% from nickel mines (S&P Global Market Intelligence 2019b). Only 7% of the global cobalt supply is sourced from mining operations where cobalt is the main product. This takes places for example at the Bou Azzer mine in Morocco and the Lubumbashi project processing slags in DRC. The ratio between copper and nickel mining as the source of cobalt is variable as it depends on the demand and associated production of copper and nickel (Al Barazi 2018).

Cobalt extraction from the ores as a by-product depends on the grade, economic feasibility and the process routes followed by individual operations (Roskill 2014). Mining of cobalt deposits is done by conventional underground and open-pit methods. Open-pit mining is the predominant method for weathered copper-cobalt deposits in DRC and Zambia (Roberts and Gunn 2014).

Specific techniques for beneficiation depend on two factors. One is the type and individual composition of the treated ore. The second one is the subsequent processes required to extract copper or nickel. Ore processing involves crushing, grinding and separating the metal-bearing material from gangue using either physical or chemical techniques as

[64] Talvivaara active mine. The average grade is sourced from (FODD, 2017)
[65] Kevitsa and Kylylahti active mines
[66] Kevitsa and Kylylahti active mines. Mineral reserves for the Talvivaara mine are not available
[67] Artisanal and small-scale mining of the mineral heterogenite in DRC is not included.

appropriate. Nickel laterite ores are usually refined directly, i.e. only after upgraded by crushing and grinding. Most other cobalt-bearing ores are first concentrated, either by flotation or gravimetric methods (Roberts and Gunn 2014). Products from copper mines are cobalt concentrates and Co-Cu-concentrates, and from nickel mines cobalt sulphide or Co-Ni-concentrates (Al Barazi 2018).

Finally, artisanal and small-scale mining (ASM) from the DRC contributes a considerable amount to the primary supply of cobalt. The relative proportion of ASM in the DRC fluctuates greatly depending on the development of large-scale mining (Al Barazi 2018). A share of between 15% and 20% of the DRC's total cobalt production is estimated to originate from ASM mine sites in the period 2015 – 2018 (BGR, 2019)(Al Barazi et al. 2018). CRU reports that the ASM supply from the DRC increased strongly in 2017 and 2018 driven by the high cobalt prices, and contributed significantly to bridge the global supply gap in 2017 (CRU 2018). In 2018, the ASM production is reported to 18,000 tonnes (BGR, 2019). However, ASM production is expected to decrease in 2019 compared to production in 2016 to 2018 due to the lower global cobalt prices, but it is estimated to continue to amount to 15%-20% of total procuction in DRC due to the expected decline in industrial cobalt production (BGR, 2019).

7.4.2.4 Production of cobalt intermediates

Cobalt-containing ores and concentrates are usually processed into intermediate products before refined production is possible. The process is often undertaken internally by integrated operations (Roskill 2014). A variety of pyrometallurgical and hydrometallurgical techniques are applied for intermediates production (Roberts and Gunn 2014). Cobalt intermediates produced from copper ores include crude mixed hydroxide precipitates, alliage blanc, cobalt crude carbonates and sulphates. From nickel ores, cobalt intermediates include Ni-Co or Ni-Cu-Co (-PGMs-Au-Ag) sulphide mattes, Ni-Co mixed sulphide or hydroxide precipitates, Co oxide sinters (Roskill 2014) (Al Barazi 2018). Each product has different cobalt content. Intermediate products are sent to captive refining operations or abroad or sold to refining companies (Roskill 2014).

7.4.2.5 World and EU cobalt mine production

In the analysed period 2012-2016, cobalt was mined in 21 countries. World production of cobalt was about 134 kt per annum (five-year average over 2012-2016). As shown in Figure 101, the Democratic Republic of Congo dominated global mine production producing nearly 79 kt with a share of 59% of the worldwide total. China (7%), Canada (5%), Australia (4%) and Zambia (4%) are other significant producers and together with the DRC account for 79% of world's mine production.

Within the EU, cobalt is mined in Finland (1% of the global total). The average EU production of cobalt ores and concentrates is about 2 kt per year in the period 2012-2016. Cobalt is also produced in New Caledonia (French overseas territory) representing 3% of the global output (WMD 2019).

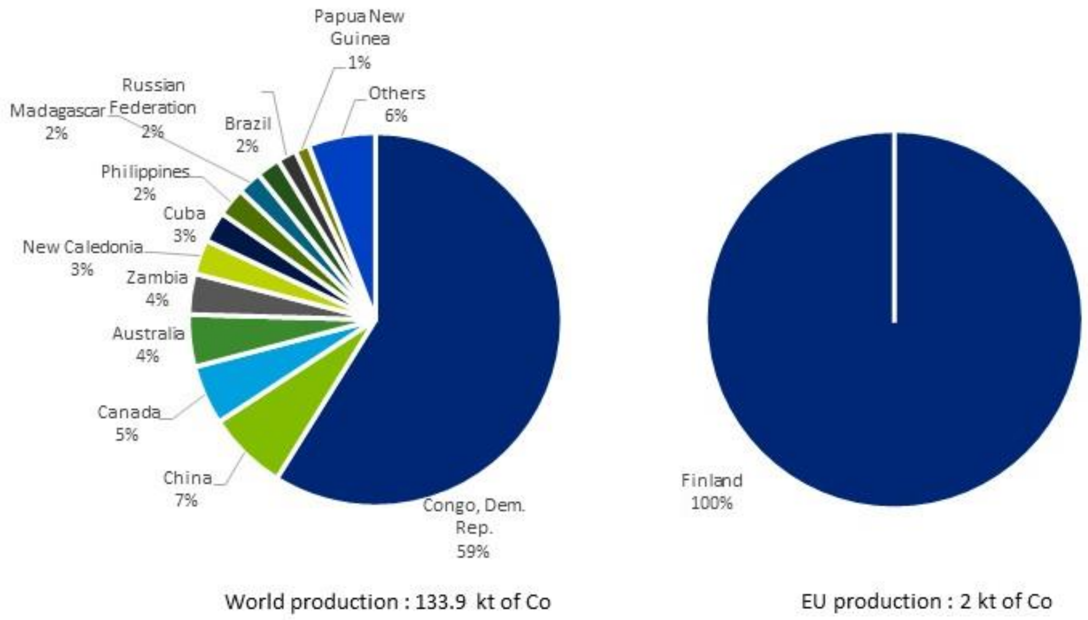

Figure 101: Global and EU mine production of cobalt. Average for the years 2012-2016. Data from (WMD, 2019)

7.4.3 Refining of cobalt

Cobalt refining includes a wide variety of hydrometallurgical and electrometallurgical techniques to recover cobalt from ores, concentrates, mattes or other intermediate products, which are often unique to the mineralogy of the ore material and very specific to the production site (Roberts and Gunn 2014). Cobalt refining generally starts after the primary metal (copper or nickel) has been recovered from the concentrated ore or other intermediate crude cobalt product. Refining processes that enable cobalt production can be summarised into three main clusters according to the type of the cobalt-bearing ore (Roskill 2014) (Roberts and Gunn 2014)(Al Barazi 2018):

• *Copper-cobalt sulphides and oxides*. The typical process for cobalt recovery involves roasting of the flotation concentrates to sulphate calcine, sulphuric acid atmospheric leach of the soluble sulphate calcine, copper recovery by solvent extraction and electrowinning, followed by impurity removal and cobalt hydroxide precipitation. Cobalt hydroxide can be marketed to produce chemicals or re-dissolved to recover cobalt metal by electrowinning. Due to the low cobalt recovery in the flotation concentration process for mixed sulphide-oxide ores, an alternative processing route is the direct whole ore leach, followed by solvent extraction to separate copper and cobalt and cobalt hydroxide precipitation;

• *Nickel sulphides*. The flotation concentrate is dried or roasted before smelting in an electric furnace (or flash smelting) to produce a nickel-cobalt sulphide matte suitable for refining. There are many refining techniques for cobalt recovery. In hydrometallurgical refining route, the process typically consists of a leaching stage using acids, chlorine, or ammonia, which is followed by a purification stage by solvent extraction or selective precipitation to separate cobalt and nickel. The final step for cobalt recovery can be hydrogen reduction (i.e. Sherritt process) where cobalt is recovered from the solution as a powder or electrowinning, which produces cobalt cathodes.

• *Nickel laterites*. Nickel laterites are processed mainly by high-pressure acid leach (HPAL), a technique combined with a variety of nickel and cobalt refining processes. A typical product is a mixed Ni (55%)-Co(5%) sulphide precipitate.

Some refineries also process scrap and cobalt intermediates, such as alloys, impure cobalt compounds, mixed metal sulphides, residues, and slags (Roskill 2014).

Refined cobalt products include cobalt metal in the form of cathodes, briquettes, ingots, granules and powder, and cobalt chemicals such as cobalt oxide, carbonate, chloride, sulphate, hydroxide, oxalate and acetate (Roskill 2014)(Al Barazi 2018).

7.4.3.1 World and EU refined cobalt production

Refined cobalt (including both metal and chemicals) is produced in 17 countries worldwide. The relative share of the global total held by the top producing countries, based on a five year average over 2012-2016, is shown in Figure 102. China dominates refined cobalt production, accounting for almost half of the world total (49%). Other significant cobalt refiners are Finland (12%), Canada (6%), Australia (5%), Zambia (5%), Japan (4%) and Norway (4%). The world production of refined cobalt totalled about 92.8 thousand tonnes on average over the period 2012-2016.

In the EU, refined cobalt is produced in Finland (71% of the EU production), Belgium and France.

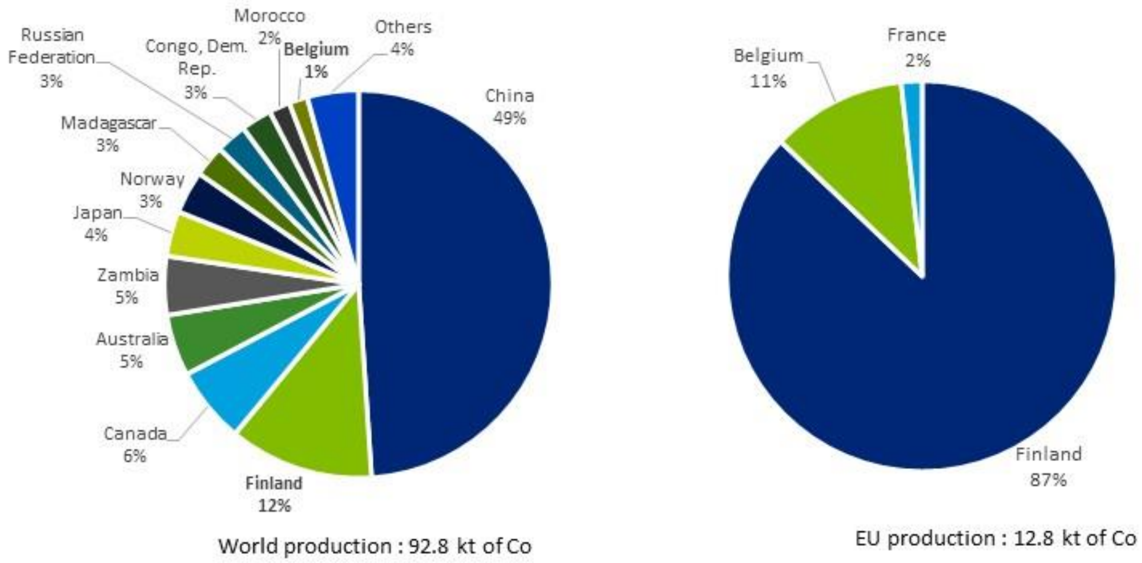

Figure 102: Global and EU production of refined cobalt. Average for the years 2012-2016. Data from (USGS 2018)(Draft Co MSA 2019)

7.4.4 Supply from secondary materials/recycling

Price volatility, geopolitics of supply, cost and environmental benefits are among the drivers for cobalt recycling. While specific cobalt uses are dissipative such as pigments in ceramics, paints, and tyre adhesives, cobalt used in applications such as superalloys, hard metals, batteries, and catalysts can be collected and recycled. (Roberts and Gunn 2014) Cobalt-bearing end-of-life scrap can be found in used jet engines, used cemented carbide cutting tools, spent rechargeable batteries, magnets that have been removed from industrial or consumer equipment and spent catalysts (Mathieux et al. 2017). Recycling of alloy and hard metal scrap is generally operated by and within the superalloy and carbide manufacturers, while the recycling of batteries and catalysts is mainly done via the cobalt industry sector or dedicated plants for batteries recycling (Roberts and Gunn 2014) (Sundqvist Ökvist et al. 2018).

According to UNEP (UNEP 2011), the global average end-of-life functional recycling rate (EOL-RR) for cobalt was estimated to be above 50%, the fraction of secondary (scrap) metal in the total input to metal production to range between 25% and 50%, and the share of old scrap in the total scrap flow (old scrap ratio) to be between 25% and 50%.

Recycling of end-of-life products is an important source of cobalt supply for the EU. It is estimated that 22% of the EU annual consumption of cobalt was sourced from end-of-life scrap in 2016 (Draft Co MSA 2019).

7.4.4.1 Post-consumer recycling (old scrap)

Cobalt content in end-of-life rechargeable batteries makes up a substantial secondary resource. Currently, the material attracting the most interest in Li-ion battery recyclers is cobalt (Mathieux et al. 2017). Recycling of cobalt in batteries is favoured as batteries are well collected at end-of-life because of EU waste legislation. The primary issues connected with cobalt recovery from spent batteries are sorting and identification of battery composition (Sundqvist Ökvist et al. 2018). In 2016 the EU the EOL recycling rate of cobalt was estimated to be 32%, considering 100% of recycling of electrical vehicles batteries (Draft Cobalt MSA 2019).

Significant opportunities to recycle cobalt from EV batteries may be anticipated over the coming years. Large-scale recycling can be expectedbeyond 2025. This projection is based on an average estimated lifetime of EVs of eight years (Patrícia Alves Dias et al. 2018).

The process choice for cobalt recovery from spent batteries depends on the type of cobalt-bearing battery. Usually, large Ni-Co smelters are also able to recover cobalt from spent batteries.

In cases where the old scrap of cobalt-bearing alloys is separately collected (e.g. superalloys) it can be remelted directly in the form of the original alloy for the same application (e.g. turbine blades, parts of jet engines, magnets) under the constraint that the composition of the alloy is certified or can be assured (European Commission 2017). The recycling rate for gas turbine engines, aircraft and rockets is reported 90% and for magnets 10% (Harper, Kavlak, and Graedel 2012). Co-bearing scrap can also be recycled industrially in sulphide smelter by mixing alloy scrap with primary cobalt sulphide concentrates. Alloy scrap (usually Ni-Co) is also treated using hydrometallurgical methods, allowing the separation and recovery of other valuable elements (W, Ta, Re) in addition to nickel and cobalt (Sundqvist Ökvist et al. 2018).

For spent catalysts, the recycling technology involves pyrometallurgical and hydrometallurgical techniques. According to Harper and colleagues (Harper, Kavlak, and Graedel 2012) only catalysts from plastics manufacture are available for recycling, but not catalysts used in petroleum refining (which are re-generated for reuse). Cobalt in cemented carbide products can be recovered for retooling and reuse (Cobalt Institute 2019d); and after the use phase, these can be recycled, for example by dissolution in molten zinc and zinc distillation (Sundqvist Ökvist et al. 2018). The rest of cobalt uses are dissipative, e.g. pigments, tyre adhesives, foodstuffs, pharmaceutical, meaning that the cobalt is not available for recycling.

According to the updated MSA study of cobalt, the end-of-life recycling input rate is 22%. The relevant flows are presented in Table 42.

Table 42: Material flows relevant to the EOL-RIR of cobalt[68] in 2016. Data from (Draft Co MSA 2019)[69]

MSA Flow	Quantity (t)

[68] EOL-RIR=(G.1.1+G.1.2)/(B.1.1+B.1.2+C.1.3+D.1.3+C.1.4+G.1.1+G.1.2)

[69] The work carried out in 2019 increased the resolution of the MSA system. Therefore, there are changes in flows in comparison with the previous MSA methodology. B1.1 and B1.2 in the table is the result of the EU

B.1.1 Production of primary material as main product in EU sent to processing in EU	0
B.1.2 Production of primary material as by-product in EU sent to processing in EU	2,224
C.1.3 Imports to EU of primary material	10,220
C.1.4 Imports to EU of secondary material	308
D.1.3 Imports to EU of processed material	8,512
E.1.6 Products at end-of-life in EU collected for treatment	20,910
F.1.1 Exports from EU of manufactured products at end-of-life	215
F.1.2 Imports to EU of manufactured products at end-of-life	311
G.1.1 Production of secondary material from post-consumer functional recycling in EU sent to processing in EU	1,983
G.1.2 Production of secondary material from post-consumer functional recycling in EU sent to manufacture in EU	4,059

7.4.4.2 Industrial recycling (new scrap)

Scrap metal is also generated during manufacturing of alloys and other cobalt-bearing materials and products (sometimes referred to as 'new scrap' or 'processing scrap'). New scrap can be in the form of material that did not meet required specifications, excess metal removed during pressing or forging, rejects from casting operations, grinding sludge or turnings waste from machining operations, swarf etc. Because of the cost of purchasing of raw materials, it is clearly in the manufacturer's interest to minimise the generation of 'new scrap' and to recycle these materials within the manufacturing process (Shedd 2004).

7.4.4.3 Cobalt recovery from industrial by-products and mine tailings

Cobalt can be recovered from sludge generated in nickel refinery and zinc smelting waste with the application of hydrometallurgical techniques (Sundqvist Ökvist et al. 2018). Slags from copper smelting operations in Zambia and the DRC are another secondary source of cobalt (Roberts and Gunn 2014). The H2020 project METGROW+ (2016-2020) is currently studying the extraction of cobalt from fayalitic and Fe-Ni slag (Mäkinen et al. 2018).

Due to the increased demand for cobalt and recent advances in processing technology, it is also possible to extract cobalt from the historic flotation tailings of copper sulphide ores with commercial grades of cobalt, like the ones found in the Democratic Republic of Congo. In these, cobalt was present in the original ores but was not previously recovered due to the low efficiency of the flotation process (Hannis and Bide 2009)(Sundqvist Ökvist et al. 2018) (Roskill 2014). The French Geological Survey (BRMG) has developed a bioleaching technology applied in the re-processing of sulphidic mine wastes at the Kasese Tailings site in Uganda, where cobalt was produced from old copper mining waste tailings (D'Hugues et al. 2019). In the DRC, a major project is under construction, which comprises the reprocessing of old cobalt and copper tailings from previous mining operations around Kolwezi, with an annual capacity of 24,000 tonnes of Co (Mining Weekly 2018).

extraction after exports (MSA flows B1.1 + B1.2 – B1.3); C1.4 incorporates all secondary raw material imported to the EU both for the processing and manufacturing stages (MSA flows C1.4 and D1.9). D1.3 Incorporates imports to the EU of both semi-processed and processed material stages (MSA flows D1.3 and C1.8).

7.5 Other considerations

7.5.1 Environmental and health and safety issues

A wide range of cobalt-containing substances is covered by Regulation (EC) 1907/2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH). Appropriate measures for handling and use are required. Cobalt metal, the five cobalt salts (see below), and other cobalt compounds have been registered for REACH, and this data is available on the ECHA website. For example, cobalt metal is currently classified as carcinogenic (by inhalation) and is a skin and respiratory sensitiser (ECHA 2019b). A formal (legal) classification of cobalt metal as CMR (Carc. 1B by all exposure routes), skin sensitizer Cat. 1 and respiratory sensitizer Cat. 1 as well as aquatic chronic Cat. 4 has been adopted by the Commission and is currently undergoing scrutiny by EP and Council. In case EP and Council do not object, the classification will enter into force in Spring 2020. Entry into application takes place 18 months after entry into force.

Among the cobalt substances, the salts cobalt diacetate, cobalt dinitrate, cobalt carbonate and cobalt sulphate are on the Candidate List for Authorisation of Substances of Very High Concern (SVHC) since 2010, and cobalt dichloride since 2008. Each of the five cobalt salts is classified as carcinogenic (Article 57a of the REACH Regulation) and toxic for reproduction (Article 57c of the REACH Regulation) (ECHA 2019a). In December 2018, in order to reduce the risk of developing cancer following occupational exposure, the European Chemicals Agency (ECHA) launched a public consultation and proposed a REACH restriction on the manufacture and use of these five cobalt salts as substances on their own or in mixtures in a concentration equal to or above 0.01% by weight in industrial and professional applications. According to the proposed restriction, the cobalt salts would not be able to be manufactured, placed on the market or used unless a reference exposure limit value is demonstrated (ECHA 2018). The proposed restriction is still undergoing review and consultation, and the exposure limit value is being assessed. The use of the five cobalt salts as an additive in feedstuffs within the scope of Regulation (EC) 1831/2003 on additives for use in animal nutrition is already authorised and, therefore, exempted from the restriction proposal (ECHA 2018).

Concerning the potential impact of REACH on defence applications, the cobalt salts included in the REACH Candidate List are critical in applications for nickel-based corrosion protection, e.g. in humidity indicator or for superalloys in aerospace used for jet engines and landing gears (EDA 2018).

7.5.2 Contribution to low-carbon technologies

Cobalt is a material of significance in the implementation of the European Commission's long-term strategy for a modern, competitive, prosperous and climate-neutral economy by 2050[70]. Cobalt is a raw material used in rechargeable batteries for electric vehicles and energy storage. These two applications are a crucial low-carbon technology for energy storage and transport. Cobalt in cathode chemistries in Li-ion batteries for vehicles (i.e. lithium-nickel-manganese-cobalt-oxide batteries) provides higher energy density and thus longer distances per charge (Blagoeva et al. 2016). Besides, energy storage emerges as a key enabling technology for addressing the flexibility requirements for integrating variable renewable energy (such as solar power, wind power and biogas) into the grid and for providing green electricity for electrified transport, industry and buildings sectors (European Commission 2018). Cobalt-based alloys are among the available alternatives

[70] https://ec.europa.eu/clima/policies/strategies/2050_en

for manufacturing magnets for wind turbines (Cobalt Institute 2019a); however, especially for large turbines (> 5 MW), the market is dominated by NdFeB magnets (Pavel et al. 2016).

7.5.3 Socio-economic issues

The leading world supplier of cobalt, the Democratic Republic of the Congo (DRC), is considered one of the countries with highest risk for business, with very poor governance according to on the Worldwide Governance Indicators (WGI) developed by the World Bank. The ranking calculated for DRC is the seventh-highest (i.e. seventh-worst) of the 216 countries included; and the top six (most) riskiest countries for business are identified as the Democratic Republic of Korea, Libya, Somalia, South Soudan, Soudan and Syria Arab Republic (World Bank 2018).

A varying part of the cobalt produced in DRC stems from artisanal and small-scale mining (ASM) (see Section 1.4.2.2). Amnesty International reports that approximately 110K to 150k artisanal miners are likely to be involved in ASM in the southern part of the country, who work alongside industrial operations (Amnesty International 2017). A recent study by (BGR 2019) estimates that the number of active miners in 2017/2018 were approximately 150k to 200k, as a result of internal migration towards the Lualaba and Haut Katanga provinces driven by the cobalt price increase and looking for better livelihood.

In this context, artisanal miners are exposed to landslide hazard, heavy metals through dust inhalation, food and water contamination, and radiation. Poor sanitary conditions and insufficient safety measures in artisanal miners' camps are often observed. Hard working conditions and widespread child labour are also reported (Al Barazi et al. 2018) (Tsurukawa, Prakash, and Manhart 2011). Despite these negative aspects, artisanal cobalt mining plays a crucial role in the local livelihoods and socio-economic landscape of the Katanga and Lubumbashi province (Tsurukawa, Prakash, and Manhart 2011). It is also noted that according to the provisions of the DRC Mining Code, ASM is a legal activity on formally designated artisanal mining areas (Al Barazi 2018).

ASM of cobalt takes place Cobalt is mined in the southern province of Katanga. This region affected by human rights abuses such as child labour and unacceptable working conditions. However, it should be noted that child labour is predominantly linked with illegal or poorly regulated artisanal mining. Cobalt is not covered by EU Regulation 2017/821 on "laying down supply chain due diligence obligations for Union importers of tin, tantalum and tungsten, their ores, and gold originating from conflict-affected and high-risk areas". However, given the high social risk associated with the cobalt supply chains, several initiatives on responsible sourcing of cobalt have been developed in the last years. For example, the Cobalt Institute has launched in 2019 a new framework, the Cobalt Industry Responsible Assessment Framework (CIRAF), to assess the risks and demonstrate responsible sourcing. CIRAF builds on the leading global standard on responsible mineral supply chains such as the OECD 'Due Diligence Guidance for Responsible Supply Chains of Minerals from Conflict-Affected and High-Risk Areas (OECD DDG)' (Cobalt Institute 2019f).

7.6 Comparison with previous EU assessments

The assessment has been conducted using the same methodology as for the 2017 list. Supply risk has been analysed at the extraction (mining), and processing (refining) stages of the value chain. In the 2017 assessment two separate criticality assessments were also carried out, the first at the ores and concentrates stage, and the second at the processing stage (refined material stage). The results of this review and earlier assessments are shown in Table 43. The results for the 2017 assessment correspond to the extraction stage, as it was evaluated to be the bottleneck in the EU supply chain.

Table 43: Economic importance and supply risk results for cobalt in the assessments of 2011, 2014, 2017, 2020 (European Commission 2011)(European Commission 2014)(European Commission 2017)

Assessment	2011			2014			2017			2020	
Indicator	EI	SR		EI	SR		EI	SR		EI	SR
Cobalt	7.1	1.1		6.7	1.6		5.7	1.6		5.8	2.5

The results of the 2011 and 2014 assessments are not comparable due to the introduction of a revised methodology in the 2017 exercise. In particular, the reduction in the economic importance between 2014 and 2017 is induced by the change in methodology for calculating this indicator as the value-added considered in the 2017 criticality assessment corresponds to a 2-digit NACE sector rather than a 'megasector' (which was used in the 2011 and 2014 assessments).

In the current assessment, the Supply Risk (SR) was calculated using both the HHI for global supply and EU supply as prescribed in the revised methodology. The assessment results demonstrate that the extraction stage, together with the imports of cobalt intermediates, has a higher supply risk (SR=2.54) compared to the processing stage (SR=0.49). The overall supply risk for cobalt is considered for the stage with the highest score, i.e. SR=2.54 (rounded to SR=2.5).

The values of the Supply Risk indicator are not directly comparable to the 2017 assessment. A different approach has been applied in the current assessment to reflect more accurately the market in the stages of extraction and processing. In particular, the trade of intermediate cobalt products requiring further refining was allocated to the extraction stage, whereas in the 2017 assessment they were considered as part of the processing (refining) stage. This approach is more realistic for evaluating the supply risk in the extraction and the processing stage separately. Cobalt intermediates are the saleable products of the cobalt mining companies and are utilised as a feedstock by cobalt refineries. Furthermore, the trade volume in Co ores and concentrates is following a strong downward trend in recent years because of a general preference of consumers in refineries worldwide for semi-processed materials rather than concentrates. In the previous assessments, only the trade of ores and concentrates was accounted for in the extraction stage, and the trade of intermediate cobalt compounds was entirely allocated to the processing/refining stage as part of bulk refinery imports.

The calculation of Economic Importance indicator is based on the use of the NACE 2-digit codes, and the value added at factor cost for the identified sectors (see Table 38). For information relating to the application share of each category, see Section 7.3.2 on applications and end-uses. Since the majority of the applications shown as "others" refer to chemical applications, the NACE 2-digit sector "C20" was allocated. In the 2020 assessment, the value-added data used in the calculation of economic importance relate to 5-year average 2012-2016 values.

7.7 Data sources

Production data for the extraction stage were sourced from the 'World Mining Data' datasets, developed by the Austrian Ministry for Sustainability and Tourism and the International Organising Committee for the World Mining Congress. The source for refined cobalt production was the US Geological Survey, with the exception of production from

Belgium, for which the datasets developed by the ongoing MSA study were utilised, as it was possible to disaggregate Umicore's production in Belgium and in China (publicly available sources do not provide this disaggregation); therefore, production of refined cobalt from China reported by the USGS has been also adjusted accordingly.

Trade data were extracted from the Eurostat (Comext) database under the Combined Nomenclature (CN) codes 26050000 'cobalt ores and concentrates', 28220000 'cobalt oxides and hydroxides', 28273930 for 'cobalt chlorides' and 81052000 'cobalt mattes and other intermediate products of cobalt metallurgy; unwrought cobalt; cobalt powders', adjusted for different cobalt contents (as described in the overview).

The analysis for 'mattes and other intermediate products of cobalt metallurgy; unwrought cobalt; cobalt powders' (CN code: 81052000) is challenging as this trading code is highly aggregated with products of varying cobalt content. In particular, 'mattes and other intermediate products' are assumed to contain 17% cobalt, while the 'unwrought cobalt' or 'powders' are likely to be 100% cobalt, and there are no data available to allow the user to distinguish the quantity of each within this trade code. As in the 2017 criticality assessment, given that the average cobalt prices in the period 2010-2014 have been similar to the prevailing average rates in the period 2012-2016, the trade data recorded against this code were adjusted by taking account the value recorded in the trade statistics. If the value divided by the quantity resulted in an average price of less than €10 per kilogram, the trade quantity was assumed predominantly 'intermediate', and a cobalt content of 17% was used. If the calculated average price was between €10 and €20 per kilogram, it was assumed a cobalt content of 60%. If the calculated average price was higher than €20 per kilogram, it was assumed the traded quantity had a cobalt content of 100%. Other organisations conducting a similar exercise may use different cut-off values and/or different cobalt contents for intermediate products, and therefore, the results will be different.

Another challenge with data availability that had to be overcome in the current assessment is the fact that since 2014 imports of CN 81052000 to Finland are not reported by Eurostat (apparently, they have become confidential). Nevertheless, statistics of the Finnish Customs (ULJAS 2019) do report data on imports of the above trade code, even though in an aggregated form and only in value (quantity is not reported). Therefore, the imports value (in EUR) was employed to calculate an average figure of EUR/kg for CN 81052000 for imports and this allowed to estimate imports to Finland for 2015 and 2016. It was also assumed that all Finish imports for 2015 and 2016 had the DRC as an origin and intermediate products with a value of less than EUR 10 per kg consisted of intermediate cobalt hydroxide, with a typical cobalt content of 17% (Roskill 2014).

The EOL-RIR is calculated from the preliminary datasets developed in the context of the ongoing cobalt MSA study (Draft Co MSA 2019), whereas the market shares of the cobalt applications by the EU manufacturing industry was provided by a recent study carried out by the Cobalt Institute. Other data sources have been mentioned elsewhere in this factsheet.

7.7.1 Data sources used in the factsheet

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