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SCRREEN2

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SCRREEN
Solutions for CRitical Raw materials - a European Expert Network

FACTSHEETS UPDATES **BASED ON THE EU FACTSHEETS 2020**

COBALT

AUTHOR(S):

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COBALT

OVERVIEW

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.

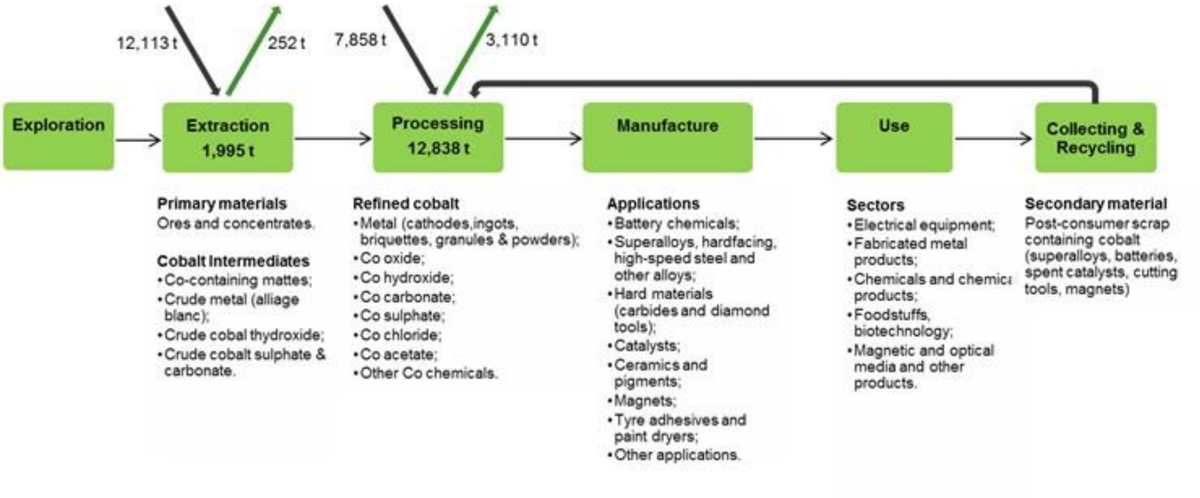

Figure 1. Simplified value chain for cobalt in the EU[1]

Table 1. Cobalt supply and demand in metric tonnes, 2016-2020 average

Global production	Global Producers	EU consumption (EU sourcing)	EU Share	EU Suppliers	Import reliance
136,385	Congo, DR 63% Russia 7% Canada 4% Other 26%	10,946 (extr)	8%	Russia 25% USA 16% Finland 16% Congo, DR 9% Madagascar 5% Canada 5% Norway 4%	81% (extr) 1% (proc)

Prices: The growth in cobalt price since 2016 has been driven by market expectations relating to cobalt demand for electric-vehicle batteries (European Commission, 2020; SCRREEN, 2022). Several explanations

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[1] JRC elaboration on multiple sources (see next sections)

have been suggested for the 'price crash' of 2018, ranging from the effects of cobalt-hydroxide market dynamics on the cobalt-metal market to market corrections after speculative behaviour (European Commission, 2020; Kilian, 2018).

Primary supply: Global mine production of cobalt from cobalt ores between 2010 and 2020 amounted between 130,000 and 158,000 tons per year (WMD 2022). Within the EU, 140 to 2,300 tons of cobalt was produced from the mines in the same period, all from Finland (Tukes 2022, WMD 2022). The main producer of cobalt ores, with 68% of all cobalt mined in the world in 2020, is the Democratic Republic of Congo (DRC); the second and third largest cobalt miners were Russia and Australia, at 4.5% and 4.1% shares, respectively (USGS 2022, WMD 2022). The EU share of the global mined cobalt was 1.1% – all of that is from Finland.

Secondary supply: 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).

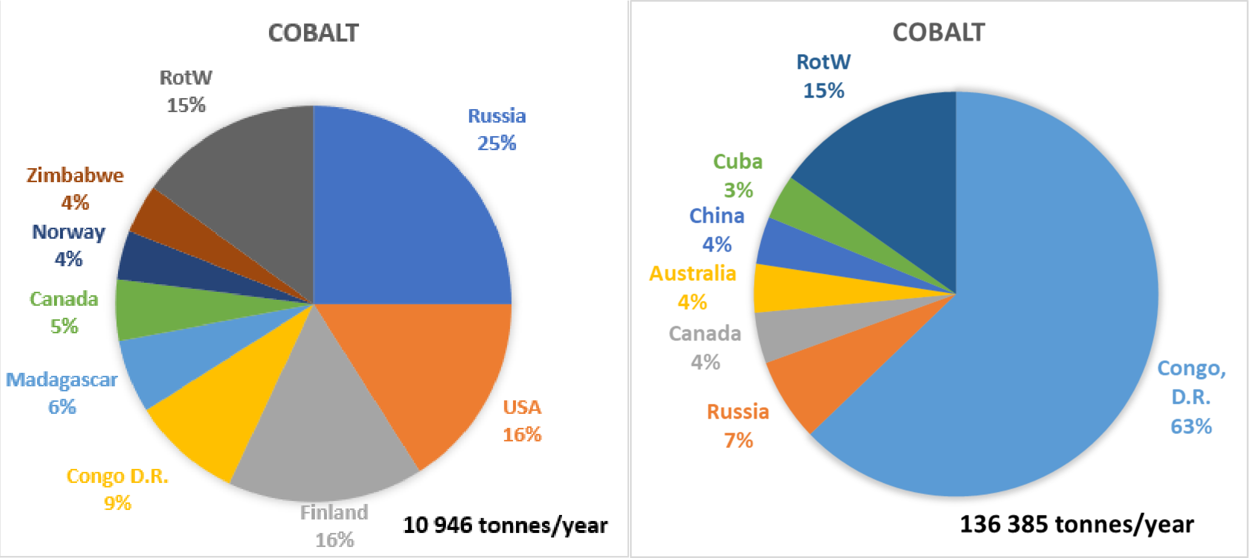

Figure 2. EU sourcing (extraction) of cobalt and global mine production, average 2016-2020

Uses: On a global scale, cobalt is primarily used in manufacturing of rechargeable lithium-ion batteries used in portable electronic devices, energy storage systems and electric vehicles. The share of batteries on the overall global demand increased significantly from 44 % in 2013 to 57 % in 2020 (Cobalt Institute, 2021). However, in the EU, batteries (3 %) and magnets (6 %) play only a minor role, while the actual demand for these products account for 13 % and 18 % of overall European cobalt demand, respectively.

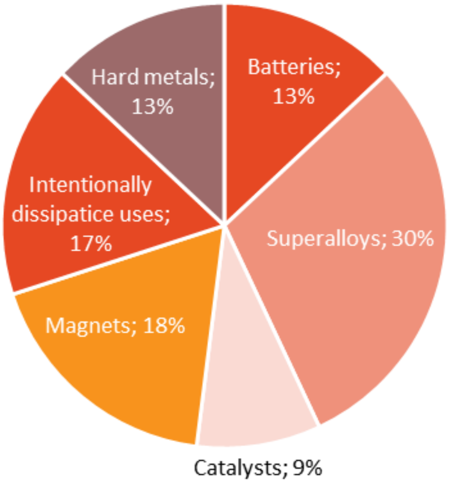

Figure 3: EU uses of cobalt

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 some 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.

Table 2. Uses and possible substitutes

Use	Substitutes	Sub share	Cost	Performance
Superalloys, hardfacing/HSS and other alloys	Composites	5%	Similar or lower costs	Reduced
	Titanium-aluminides	4%	Similar or lower costs	Similar
	Nickel-based alloys	5%	Similar or lower costs	Reduced
	Iron-based alloys	5%	Similar or lower costs	Reduced
	Ceramics	5%	Similar or lower costs	Reduced
	Hafnium	5%	Similar or lower costs	Similar
Hardmaterials (carbides and diamond tools)	Nickel	8%	Similar or lower costs	Reduced
	Nickel-Aluminium	8%	Similar or lower costs	Reduced
	Iron	5%	Similar or lower costs	Reduced
	Iron-copper	5%	Similar or lower costs	Reduced
Catalysts	Nickel	0%	Similar or lower costs	Reduced
	Rhodium	0%	Very high costs (more than 2 times)	Reduced
Pigments and inks	Zinc	0%	Similar or lower costs	Reduced
	Magnesium	0%	Similar or lower costs	Reduced
Batteries	Lithium-nickel-manganese-cobalt-oxide (NMC)	5%	Similar or lower costs	Similar
	Lithium-manganese-oxide (LMO)	5%	Similar or lower costs	Reduced
	Lithium-iron-phosphate (LFP)	5%	Similar or lower costs	Similar
	Lithium-nickel-cobalt-aluminium-oxide (NCA)	5%	Similar or lower costs	Similar
	NiCd/NiMH	5%	Similar or lower costs	Reduced

Other issues: The (REACH Regulation, 2006) classifies cobalt nickel oxide, cobalt nickel dioxide and cobalt nickel grey periclase as 1A carcinogens, given that they are known to have carcinogenic potential for humans. Cobalt, cobalt dichloride, cobalt sulphate, cobalt acetate, cobalt nitrate, and cobalt carbonate are listed as carcinogens of class 1B. As for the (CLP Regulation, 2008) cobalt was added in 2020 with hazard codes H413 (chronic aquatic hazard, may cause long-lasting harmful effects to aquatic life). The countries for which this material has a higher economic importance related to their total exports are Madagascar (3.9 % of total exports), Morocco (0.2 %) and Norway (0.1 %). In the three cases, all the cobalt is exported in form of matte or other intermediate products.

MARKET ANALYSIS, TRADE AND PRICES

GLOBAL MARKET

Table 3. Cobalt supply and demand at extraction and processing stage, in metric tonnes cobalt content, 2016-2020 average

Global production	Global Producers	EU consumption (EU sourcing)	EU Share	EU Suppliers	Import reliance
136,385	Congo, DR 63% Russia 7% Canada 4% Other 26%	10,946 (extr)	8%	Russia 25% USA 16% Finland 16% Congo, DR 9% Madagascar 5% Canada 5% Norway 4%	81% (extr) 1% (proc)

Since the mid-1990s through the 2000s, cobalt mine supply has grown at an annual rate of 9.3% on average; the growth slowed down to 2.1% in the 2010s (Barazi, 2018). Congo recording annual cobalt-production growth of 20% on average was the main driver of this expansion. In the present, global primary cobalt production is ca. 136 ktonnes (Table 3). The contribution of artisanal and small-scale mining (ASM) to primary-cobalt supply varies over time; in the period 2009-2019, the share of ASM in global primary-cobalt supply was 10% on average; in 2020, ASM accounted for ca. 9% of mine production in Congo (Cobalt Institute, 2021; Schütte, 2021). Recycling has a significant contribution to cobalt supply. Here, the end-of-life recycling input rate (for the EU) is assumed to be 22%. For the period 2017-2019, Roskill (2019) estimates an average annual supply of 13 kilotonnes cobalt from recycling (Schütte, 2021).

Congo is the largest producer of cobalt globally, and the country-concentration of global cobalt supply is high (see Table 1). The main actor in the field of cobalt *refining* is China, accounting for 67% of global refined-cobalt production in 2020 (Cobalt Institute, 2021). Key company-level actors at the cobalt market include Glencore, China Molybdenum Co., Chemaf, Jinchuan Group, Norilsk Nickel (Cobalt Institute, 2022; Schütte, 2021).

The strong cobalt-supply growth over the last decades has been driven by cobalt-*demand* for lithium-ion batteries and demand from China (Barazi, 2018; Cobalt Institute, 2021; European Commission, 2020; USGS, 2021). On the demand side of the cobalt market, China is the main actor; its share in global cobalt consumption is 32%; Europe is the second largest cobalt consumer, accounting for approximately 24% of global cobalt consumption (Cobalt Institute, 2021). In 2020, the consumption of cobalt was distributed across applications as follows: batteries (57%), nickel-base alloys (13%), tool materials (8%), pigments (6%), catalysts (5%) and other, e.g., magnets, soaps and dryers (Cobalt Institute, 2021). For battery production, cobalt chemicals are used (cobalt metal accounts for a very small fraction of cobalt used for batteries); the production of nickel-base alloys, tool material and magnets relies on cobalt metal; in pigments, soaps and dryers cobalt chemicals are used (Cobalt Institute, 2021).

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There is 'free-market' trade for cobalt in form of, e.g., cathodes, ingots, briquettes (European Commission, 2020). Cobalt in these forms is traded at London Metal Exchange. Corresponding price indices are published. The cobalt market has been affected by the Covid crisis: Rather supply structures (shipment) than production were affected; global cobalt consumption fell back marginally; and cobalt-demand growth came to a halt in most categories; yet, in 2021, the demand-growth rate recovered (Cobalt Institute, 2021).

OUTLOOK FOR SUPPLY AND DEMAND

In the medium and long term, cobalt demand is expected to grow, driven by energy transition and electric-vehicles demand; supply may, however, struggle to keep pace with demand growth in the medium term (Cobalt Institute, 2022; European Commission, 2020; SCRREEN, 2022). There are long-run barriers to supply expansion, which may result from, e.g., country-concentration of supply or lags between exploration and capacity creation; investments in production structures are crucial for ensuring that supply can follow demand growth in the longer run (Cobalt Institute, 2022; European Commission, 2020). The Ukraine crisis poses risks on cobalt supply (SCRREEN, 2022).

EU TRADE

For this assessment, cobalt is evaluated at both extraction and processing stage.

Table 4. Relevant Eurostat CN trade codes for cobalt

Mining		Processing/refining	
CN code	**title**	**CN code**	**title**
26050000	Cobalt ores and concentrates	**28220000**	Cobalt oxides and hydroxides; commercial cobalt oxides
81052000	Cobalt mattes and other intermediate products of cobalt metallurgy; cobalt and articles thereof, n.e.s.; cobalt waste and scrap (excl. ash and residues containing cobalt)	**28273400**	Cobalt chlorides
		29152300	Cobalt acetates

Figure 4 to Figure 6 illustrate import and export trend for cobalt products in EU evaluated both at Mining and refining stage. Cobalt ores and concentrates have seen a declining trend since early 2005 and currently both import and export quantities in EU is less than 10,000 tonne per year. Cobalt oxides and hydroxides imports on the other hand have been showing a growing trend since past year after the decline in 2019. In 2018, the quantity of import and export where highest across the 2000 – 2020 period crossing 5000 tonnes for both. For cobalt waste and scrap the import quantity has fallen since 2014 and have remained stable thereafter. Present quantity is closed to 10,000 tonne per year. Based on the expert advice, the CN 81052000 is considered at extraction stage and it covers the imports of intermediate products from DRC.

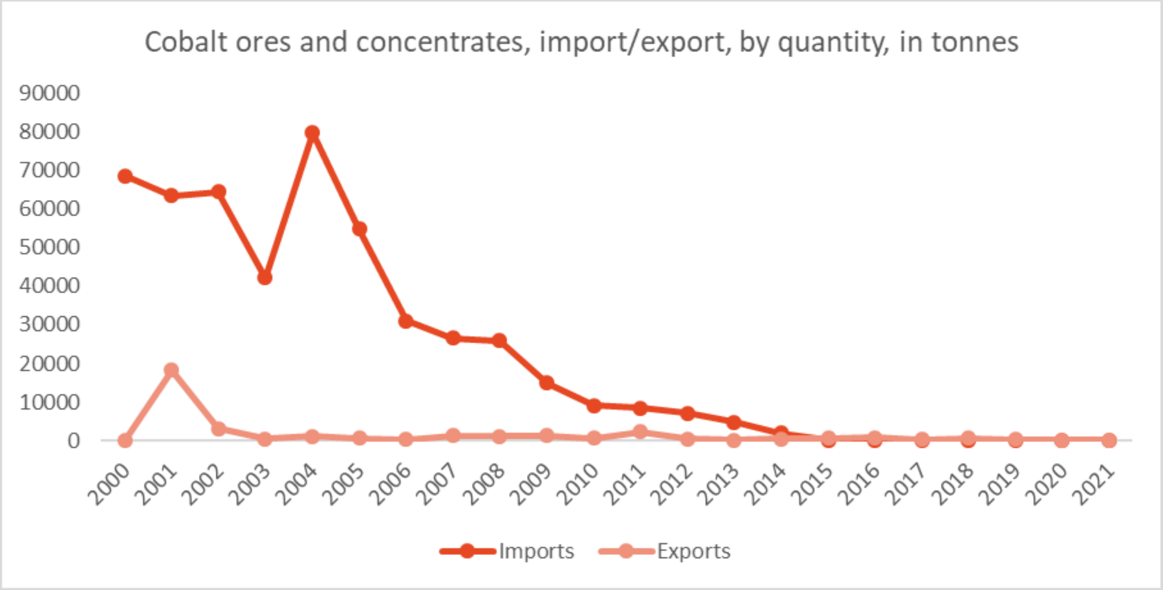

Figure 4. EU trade flows of Cobalt ores and concentrates (CN 26050000) from 2000 to 2021 (based on Eurostat, 2021)

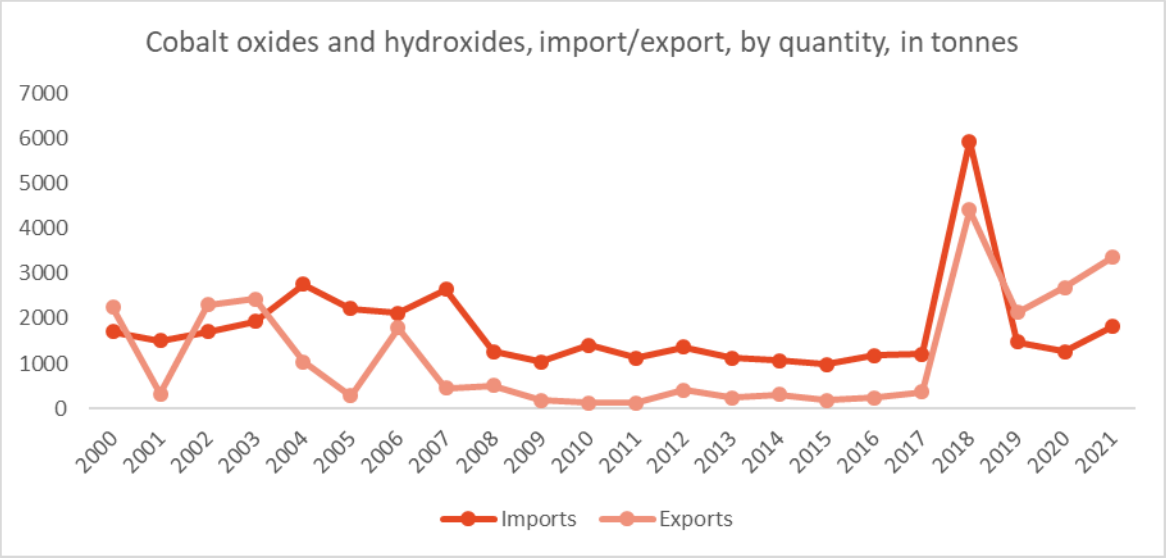

Figure 5. EU trade flows of Cobalt oxides and hydroxides; commercial cobalt oxides (CN28220000) from 2000 to 2021 (based on Eurostat, 2021)

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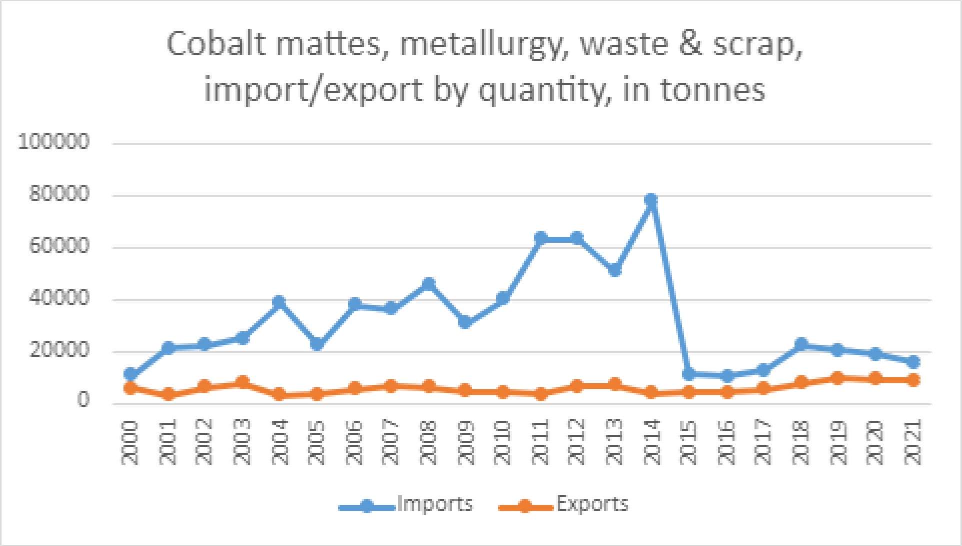

Figure 6. EU trade flows of Cobalt mattes and other intermediate products of cobalt metallurgy; cobalt and articles thereof, n.e.s.; cobalt waste and scrap (excl. ash and residues containing cobalt) (CN81052000) from 2000 to 2021 (based on Eurostat, 2021)

Figure 7 to Figure 9 show import from various countries to EU region. The DRC is the major supplier of both ores and concentrates as well as waste and scraps. However, since 2015 import data imported quantities are confidential and only reported in EUR for 81052000 Cobalt mattes and other intermediate products of cobalt metallurgy; unwrought cobalt; cobalt powders. This code contains major imports of intermediates in value from the DRC.

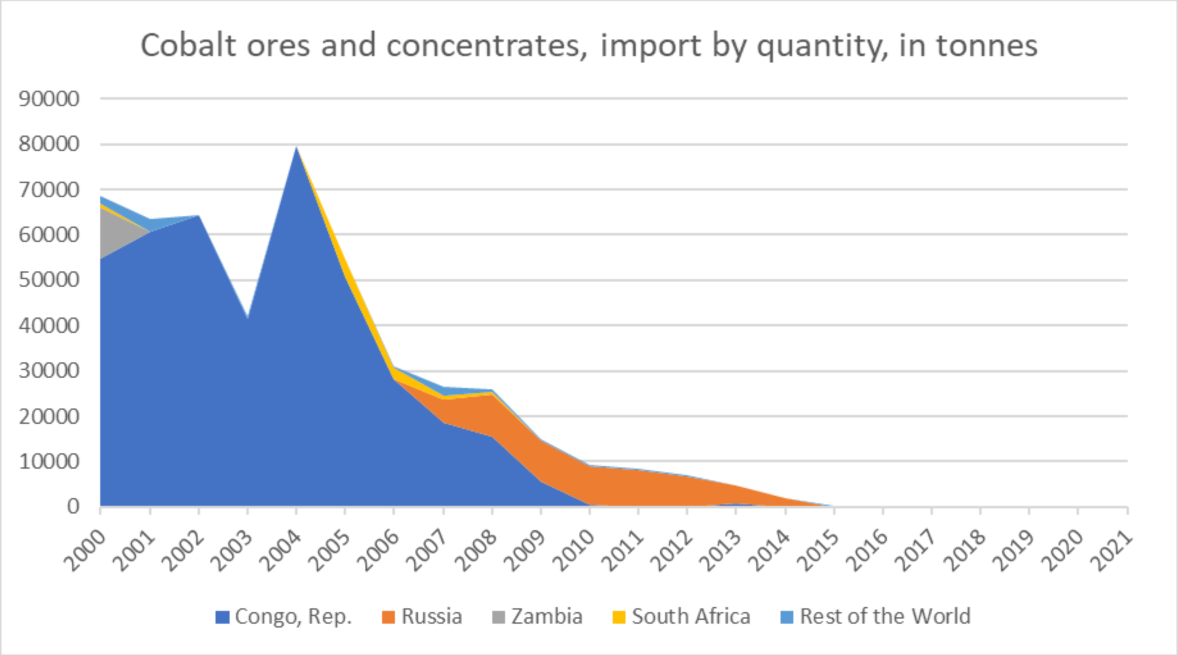

Figure 7. EU imports of Cobalt ores and concentrates by country between 2000 and 2021 (based on Eurostat, 2021).

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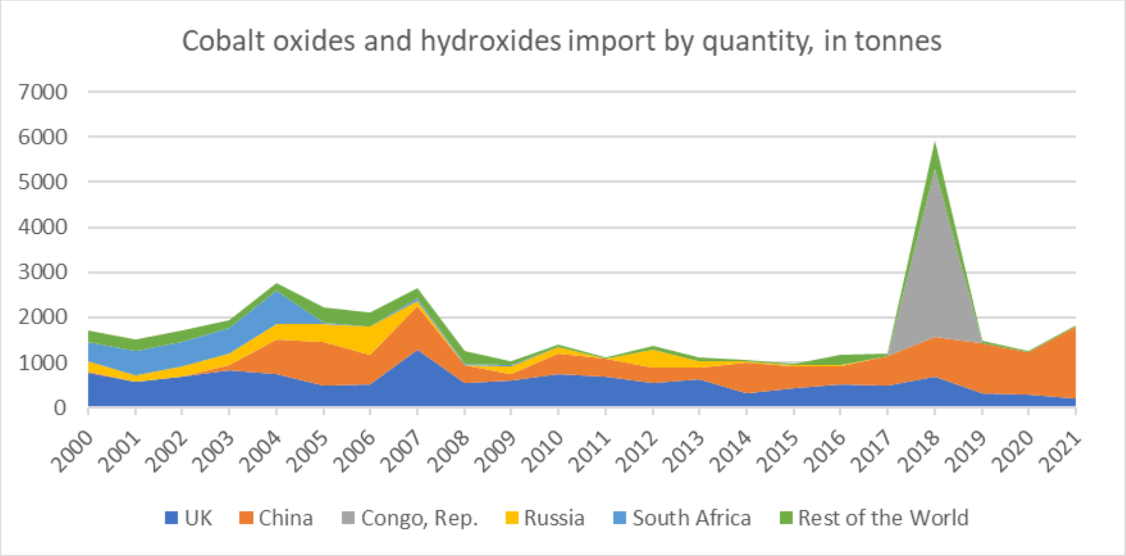

Figure 8. EU imports of Cobalt oxides and hydroxides by country between 2000 and 2021 (based on Eurostat, 2021).

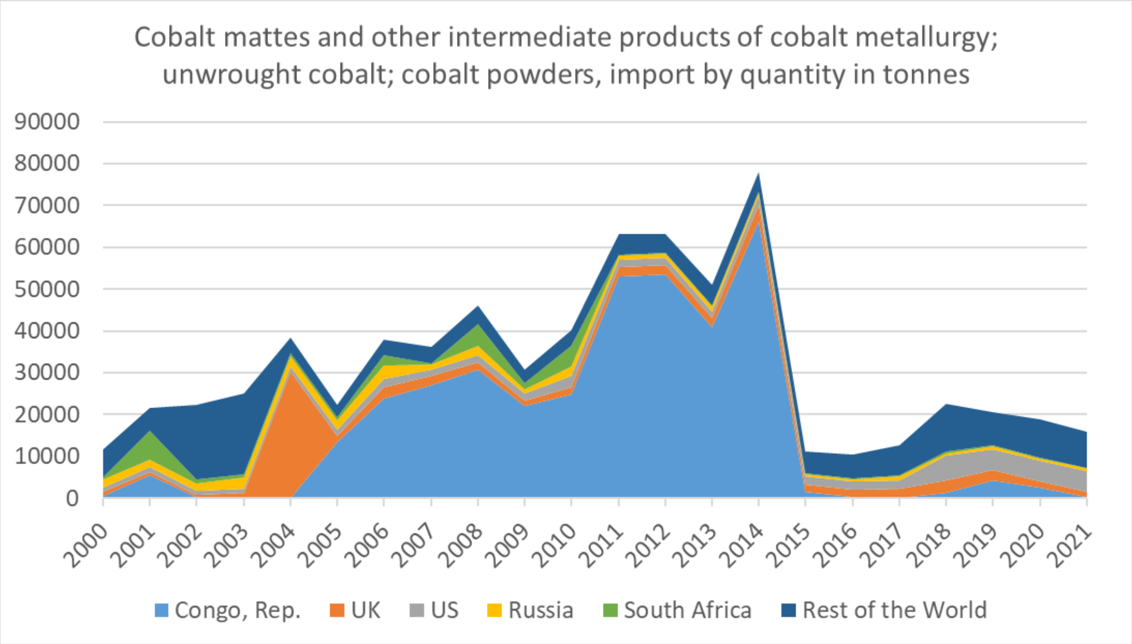

Figure 9. EU imports of Cobalt mattes and other intermediate products of cobalt metallurgy; cobalt and articles thereof, n.e.s.; cobalt waste and scrap (excl. ash and residues containing cobalt) by country between 2000 and 2021 (based on Eurostat, 2021).

PRICE AND PRICE VOLATILITY

The cobalt-price dynamics of the 2000s and early 2010s seem quite well explainable by two major factors (Barazi, 2018; European Commission, 2020): First, cobalt-price growth in the 2000s was driven by strong growth in cobalt demand; demand for lithium-ion batteries and demand from China were the main factors behind this growth among others. Second, effects of the global financial crisis started materializing in 2007/2008, as indicated by stock-market dynamics at that time. The crisis caused a contraction in cobalt demand, which was reflected by cobalt-price dynamics following 2008.

The growth in cobalt price since 2016 has been driven by market expectations relating to cobalt demand for electric-vehicle batteries (European Commission, 2020; SCRREEN, 2022). Several explanations have been suggested for the 'price crash' of 2018, ranging from the effects of cobalt-hydroxide market dynamics on the cobalt-metal market to market corrections after speculative behaviour (European Commission, 2020; Kilian, 2018).

In the period 2017-2021, the volatility of the cobalt cash price at London Metal Exchange was 36.2%, as indicated by the measure of standard deviation of logarithmic return calculated by DERA (2022).

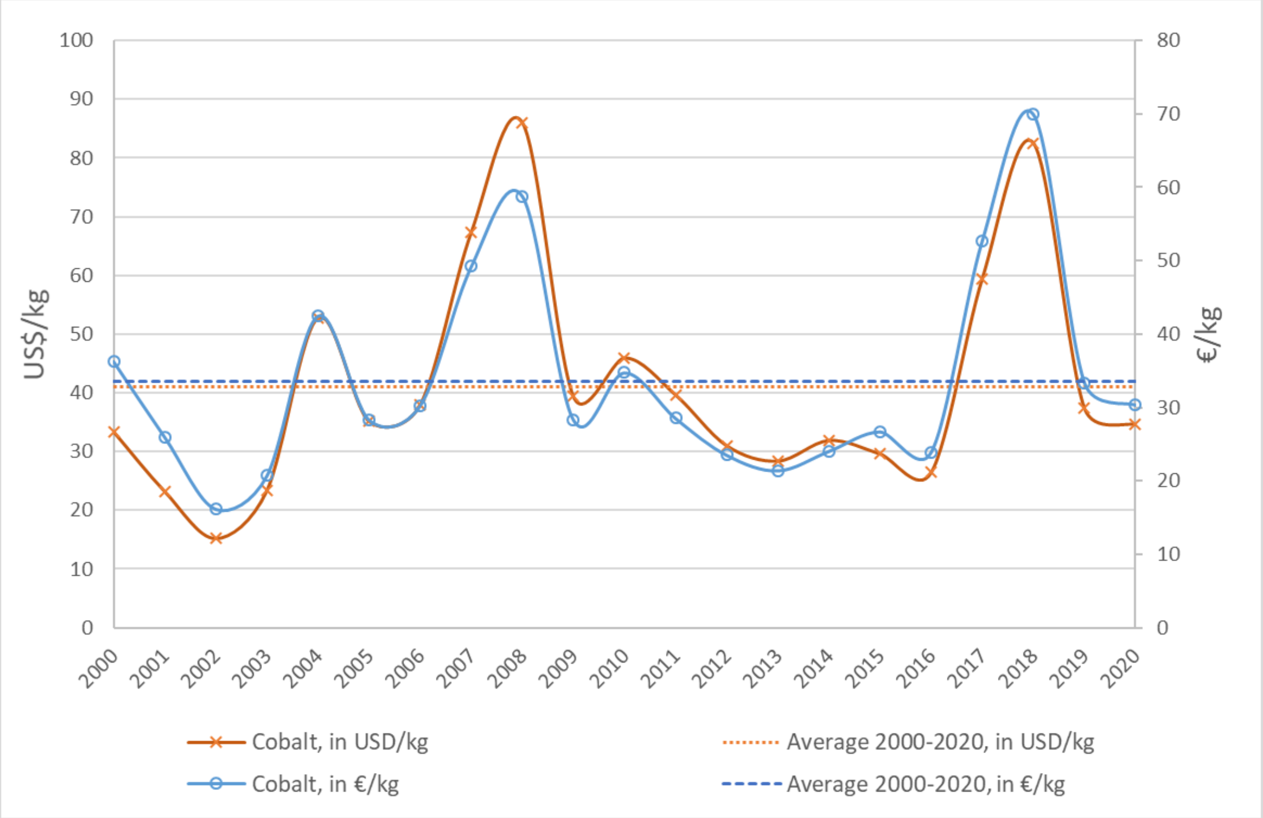

Figure 10. Annual average spot price of cobalt (cathodes), between 2000 and 2020, in US$/kg and €/kg.[1] **Source: USGS, 2004, 2007, 2010, 2013, 2016, 2019, 2022**.

DEMAND

GLOBAL AND EU DEMAND AND CONSUMPTION

The world refined cobalt consumption was about 175,000 tonnes in 2021 (Cobalt Institute, 2022).

For **cobalt ores**, concentrates and intermediates the EU consumption is close to zero since 2015. The apparent consumption of **refined cobalt** in the EU amounts to less than 300 tonnes of cobalt content per year on average during 2016–2020 (BGS 2022 and Eurostat Comext, 2022).

Cobalt extraction stage EU consumption is presented by HS code CN 26050000 Cobalt ores and concentrates. Import and export data is extracted from Eurostat Comext (2022). Production data is extracted from WMD (2022). Cobalt intermediary processing stage, accounted at the extraction stage, is presented by HS codes CN 75011000 Nickel mattes (2% of Co content) and CN 81052000 Cobalt mattes and other intermediate products of cobalt metallurgy; unwrought cobalt; cobalt powders[2] (60% of Co content). Import and export data is extracted from Eurostat Comext (2022). Production data from Eurostat Prodcom (2022) using PRCCODE 24451210 Nickel mattes and PRCCODE 24453035 Cobalt mattes and other intermediate products of cobalt metallurgy; unwrought cobalt; powders (excl. cobalt waste and scrap) were not considered, due to their low level of reliability.

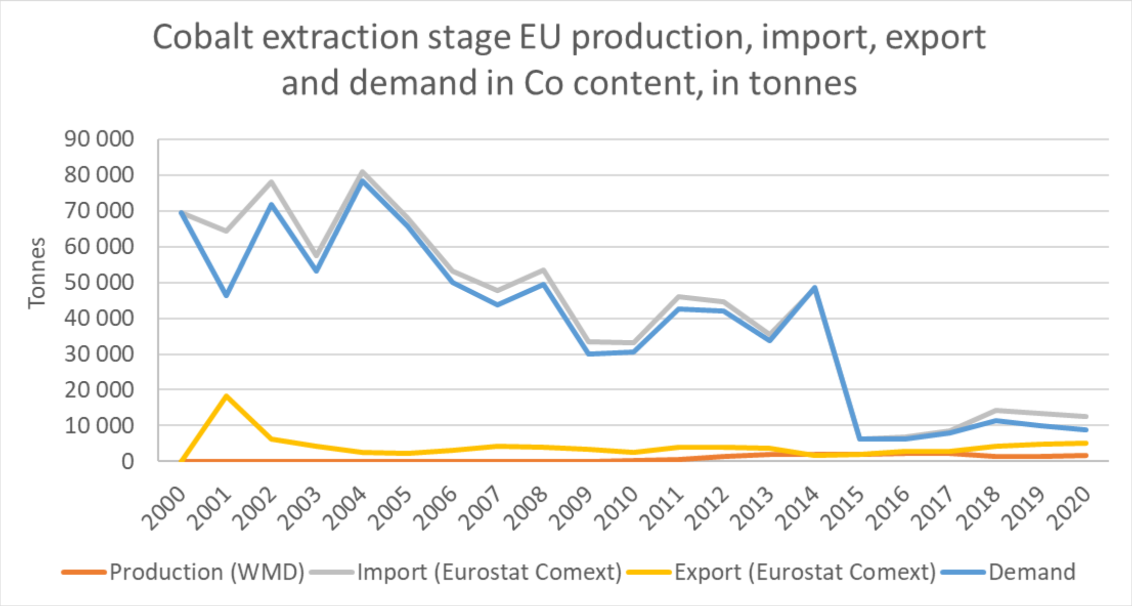

Figure 11. Cobalt ores and concentrates (CN26050000), Nickel mattes ((CN 75011000) and Cobalt mattes and other intermediate products of cobalt metallurgy; unwrought cobalt; cobalt powders (CN 81052000) extraction stage apparent EU consumption. Production data is available from WMD (2022) for 2008-2020. Consumption is calculated in cobalt content (EU production+import-export).

Based on Eurostat Comext (2022) and WMD (2022) the average import reliance of cobalt at extraction stage for 2016-2020 is 81%.

Cobalt processing stage EU consumption is presented by HS codes CN 28220000 Cobalt oxides and hydroxides, CN 28273930 Cobalt chloride, CN 28332930 Sulphates of cobalt and of titanium and CN 81052000 Cobalt mattes and other intermediate products of cobalt metallurgy; unwrought cobalt; cobalt powders. Import and export data is extracted from Eurostat Comext (2022). Production data is extracted from Eurostat Prodcom

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[2] This is a code used for imports of concentrates/intermediates from DRC to Finland

(2022) using PRCCODE 20121930 Cobalt oxides and hydroxides; commercial cobalt oxides, PRCCODE 20133134 Cobalt chlorides, PRCCODE 20134162 Sulphates of cobalt; of titanium and PRCCODE 24453035 Cobalt mattes and other intermediate products of cobalt metallurgy; unwrought cobalt; powders (excl. cobalt waste and scrap).

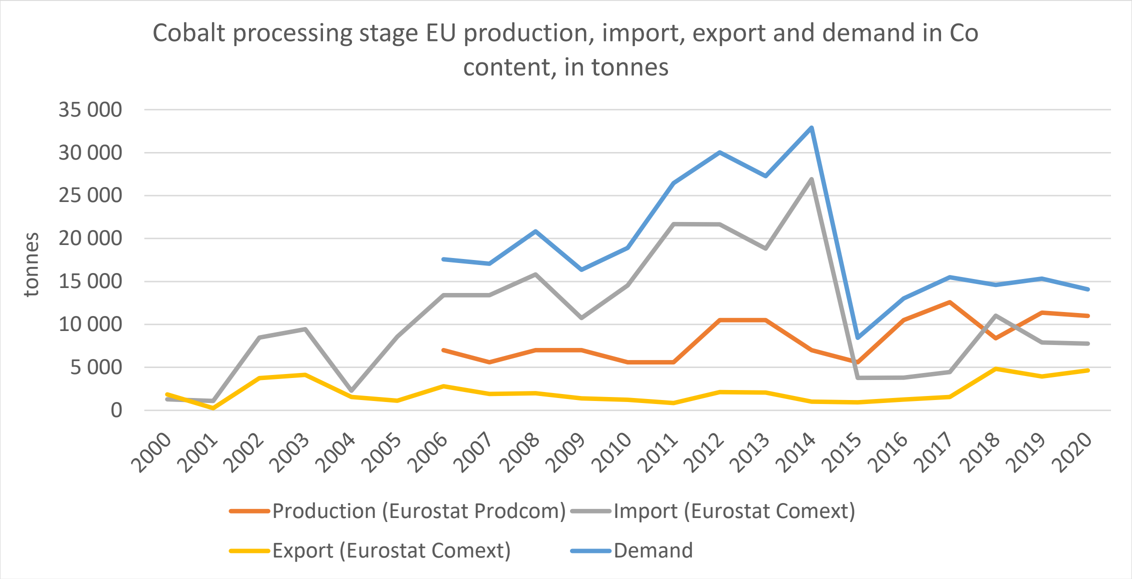

Figure 12. Cobalt (CN 28220000, CN 28273930 and CN 28332930) processing stage apparent EU consumption. Production data is available from Eurostat Prodcom (2022) for cobalt oxides and hydroxides for 2006-2020 and for cobalt chlorides, sulphates of cobalt and of titanium and Cobalt mattes and other intermediate products of cobalt metallurgy; unwrought cobalt; powders (excl. cobalt waste and scrap) for 2019-2020. Cobalt processing stage is calculated to contain 1/3 of Cobalt mattes and other intermediate products of cobalt metallurgy; unwrought cobalt; powders (excl. cobalt waste and scrap) with 100% cobalt content. Consumption is calculated in cobalt content (EU production+import-export).

Based on Eurostat Comext (2022) and Eurostat Prodcom (2022) average import reliance of cobalt at processing stage is 25.7% for 2016-2020.

GLOBAL AND EU USES AND END-USES

On a global scale, cobalt is primarily used in manufacturing of rechargeable lithium-ion batteries used in portable electronic devices, energy storage systems and electric vehicles. The share of batteries on the overall global demand increased significantly from 44 % in 2013 to 57 % in 2020, as shown in Figure 13 (Cobalt Institute, 2021).

Other significant uses include:

- superalloys mainly used in turbine engine components (13 % of world consumption)
- 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 (4 %)

- tyre adhesives and paint dryers (2 %) (Cobalt Institute, 2021).

Other minor end uses including foodstuffs, biotechnology, medicine, electroplating, electronics etc. make up the remaining of global consumption.

Due to the enormous increase of cobalt demand for Li-ion batteries, the share of all non-battery applications decreased between 2013 and 2020.

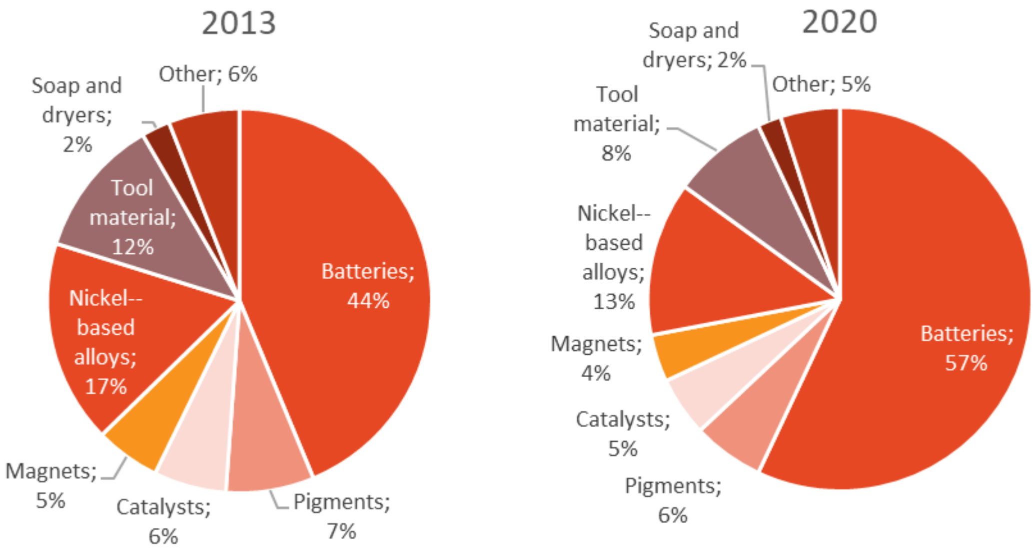

Figure 13 Global first uses of cobalt in 2013 and 2020 (Cobalt Institute, 2021)

The cobalt containing products in the finished goods shown in Figure 13 are applied in different sectors as shown for the global demand of 2020 in Figure 14. Portable electronics (48 %) and automotive sector (26 %) are the most important industries for cobalt demand (Cobalt Institute, 2021). In 2021, electrical vehicles (EVs) became the most important sector for battery related cobalt demand, accounting for 52 % of the battery sector (Cobalt Institute, 2022).

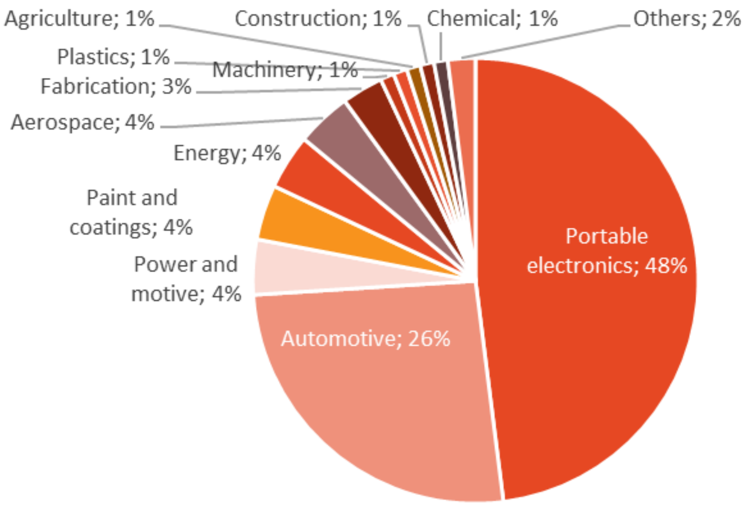

Figure 14 Global demand of cobalt by end use sector in 2020 (Cobalt Institute, 2021)

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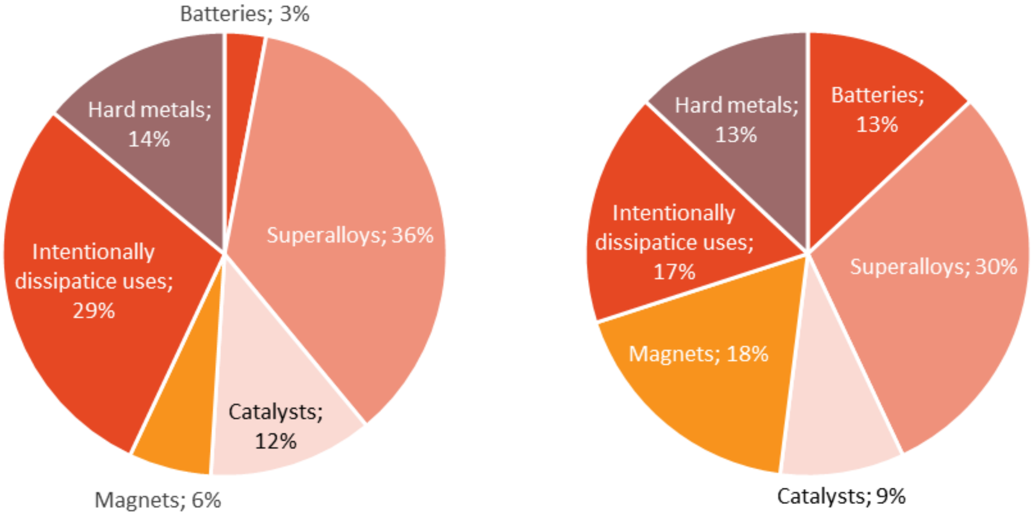

Figure 15. EU cobalt demand for the production of goods by end use (left) and for products used in the EU by end use (right) in 2016 (Torres de Matos et al., 2020).

In the EU, the cobalt demand patterns for the manufacturing of goods (Figure 15) and for finished goods used, but not necessarily produced in the EU, differ significantly. These shares are for 2016, as no more present data has been published.

In production, batteries (3 %) and magnets (6 %) play only a minor role, while the actual demand for these products account for 13 % and 18 % of overall European cobalt demand, respectively.

This emphasises that battery and magnet production takes place mainly outside of Europe, while these products still have a high economic importance for the region.

In production, European cobalt demand is mainly driven by superalloys (36 %), intentionally dissipative uses (29 %), hard metals (14 %) and catalysts (12 %) (Torres de Matos et al., 2020).

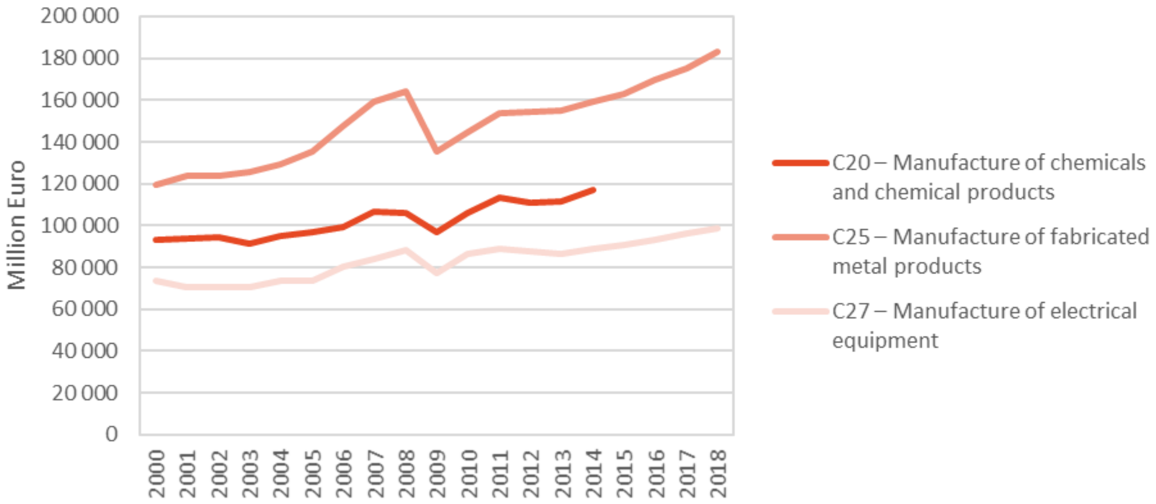

Figure 16. Value added per 2-digit NACE sector over time (Eurostat, 2021).

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Table 5 Cobalt applications, 2-digit and examples of associated 4-digit NACE sectors, and value-added per sector for 2019 (* for 2014) (Eurostat, 2022).

Applications	2-digit NACE sector	Value added of NACE 2 sector (M€)	4-digit CPA
Battery chemicals	C27 – Manufacture of electrical equipment	97,292	C2720 – Manufacture of batteries and accumulators
Superalloys, hardfacing, HSS, other alloys	C25 – Manufacture of fabricated metal products	186,073	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	186,073	C2573 – Manufacture of tools
Catalysts	C20 – Manufacture of chemicals and chemical products	117,150*	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	117,150*	C2012 – Manufacture of dyes and pigments
Magnets	C27 – Manufacture of electrical equipment	97,292	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	117,150*	C2030 – Manufacture of paints, varnishes and similar coatings, printing ink and mastics; C2052 – Manufacture of glues

APPLICATIONS OF COBALT

The applications of cobalt can be differentiated in metallurgical and chemical applications.

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

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 2019a).

HARDFACING ALLOYS

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).

HIGH-SPEED STEELS

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).

MAGNETS

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.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958211

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 2019a).

Co-bearing coatings may be applied to neodymium-iron-boron magnets for improved thermal stability and corrosion resistance (Cobalt Institute 2019a).

HARD MATERIALS

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 2019a). 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).

SPECIAL ALLOYS

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 2019a) (Roskill 2014).

CHEMICAL APPLICATIONS

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

BATTERIES

Cobalt is utilised mostly in rechargeable batteries.

Cobalt substances used as chemical precursors for cathode materials are cobalt sulphate, dichloride and dinitrate (Cobalt Institute 2019b).

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 recycling 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.

The 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 2019a).

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 2019b).

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 2019a).

The significant increase in the numbers of both electric vehicles and 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 2020 battery chemicals for rechargeable accounted for 57 % of total cobalt consumption (Cobalt Institute, 2021).

CATALYSTS

As cobalt is multivalent, it enhances 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.

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 used in hydroformylation reactions for the synthesis of alcohols for detergents, and aldehydes for the manufacture of plastics.

Catalysts containing cobalt are 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 and cobalt carboxylates (Cobalt Institute 2019a; Roberts and Gunn 2014).

PIGMENT

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 colorants 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 2019a).

ADHESIVES

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 2019a). The typical concentration of cobalt in ambient cure alkyd paint is around 0.06 % (Roskill 2014).

VITAMIN B12

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. 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 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.

Cobalt is 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 2019a; Roskill 2014).

OTHER CHEMICAL APPLICATIONS

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 2019a; Roskill 2014).

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 some 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 (Alves Dias et al. 2018). A study carried out by Graedel et al. (2015) assessed cobalt's substitutes performance as 54 on a scale from 0 to 100 (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).

Table 6 Substitution options for cobalt by application.

Use	Substitutes	Sub share	Cost	Performance
Superalloys, hardfacing/HSS and other alloys	Composites	5%	Similar or lower costs	Reduced
	Titanium-aluminides	4%	Similar or lower costs	Similar
	Nickel-based alloys	5%	Similar or lower costs	Reduced
	Iron-based alloys	5%	Similar or lower costs	Reduced
	Ceramics	5%	Similar or lower costs	Reduced
	Hafnium	5%	Similar or lower costs	Similar
Hardmaterials (carbides and diamond tools)	Nickel	8%	Similar or lower costs	Reduced
	Nickel-Aluminium	8%	Similar or lower costs	Reduced
	Iron	5%	Similar or lower costs	Reduced
	Iron-copper	5%	Similar or lower costs	Reduced
Catalysts	Nickel	0%	Similar or lower costs	Reduced
	Rodium	0%	Very high costs (more than 2 times)	Reduced
Pigments and inks	Zinc	0%	Similar or lower costs	Reduced
	Magnesium	0%	Similar or lower costs	Reduced
Batteries	Lithium-nickel-manganese-cobalt-oxide (NMC)	5%	Similar or lower costs	Similar
	Lithium-manganese-oxide (LMO)	5%	Similar or lower costs	Reduced
	Lithium-iron-phosphate (LFP)	5%	Similar or lower costs	Similar
	Lithium-nickel-cobalt-aluminium-oxide (NCA)	5%	Similar or lower costs	Similar
	NiCd/NiMH	5%	Similar or lower costs	Reduced

METALLURGICAL APPLICATIONS

SUPERALLOYS, HARDFACING, HSS AND OTHER ALLOYS

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 PGMs 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; Sverdrup et al. 2017). Substitution of cobalt in turbine engine components by nickel has been evaluated from poor (Tercero et al. 2018) to adequate (Alves Dias et al. 2018).

HARD MATERIALS

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).

MAGNETS

There is potential for substitution of cobalt-alloyed magnets by nickel-iron alloys, or, primarily, by neodymium-iron-boron alloys (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 2019a).

Other potential substitutes include barium or strontium ferrites (Alves Dias et al. 2018) (USGS 2019).

CHEMICAL APPLICATIONS

BATTERIES

Substitution of cobalt in Li-ion cells is possible by both substitution and reduction of cobalt in usually cobalt containing cell chemistries as well as in substitution of the cell chemistry by a non-cobalt-containing cell chemistry. Typically used and cobalt containing cathode materials for Li-ion batteries are lithium-nickel-manganese-cobalt-oxide (NMC), lithium-nickel-cobalt-aluminium-oxide (NCA) and lithium-cobalt-oxide (LCO). A decrease of cobalt content is possible for both and a currently ongoing trend in battery development due to high prices of cobalt.

Lowering the cobalt content usually leads to adequate to good performance (Alves Dias et al. 2018; Tercero et al. 2018), but with a potential compromise on thermal stability and safety (Cobalt Institute 2019b).

For NMC, several configurations with different cobalt contents are available (Alves Dias et al. 2018). In particular, NMC111 composes of equal proportions of nickel, manganese and cobalt, leading to a cobalt concentration in cathode material of 33 %, while NMC811 utilizes a much higher nickel content leading to a cobalt concentration of only 10 %. Even a complete cobalt-free high-energy NMC cell is conceivable, which comes with high lithium and manganese contents and could reach marked readiness in 2025 (Marscheider-Weidemann, 2021). Nevertheless, the cobalt contents of Li-ion batteries are expected to be reduced rather than eliminated in the future (USGS 2019; Roskill 2019). 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.

There is a wide range of different battery technologies available which could be considered as potential substitutes for the battery chemistries that contain cobalt. Within the Li-ion batteries, lithium-iron-phosphate (LFP) and lithium-manganese-oxide (LMO) are cobalt-free cathode material options. Further potential battery technologies, which also not utilize cobalt are nickel-cadmium (NiCd) and nickel-metal hydride batteries (NiMH). In LMO, NiCd and NiMH technologies, the performance is considered to be lower than for the battery chemistries that contain cobalt, whereas LFP is deemed to perform similar to cobalt containing NMC and NCA batteries. For all potential substitutes, the cost is assessed equal or lower relative to cobalt-based chemistries (Battery University 2018).

Beside the substitution of cobalt in batteries, other energy storages like hydrogen technology or redox-flow batteries can serve as a substitute in specific applications.

PIGMENTS

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 (Alves Dias et al. 2018; USGS 2019; Sverdrup et al. 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 (Alves Dias et al. 2018).

For chemical catalysts, platinum and palladium are also reported as potential substitutes for some of the used cobalt (Sverdrup et al. 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 (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).

SUPPLY

EU SUPPLY CHAIN

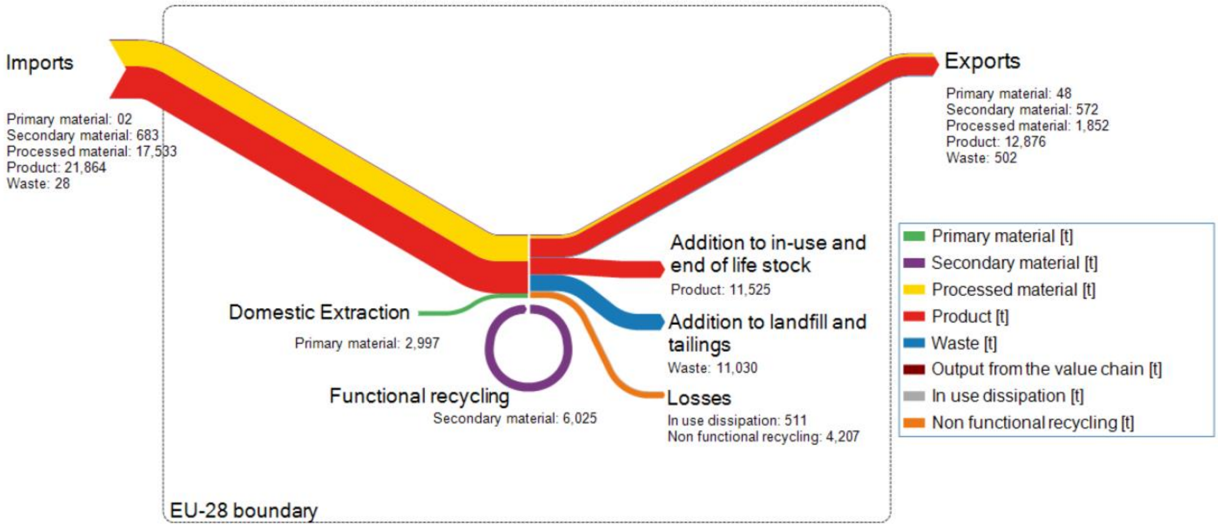

Figure 17. Simplified MSA of cobalt flows in the EU, 2016. (Draft MSA of Cobalt 2019)

An average annual production of 10.7 kt of refined Co is reported in EU during the period 2016–2020 (Eurostat, 2020). The respective amounts of imported and exported metallic cobalt in the same period were about 7 kt and 3.2 kt. Eurostat (2020) provides data in relation to the amounts of various other traded products containing cobalt during 2016–2020. The most significant are: (a) Co oxides and hydroxides (produced: 12.6 kt, imported: 2.2 kt, exported: about 2 kt) and (b) “cobalt mattes and intermediate products” (produced: 6.4 kt only for the years 2019 and 2020, imported: 15 kt, exported: 4.6 kt). The cobalt trade at the preliminary step (primary Co concentrates) in EU is negligible at the range of few hundreds of tonnes (Eurostat, 2020). As it can be concluded, refined Co and cobalt mattes and other intermediated product imports present the most important necessity. The cobalt flows through the EU economy in 2016 are demonstrated in Figure 17Figure 17.

Based on WMD data (WMD, 2022), 1,559 tons of cobalt was produced in Europe 2020 (all from Finland). The EU refinery production of cobalt in the same year was 21,648 tons; of that, 15,148 tons (70 %) was produced in Finland (Iodine et al. 2022). In 2021, Finland produced 14,248 tons of refined cobalt (Tukes 2022). The last numbers are probably referred to the total production including the production by secondary resources. According to JRC data (Matos et al. 2020), the recycling rate of cobalt in 2016 in EU was estimated to 22 %. Superalloys, batteries, and catalysts are the main end-of-life recycled materials. According to recent case studies (León et al. 2020), the recycling rate of cobalt from is expected to be increased during the next years by 5–20 % annually.

SUPPLY FROM PRIMARY MATERIALS

GEOLOGY, RESOURCES AND RESERVES OF COBALT

GEOLOGY

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 0.1–0.4 % 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 deposits mainly worked for nickel. Significant examples are found in New Caledonia and Cuba. Typical ore grades in these deposits range at 0.05–0.15 % 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 0.05–0.1 % Co.

- Shale-hosted polymetallic sulphide deposits. These typically are thin, horizontally very extensive, and subeconomic due to very low metal concentrations. Main commodities may include Ni, Mo, U, V, and Zn, whereas cobalt is in all known cases a potential by-product. Such deposits are known from, e.g., Australia, Canada, Czechia, China, Estonia, Finland, and Sweden. Possibly the only such deposit producing cobalt is the Terrafame Sotkamo mine in Finland, previously known with the name Talvivaara.
- 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 et al., 2017). The highest known concentrations occur in the Pacific Ocean, in the Clarion-Clipperton Zone (CCZ), which extends from off the west coast of Mexico to as far west as Hawaii, and 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). The CCZ resources referred to by Mudd & Jowitt (2022) include 5 deposits jointly forming 1,807.1 Mt of ore with average Co grade at 0.157–0.22 %; these are all CRIRSCO-compliant resources of which 1,737.9 Mt at inferred category.
  Co-rich ferromanganese crusts occur at relatively shallow depths of 800 to 3,000 m (Slack et al., 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 (Roberts and Gunn 2014; Slack et al., 2017). 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 (Sverdrup et al., 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:

The world identified resources of cobalt are about 25,000,000 tonnes (USGS 2022). Because cobalt is typically recovered as a by-product or co-product, especially from copper and nickel ores, demonstrated world resources of the element are not fully indicative of potentially available supplies. Main minerals wherefrom cobalt is extracted include carrollite, erythrite, heterogenite, and cobaltpentlandite. According to USGS (2022), the world known reserves of cobalt (material content) are about 7,800,000 tonnes. About 45 % of the reserves are in the DRC. Additional 18 % are in Australia, 7.8 % in Indonesia and 6.5 % in Cuba (Table 7).

Table 7. Cobalt reserves by country (USGS, 2022). Data for Finland is from Mineral Deposit Database of Finland (2022), and for Greece and Poland from Horn et al. (2021).

Country	*Reserves (tonnes)*		*Country*	*Reserves (tonnes)*
Congo, Democratic Republic	3,500,000		Finland	112,000
Australia	1,400,000		Madagascar	100,000
Indonesia	600,000		Greece	95,000
Cuba	500,000		China	80,000
Philippines	260,000		Poland	75,000
Russia	250,000		USA	69,000
Canada	220,000		Papua New Guinea	47,000
Total, rounded	**7,800,000**			

EU RESOURCES AND RESERVES

The largest cobalt resource in Europe is located at the Terrafame Sotkamo (Talvivaara) polymetallic Ni-Cu-Zn-Co sulphide deposit in Finland. Other significant deposits in Finland, by tonnes of contained cobalt, include Hannukainen Fe-Cu-Au, Kevitsa Ni-Cu-PGE, Sakatti Ni-Cu-PGE, Hautalampi Ni-Cu-Co, and the Juomasuo Au-Co, and tens of smaller deposits (Mineral Deposit Database of Finland 2022). In Sweden, the total reported resources amount to about 24,000 tonnes of cobalt (Eilu et al. 2021a). In Spain, the Corcel deposit has about 6,000 t of cobalt (Eurobattery Minerals 2022). In Greece, resources reported for the lateritic nickel deposits include about 95,000 tonnes of cobalt (Horn et al. 2021). Reserves listed for Poland contain 75,000 tonnes of cobalt and additional 7,300 tonnes of resources but are poorly documented (Lauri et al. 2018). Table 8, Table 9 and Table 10 present cobalt resources and reserves data for the EU.

Table 8. Cobalt resource data in the EU. These are additional to reserves. Note that a number of deposits in Finland is not included, as each contains 20 to 3,000 t cobalt, mostly non-compliant with the CRIRSCO reporting codes.

Country	Classification	Quantity (Mt of ore)	Grade (% Co)	Reporting code	Reporting date	Deposit, Source
Finland	Measured + indicated + inferred	932.8	0.0172	JORC	12/2020	Terrafame mine (Mineral Deposit Database of Finland 2022)
	Measured	50.0	0.010	JORC	12/2021	Kevitsa mine (Boliden 2022)
	Indicated	88.0	0.010		12/2021	
	Inferred	0.2	0.010		12/2021	
	Indicated	3.5	0.11	NI43-101	2017	Sakatti deposit (Anglo American 2017)
	Inferred	40.9	0.04		2017	
	Measured	2.582	0.08	JORC	04/2021	Hautalampi deposit (Seppä 2021)
	Indicated	2.701	0.08		04/2021	
	Inferred	2.186	0.06		04/2021	
	Measured	2.51	0.14	PERC	12/2018	Kylylahti closed mine (Boliden 2019)
	Indicated	3.639	0.11		12/2018	
	Inferred	0.737	0.06		12/2018	
	Indicated	9.6	0.084	JORC	10/2020	

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	Inferred	14.6	0.052		10/2020	Juomasuo deposit (Latitude66 2020)
	Indicated + Inferred	221	0.0135	Historic	12/2012	Hannukainen mine project (Niiranen 2016)
	Inferred	4.86	0.166	Historic	1984	Haarakumpu deposit (Mineral Deposit Database of Finland 2022)
	Inferred	10.907	0.0443	NI43-101	08/2021	Rajapalot deposit (Seppä et al. 2021)
	Inferred	187.77	0.007	Historic	2018	Ahmavaara mine project (Eilu et al. 2021b)
	Inferred	35.6	0.01	Historic	2008	Ruossakero deposit (Eilu et al. 2021b)
Greece	Total resource	137	0.05	JORC	2019	Evia mine (Eliopoulos et al. 2012; Horn et al. 2021)
	Total resource	8.7	0.06	JORC	2019	Ieropigi mine (Eliopoulos et al. 2012; Horn et al. 2021)
	Total resource	43.6	0.05	JORC	2019	Agios Ioannis mine (Eliopoulos et al. 2012; Horn et al. 2021)
Slovakia	Inferred	17	0.016	Historic	2015	Hodkovce deposit (Baco et al. 2015)
Spain	Inferred	60	0.01	NI 43-101	03/2022	Corcel deposit (Eurobattery Minerals 2022)
	Measured + indicated + inferred	2.384	0.01	NI 43-101	2015	Aguablanca mine (Mudd & Jowitt 2022)
Sweden	Inferred	38.3	0.01	Historic	2019	Njeretjakke deposit (Eilu et al. 2021b)
	Inferred	1.139	0.02	JORC	2015	Lappvattnet deposit (Eilu et al. 2021b)
	Total resource	6.37	0.01	NI43-101	2009	Römyrberget deposit (Eilu et al. 2021b)
	Total resource	332.1	0.003	NI43-101	12/2017	Rönnbäcken (Eilu et al. 2021b)
	Inferred	13	0.03	Historic	12/2017	Älgliden deposit (Eilu et al. 2021b)
	Inferred	7.672	0.0344	JORC	12/2018	Kiskamavaara deposit (Eilu et al. 2021b)

Table 9. Cobalt reserves data in the EU. The Polish data, 75,000 tons, are not detailed here, as only aggregated figures for these countries are known.

Country	Classification	Quantity (Mt of ore)	Grade (%Co)	Co content (t)	Reporting code	Reporting date	Source
Finland	Proven + probable	525.2	0.019	99,788	JORC	12/2020	Terrafame mine (Mineral Deposit Database of Finland 2022)
	Proven	72.0	0.010	7,200	PERC	12/2021	

	Probable	52.0	0.010	5,200			Kevitsa mine (Boliden 2022)
Spain	Proven + probable	3.44	0.01	344	NI43-101	2015	Aguablanca mine (Mudd & Jowitt 2022)

Table 10. Aggregated cobalt resource and reserve data in Finland categorised into UNFC classes (Mineral Deposit Database of Finland 2022). Combination classes (e.g., 111+112) given where there is not enough information available to distinguish between individual UNFC classes. Figures indicate Co tonnes. Class 344* indicates additional 'undiscovered' resources at 50 % probability, indirectly estimated from existing geodata, resources which cannot be connected to any yet discovered deposit (Rasilainen et al., 2017 and 2020).

UNFC	111	112	111+112	221	222	223	221+222+223
Co (t)	7,200	5,100	99,788	11,271	38,752	49,349	177,232
UNFC	**332**	**333**	**331+332+333**	**334**	**343**	**344**	**344***
Co (t)	1,622	1,815	944	39,730	39,254	16,204	108,000

EXPLORATION AND NEW MINE DEVELOPMENT PROJECTS IN THE EU

Exploration projects targeting cobalt among other metals in polymetallic deposits were in 2019 ongoing across the EU, mainly in Finland and Sweden, but also in Slovakia, Germany, Spain, Cyprus, Austria, Poland, and Czechia. The extent of cobalt exploration has remained similar since. The more advanced projects are in Finland and Sweden. In Sweden, e.g., the Häggån vanadium project and the Rönnbäcken nickel project at prefeasibility or scoping stage. In Finland, the most advanced are Suhanko PGE, Sakatti Ni-Cu-PGE, Hannukainen Fe-Cu-Au, and Hautalampi Co-Ni-Cu; in all these, work is ongoing for full feasibility and permitting. The Suhanko project includes several deposits of which the largest, Ahmavaara, is listed in Table 8. Elsewhere in the EU, cobalt exploration projects are less developed, even though many are in brownfields areas (e.g., Dobsina in Slovakia and Tisova in Chechia), rarely have any resource estimate published, and in a very few the cobalt is among main commodities of the target deposits.

GLOBAL AND EU MINE PRODUCTION

Global mine production of cobalt from cobalt ores between 2010 and 2020 amounted between 130,000 and 158,000 tons per year (WMD 2022) (Figure 18). Within the EU, 140 to 2,300 tons of cobalt was produced from the mines in the same period, all from Finland (Tukes 2022, WMD 2022). The main global producer of cobalt ores, with 68 % of all cobalt mined in the world in 2020, is the Democratic Republic of Congo (DRC); the second and third largest cobalt miners were Russia and Australia, at 4.5 % and 4.1 % shares, respectively (USGS 2022, WMD 2022). The EU share of the global mined cobalt was 1.1 % – all of that is from Finland. The DRC has been the largest cobalt miner since 1999 (WMD 2022).

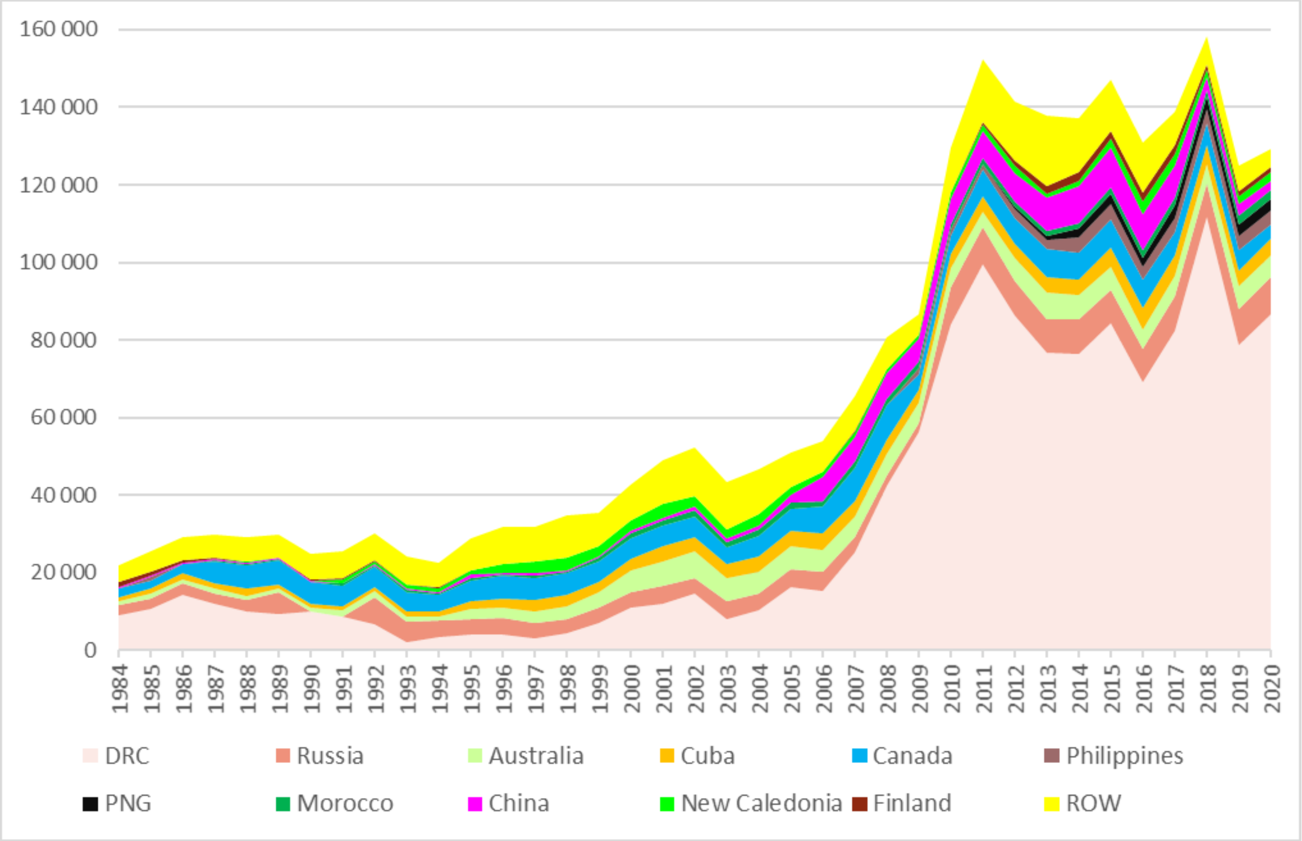

Figure 18. Global mine production of cobalt in tonnes (WMD 2022). DRC = Democratic Republic of Congo, PNG = Papua New Guinea, ROW = rest of the world.

OUTLOOK FOR SUPPLY

Cobalt demand is expected to rise rapidly with the global energy transition aiming substantial decrease in CO_2 emissions in climate change mitigation (e.g., Hund et al. 2020, IEA 2021). In this context, for example the Cobalt Institute (2022) forecasts cobalt demand to increase from the current 175,000 t to 320,000 t by 2026 and the IEA (2021) forecasts the demand to about double by 2040 only due to green energy transition. This would put large challenges for the supply cobalt, unless the battery technology significantly moves towards low-cobalt and no-cobalt alternatives.

According to the Cobalt Institute (2022): "Supply growth will lag demand in the medium term, particularly for mined supply. DRC and Indonesia will contribute close to 90 % of mined cobalt growth in the medium term, with smaller but rising volumes also from the USA and Canada. The key assets in the DRC include the Tenke Fungurume expansion (China Molybdenum Co.), the start of Mutoshi (Chemaf, part of the Shalina Group), Mutanda's ramp up (Glencore), increased output from Katanga (also Glencore), and new cobalt production at Kinsevere (Minerals and Metals Group, which is 66.7 % owned by China Minmetals). In Indonesia, increased domestic mined supply will support the new HPAL refining capacity."

Major additional issues for the supply, in short and possibly medium term, include infrastructure and civil unrest problems in the DRC, covid-19 lockdowns in major ports through which shipping of cobalt concentrates and intermediates are shipped and in refineries in China. Also, the war in Ukraine has resulted in supply uncertainties (JRC, 2022). The latter mostly affects the EU, as the Nornickel Harjavalta nickel smelter and refinery has received a significant part of its raw material from Russia.

No major changes for cobalt production from the EU mines are expected for short to medium term. The currently active mines in Finland (Terrafame and Kevitsa) have expected mine life of, at least, 20 years with the current production. Mines with by-product cobalt may open in 2030s in Finland; these are currently not expected to jointly produce more than perhaps 2,000 to 5,000 t cobalt per year (Törmänen & Tuomela 2021). Similar annual volumes of cobalt could become into market from the laterite-hosted nickel mines in Greece, but there is no information as when such production could start. An additional issue is that the real additional metal production may well be much less than the content in reserves, as only 30–75 % of mined cobalt typically ends up in final products due to losses in flotation and downstream treatment processes (Dehaine et al., 2021; Törmänen & Tuomela, 2021). This loss of cobalt during processing is a direct consequence of the principal focus resting on other commodities in the deposits (Dehaine et al., 2021).

PROCESSING

COBALT MINING

Cobalt is mostly extracted as a by-product of copper and nickel mining. Data67 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 appropriate. Nickel laterite ores are usually refined directly, that is, only after upgraded by crushing and grinding. Most other cobaltiferous 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). The ASM production was expected to decrease compared to production in 2016–2018 due to expected lower global cobalt prices; however, it was at 12 % in 2021 of total production in DRC (Cobalt Institute, 2022).

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; Dehaine et al., 2021). Each product has different cobalt content. Intermediate products are sent to captive refining operations or abroad or sold to refining companies (Roskill 2014).

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; Dehaine et al., 2021):

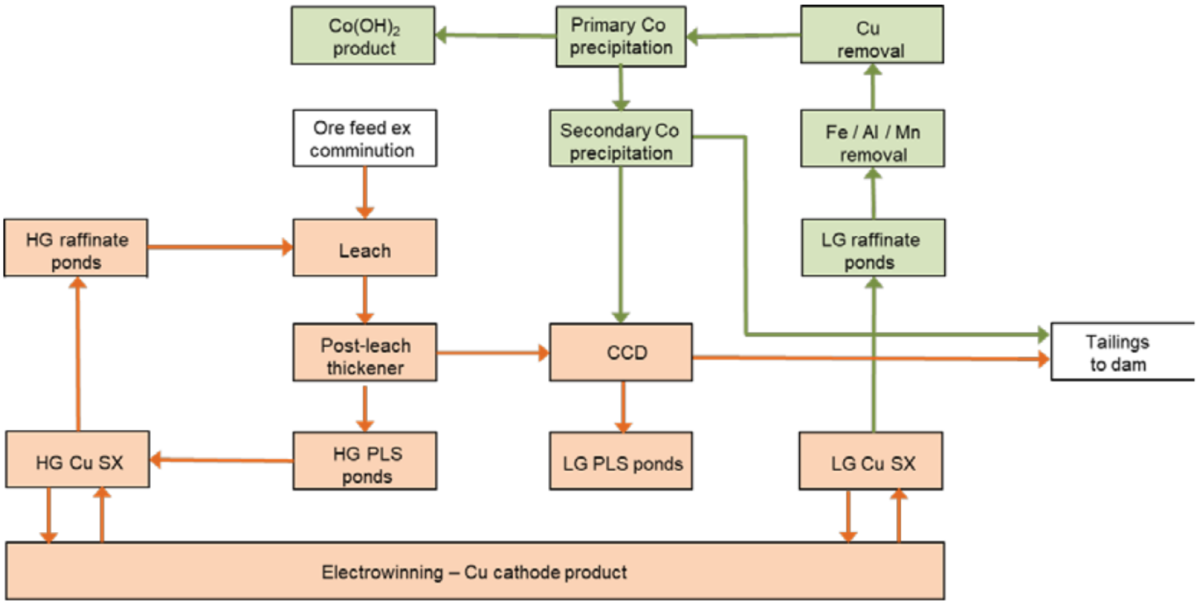

Figure 19. Flowsheet of the extraction of cobalt by Cu-Co sulphide ores (Sole et al. 2018).

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 958211

- 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 (Figure 19). 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.

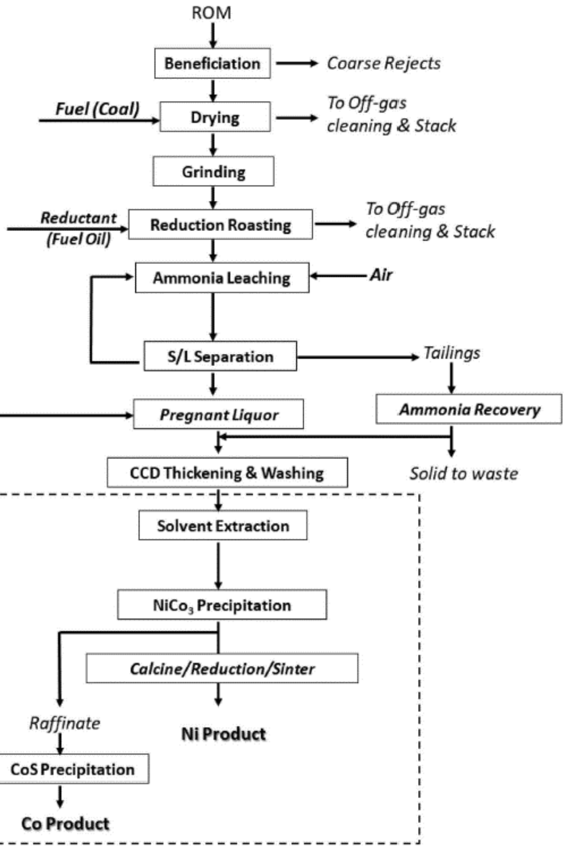

Figure 20. Caron process for the production of nickel and cobalt by laterites (Abhilash and Pandey, 2018).

- 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) or Caron process which involves reduction roasting of the ore followed by ammonia leaching (Figure 20). 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; Dehaine et al. 2021).

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 and 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 (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 at 25–50 %, 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 was estimated that 22 % of the EU annual consumption of cobalt was sourced from end-of-life scrap in 2016 (Draft Co MSA 2019).

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 in 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 expected beyond 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 et al., 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 et al., 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 11.

Table 11. Material flows relevant to the EOL-RIR of cobalt in 2016. Data from (Draft Co MSA 2019).

MSA flow	Quantity (t)
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

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).

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; Roskill 2014; Sundqvist Ökvist et al. 2018). 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).

OTHER CONSIDERATIONS

HEALTH AND SAFETY ISSUES RELATED TO THE COBALT OR SPECIFIC/RELEVANT COMPOUNDS AT ANY STAGE OF THE LIFE CYCLE

The (REACH Regulation, 2006) classifies cobalt nickel oxide, cobalt nickel dioxide and cobalt nickel grey periclase as 1A carcinogens, given that they are known to have carcinogenic potential for humans. Cobalt, cobalt dichloride, cobalt sulphate, cobalt acetate, cobalt nitrate, and cobalt carbonate are listed as carcinogens of class 1B.

According to the International Agency for Research on Cancer (IARC), cobalt and cobalt compounds are possibly carcinogenic to humans (group 2B) (IARC, 1991). (IARC, 2006) included cobalt metal with tungsten carbide in group 2A (probably carcinogenic to humans). Cobalt metal without tungsten carbide and cobalt sulphate and other soluble cobalt(II) salts are listed in group 2B (possibly carcinogenic to humans). On the IARC webpage[3] the evaluation of newly classified materials includes soluble cobalt(II) salts in group 2A and other cobalt(II) compounds (not including Soluble cobalt(II) salts, cobalt(II) oxide, Cobalt(II,III) oxide, and Cobalt(II) sulphide) in group 3, given that they are not classifiable as to their carcinogenicity to humans.

Cobalt is identified as persistent, bio-accumulative and toxic substance and thus it is included in the Appendix 13 of the (REACH Regulation, 2006). For cobalt, a concentration limit of 0.00005 % by weight is set in Annex VIII in tattooing inks and mixtures.

As for the (CLP Regulation, 2008) cobalt was added in 2020 with the following hazard codes: H350 (carcinogenicity 1B, may cause cancer), H341 (mutagenicity 2, suspected of causing genetic defects), H360F (reproductive toxicity, may damage fertility), H334 (respiratory sensitisation, may cause allergy or asthma symptoms or breathing difficulties if inhaled) and H317 (skin sensitisation, may cause an allergic skin reaction).

To date, the (Carcinogens, mutagens or reprotoxic substances at work EU Directive, 2004) doesn't set any limit to occupational exposure to cobalt. Nonetheless, the amendment of March 9th 2022 states that by the end of

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[3] https://monographs.iarc.who.int/list-of-classifications/

2024 the commission will have to propose an appropriate occupational exposure limit to cobalt and inorganic cobalt compounds, once the most up-to-date scientific knowledge has been taken into account. The (US Occupational Safety and Health Standards, 2022) subpart Z “Limits for Air Contaminants” sets a limit of 0.1 mg/m^3 of air as an 8-hour concentration for cobalt metal, dust, and fume (as Co).

ENVIRONMENTAL ISSUES

According to the (Industrial Emissions Directive, 2011) cobalt and cobalt compounds average emissions from industrial activities cannot exceed 0.5 mg/m^3. As for the (CLP Regulation, 2008) cobalt was added in 2020 with hazard codes H413 (chronic aquatic hazard, may cause long-lasting harmful effects to aquatic life).

A Life cycle assessment of the cobalt production from ore extraction to final delivery of the cobalt metal, including electricity generation and waste emissions shows that the dominating impacts category is the global warming potential, followed by resource depletion, eutrophication, and human toxicity. Most impacts are due to fossil fuels consumed to generate electricity for mining, smelting, and refining. The other drivers of health and environmental hazards are the blasting process and diesel burning, emitting particles such as carbon dioxide, nitrogen oxides, fluorides, cadmium, cobalt, arsenic, manganese, and methane. (Farjana et al., 2019)

NORMATIVE REQUIREMENTS RELATED TO MINING/COBALT PRODUCTION, USE AND PROCESSING OF THE MATERIAL

The responsible mining initiative (RMI) developed a set of Standards, for smelters and refiners that participate in the Responsible Minerals Assurance Process (RMAP). The standards development process described in the RMI Standard and Assessment Criteria Development Procedure is guided by the ISEAL Standard Setting Code of Good Practice and includes extensive stakeholder consultations to ensure our standards are aligned with regulatory requirements, meet best practice expectations and are of high quality in a way that is verifiable and promotes the RMAP’s credibility and acceptance by our stakeholders (RMI 2022). The cobalt refiner due diligence standards are available at this page: https://www.responsiblemineralsinitiative.org/media/docs/standards/Cobalt%20Refiner%20Supply%20Chain%20Due%20Diligence%20Standard%20(Version%202.0)_EN.pdf (RMI 2022b).

SOCIO-ECONOMIC AND ETHICAL ISSUES

ECONOMIC IMPORTANCE OF RAW MATERIAL FOR EXPORTING COUNTRIES

Table 12: Countries with the highest economic shares of cobalt exports in relation to their total exports.

Country	Export value (USD)	Share in total exports (%)
Madagascar	105,584,356	3.9
Morocco	84,331,707	0.2
Norway	184,004,430	0.1

Source: COMTRADE (2022), based on data for 2021.

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 958211

Table 12 lists the countries for which the economic value of exports of cobalt represents more than 0.1% of the total value of their exports.

The countries for which this material has a higher economic importance related to their total exports are Madagascar (3.9 % of total exports), Morocco (0.2 %) and Norway (0.1 %). In the three cases, all the cobalt is exported in form of matte or other intermediate products.

SOCIAL AND ETHICAL ASPECTS

Cobalt is mainly mined in the Democratic Republic of Congo (DR Congo) in large-scale mines (LSM), owned by local, Canadian, Australian, European, and Chinese companies, as well as in artisanal and small-scale mines (ASM). Mines' and smelters' discharges into the environment have led to heavy metal contamination of air, water, and soil assets, severely impacting on human health. Even though long-term consequences aren't fully known yet, recent studies of heavily mined regions detected DNA damages and a high prevalence of rare birth defects (Institute for Sustainable Futures, 2019).

A situation of worker exploitation has been reported in Morocco, in the Bouazar Cobalt deposit, run by the Compagnie de Tifnout Tiranimine. Here, 1200 miners work in unsafe conditions at 600 m under the surface, without proper equipment and safeguards against landslides. The company doesn't recognize responsibility for the death of workers and doesn't provide proper protection against dust, which causes silicosis, a typical and widespread miners' disease. In the spring of 2011, the miners started protesting, asking for better protection, higher wages, and overall better working conditions. The rebellion went on until summer 2012, without many results for miners. The small gains were the delivery of professional cards and the distribution of dust-protective masks (Environmental Justice Atlas, 2023a).

In the Indonesian island of Maluku, a joint venture of three Chinese companies runs an integrated nickel mining and smelter project, the "first vertical, from mine mouth to finished products, integrated electric vehicle battery and stainless-steel industry complex in the world". The construction started in 2018 and it entails a pyrometallurgy ferronickel smelter, a cobalt hydroxide production site and plants to produce batteries for electric vehicles. The impact of the project on the environment is huge and includes deforestation, biodiversity reduction, water stream modification and air and acoustic pollution. Moreover, local indigenous tribes, called O Hongana Manyawa, were resettled outside the forest by the government and forced to adapt to conventional lifestyles. In 2019, students and other citizens protested in the city of Ternate asking for a regulation to protect the indigenous tribes and the natural assets of the island. Nonetheless, construction works continue, tribes are being resettled and as of July 2022, a new coal-fired power plant was finished with the aim of providing energy to the new industrial park (Environmental Justice Atlas, 2023b).

RESEARCH AND DEVELOPMENT TRENDS

RESEARCH AND DEVELOPMENT TRENDS FOR LOW-CARBON AND GREEN TECHNOLOGIES

- Cobalt in low-temperature solid-oxide fuel cells (LT-SOFC)

According to (Vinoth Kumar, R. et al., 2022), solid-oxide fuel cells (SOFC) are a promising carbon-free technology for energy production, both for power supply for buildings and for vehicles. Despite their positive aspects, some downsides are limiting their wider application in the market, namely they require high operation temperatures (between 800 °C and 1000 °C). This issue makes this technology expensive, and it accelerates the degradation of the cell components given the high temperature, eventually leading to a short lifetime and reduced applicability in the transportation market. (Vinoth Kumar, R. et al., 2022) reviewed the state-of-the-art of cobalt-based cathode materials for low-temperature (LT, below 600 °C) application in SOFC technology. The authors stress that single-phase, stable cobalt-based perovskites and some related materials are the most suitable thanks to their high performance even at low temperatures. The most promising technology which emerged from the study was a SOFC based on a perovskite cathode (the niobium and tantalum co-doped $SrCoO_3$) with gadolinium doped ceria electrolyte, given that it exhibited a peak power density of 1200 mW/cm^2 at 500 °C.

OTHER RESEARCH AND DEVELOPMENT TRENDS

- CROCODILE project:[4] First of a kind commercial Compact system for the efficient Recovery Of COBalt Designed with novel Integrated LEading technologies (2018-2022)

The CROCODILE project showcased innovative metallurgical systems based on advanced pyro-, hydro-, bio-, iono- and electrometallurgy technologies for the recovery of cobalt and the production of cobalt metal and upstream products from a wide variety of secondary and primary European resources. CROCODILE will demonstrate the synergetic approaches and the integration of the innovative metallurgical systems within existing recovery processes of cobalt from primary and secondary sources at different locations in Europe, to enhance their efficiency, improve their economic and environmental values, and will provide a zero-waste strategy for important waste streams rich in cobalt such as batteries. Additionally, CROCODILE produced a first of a kind economically and environmentally viable mobile commercial metallurgical system based on advanced hydrometallurgical and electrochemical technologies able to produce cobalt metal from black mass containing cobalt from different sources of waste streams such as spent batteries and catalysts.

- NEMARCO project:[5] New Manufacturing Routes (for NiCrSiFeB alloys to) to Replace cobalt in aircraft components (2021-2022)

The EU-funded NEMARCO project targete the development of nickel-based aircraft components that will be more resistant to wear and high temperatures and less harmful to human health. Specifically, the project will work on a new generation of sealing rings for butterfly valves that belong to the cabin pressurisation air

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[4] https://cordis.europa.eu/project/id/776473

[5] https://cordis.europa.eu/project/id/101007948

purging system. These rings are currently manufactured using cobalt-based alloys. New NiCrSiFeB alloy compositions were explored by adapting centrifugal casting manufacturing parameters or using additive production processes (laser metal deposition). A rigorous lifecycle assessment and a preliminary toxicity study will be carried out to evaluate the environmental and economic impact of the new developments.

- Resilience assessment of the cobalt supply chain in China under the impact of electric vehicles and geopolitical supply risks[6], Liu et al. (2023)

Cobalt, one of the essential new energy materials, is widely applied in many crucial industries. In recent years, the rapid development of electric vehicles (EVs) has led to increased cobalt demand, and geopolitical changes have increased the risk of cobalt supply disruption. To investigate the impact of geopolitical risks and demand shocks of EVs on the cobalt supply chain system, we applied the system dynamics model to assess the cobalt supply chain resilience and construct four subsystems of price, production capacity, supply, and demand to explore the resilience mechanism of the cobalt supply chain. Through Vensim simulation experiments, three resilience enhancement measures from recycling technology, inventory, and material substitution under the impact of the EVs demand and geopolitical supply risks were used as model scenarios.

- Study on cobalt removal process of polycrystalline diamond compact with high efficiency and environmental protection[7], Zheng et al (2023)

Polycrystalline diamond compact (PDC) is a widely used superhard material that needs to be treated with cobalt removal to enhance its thermal stability. However, the traditional acid soaking process has some shortcomings, such as low cobalt removal efficiency, high cost and unfriendliness to the environment. To solve the above problems, this research used a self-made electrolytic system to study the electrolytic cobalt removal process of PDC and uses the control variable method to explore the influence of current density, electrolyte concentration and pH on the electrolytic cobalt removal process.

- Cobalt nanoparticles for anticancer treatments

(Huangshao, H. et al., 2021) reviewed the synthesis methods and anticancer functions of cobalt oxide nanoparticles (CONP, including CoO, Co_2O_3 and Co_3O_4). As reported by the study, CONPs can be directly used as anticancer drugs to damage tumoral cells or, by contrast, to protect healthy cells during chemotherapeutics, reducing the side effects of this practice. Furthermore, the authors state that cobalt nanoparticles might also be used to increase the effects of immunotherapy as anticancer vaccines, or to be applied in photothermal therapy of cancer. Finally, similar to many other nanoparticles, CONPs could act as drug carriers for anti-cancer drug delivery, improving their targeting.

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